A STUDY OF ALTERNATIVE FORMS OF FLEXIBLE MANUFACTURING SYSTEMS

by

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TO SUE, THE CHILDREN AND

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DECLARATION

No part of the work described in this Thesis has been submitted in support of an application for any other degree or qualification of this or any other University or other Institution of Learning.

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T. K. Dan

ABSTRACT

The study relates to manufacturing conditions in a particular company. Flow synthesis and cell formation analysis have been conducted. A modification of methodology proposed by other researchers has assisted analysis.

The main investigation is concerned with modelling, simulation and evaluation of seven alternative FMS configurations conceived for the machining cell manufacturing prismatic parts. The alternative systems encompass 6 CNC machines with (i) manual transport of materials and tools, (ii) with two and four station automated pallet changers, (iii) conveyor system, (iv) stacker crane, (v) rail guided shuttle, and (vi) AGV transport.

Simulation programs written in ECSL were used for some 264 tests of performance using various resources of manpower, in-process work stations and pallets/trolleys. Measures have been obtained in regard to relative output, average process times, unmanned machining times, machine and manpower utilisation, and utilisation of automated transport systems.

Cost appraisal of alternative systems based on annual average production cost with discounted cash flow, and Investment Analysis have been performed. The FMS configurations have been ranked in order of superiority relating cost to the attainment of company output requirements and to average process time.

A limited investigation of the financial advantage of direct and incremental automation over a seven year time span for five selected sequences of system automation has also been made. The analysis has aided in identifying the conditions under which direct and incremental automation may be appropriate. It is clear that the superiority of incremental automation cannot be assumed for all conditions.

SYNOPSIS

The study examines the part spectrum for a product line manufactured in-house in a particular industrial firm. A manufacturing flow synthesis is performed and three FMS cells for the manufacture of prismatic, disc/disc gear and shaft/shaft gear components are defined. Methods of cell formation are examined, and an approach which removes arbitrary aspects in the methodology developed by other researchers is proposed. The development of the technique focuses on cell formation aspects in relation to FMS systems.

The main investigation is concerned with modelling, simulation and evaluation of seven alternative FMS cell configurations, each comprising 6 machining centres conceived for the manufacture of prismatic parts. The alternative systems encompass CNC machines with (i) manual transport of materials and tools, (ii) with two and four stations automated pallet changers, (iii) conveyor system, (iv) stacker crane, (v) rail guided shuttle, and (vi) AGV transport. The systems have been modelled to meet the requirements existing in the company such as output volume required, part/machine dedication, batch production, scheduling, tool management and fixturing practice.

Simulation programs written in ECSL are used for some 264 tests of performance using various resources of manpower, in-process work stations and pallets/trolleys. Measures have been obtained in regard to relative output,average process times, unmanned machining times, machine and manpower utilisation, and utilisation of automated transport systems.

An appraisal has been made of the cost effectiveness of the

alternative systems by estimating average production cost on the basis of Discounted Cash Flow (DCF). In addition Investment Analysis based on Net Present Value (NPV) techniques has been performed. Cost analysis has considered different conditions such as manpower levels and output volumes. The different FMS configurations with preferred resourcing have been ranked in regard to the cost of achieving particular output requirements.

Conclusions drawn indicate that CNC machines with automated pallet changers and specific associated manpower could achieve output levels required by the company at lesser cost than the more fully automated systems. However, advantage can be expected from two systems in regard to marked reductions in average process time, viz. from the rail guided shuttle system and the integrated conveyorised transport system. It should be kept in mind that the conclusions drawn are qualified in regard to related conditions and resourcings. The study has supported an expectation of advantage in regard to reducing average process time and manpower requirements. No advantage was found for increasing the number of AGVs beyond two units. Other conclusions provide insight into machine utilisation, manpower utilisation , and unmanned operation from shift work.

A limited exploratory investigation of the financial advantage of direct and incremental implementation of alternative configurations over a seven year time span for five selected sequences of system automation has also been made. Five sequences were examined for two methods of incremental automation: Single stage and Two stage implementation. The analysis has aided in identifying the conditions under which direct and incremental automation may be considered. It is clear that the superiority of incremental automation cannot be assumed for all conditions.

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CHAPTER 1

ASPECTS OF FLEXIBLE MANUFACTURING

1.1 INTRODUCTION TO FLEXIBLE MANUFACTURING

The twentieth century is noteworthy for rapid advances in science and technology in general and in the worldwide expansion of industrial production. Companies are being increasingly confronted with the need for frequent and rapid changes in product design in response to business competition and changing market demands. Greater attention is being focused on the manufacturing function in order to transform it into major competitive advantage as reflected by improved performance such as faster introduction of new models, reduction in throughput time, lead time and work-in-process. These benefits have been sought by leading companies from a marked improvement of workflow and reduction in stock levels releasing capital to general business advantage and for investment in manufacturing facilities. Increasing effort is also being directed at the attainment of better product quality.

Advantages of flexibility have been sought alongside developments in the application of automation in companies manufacturing under conditions of batch production. A reduction in batch sizes has been pursued which assists an improvement of workflow and reduces work-in-process investment. In addition to concomitant objectives of cost reduction and high resource utilisation, modern concepts of manufacturing strategy seek to incorporate such features within the overall goal of obtaining high levels of customer satisfaction.

The concept of Flexible Manufacturing has been described in a Guide published by the Institution of Production Engineers, England (1986) as the "provision of a total facility which can serve a volatile market with minimum response time from order input to saleable product using the minimum of working capital". However, the concept of flexible manufacturing systems has been interpreted differently by various authors.

For example, Hartley (1984) describes flexible manufacturing systems (FMS) as a system of combining the flexibility inherent in computer controlled machines with very low manning levels. Kochan (1986) views FMS as the combined action of four "flows" - the parts flow, the tool flow, the information flow and the energy flow. The International Institution of Production Engineering Research (CIRP) (1986) adopted the definition of FMS, "or more correctly Flexible Manufacturing Production System (FMPS) as an automated system which is capable, with a minimum of manual intervention, of producing any of a range or family of products for which the system was designed. The flexibility is usually restricted to the family of products for which the system was designed".

Emphasis on different aspects of FMS is reflected in the various definitions that have emerged. Characteristics which are integral to this advance in manufacturing practice are the inclusion of flexibility in the planning and control of manufacturing operations together with the application of chosen levels and forms of automation.

Bouchut and Besson (1983) observed that transformation of production systems has closely followed the development of mechanical and electro-mechanical automation, and in particular advances in electronics and computer technology. Growing attention to the importance of Advanced Manufacturing Technology (AMT) has been complemented by notions of improvement of flexibility by the use of Group Technology (GT).

Gallagher and Knight (1986) explain the basic GT concept as one which is to "identify and bring together related or similar parts and processes, to take advantage of the similarities which exist, during all stages of design and manufacture". By this method benefits such as lead times, improved work flow, reduced work-in-progress, improved output, and reduced changeover times and materials handling may be attained with production planning flexibility.

With advances in manufacturing technology it is possible to combine different machining operations on a single machine, and processing is achieved in less time with improved quality of the end product. The new machines are more flexible with the addition of computer numerical control (CNC). These machines may be operated as independent stand-alone systems or can be organised into production cells. Jackson (1978) explains that cellular organisation enables parts "to progress speedily from machine to machine, either individually or in small batches, thus reducing considerably the inter-operational losses". Flexibility of these production cells may be further enhanced by the introduction of automated transport and handling systems, computer hardware, and software. However, these systems are expensive and, with the widening of technological advance, the decision making in production systems design becomes increasingly complex.

1.2 CELLULAR MANUFACTURING ASPECTS OF FMS

The process of design and planning of the transformation of a traditional production system into a new flexible manufacturing system presupposes a consideration of the organisational aspects. Indeed, Gallagher and Knight (1986) quote E. Merchant, previously Director of Research Planning at Cincinnati Milacron, who viewed "GT as the underlying organisational principle of computer integrated manufacturing systems". An analysis of work flow is fundamental in the formation of flexible manufacturing cells.

1.2.1 CELL FORMATION

In traditional GT, the approach involved a grouping of parts according to their similar characteristics such as machining operations. Machines were then grouped to match the machining sequence of related groups of parts. However, the combination of operations performed by several machines (such as milling, drilling, boring, etc.) by the use of machining centres has a marked influence on work flow. The benefits of the cell approach have been pursued, for example by Jackson (1978), Athersmith and Crookall (1974), Willey and Ang (1980), Wemmerlov and Hyer (1987), Black (1983) with cell formation methods based on machine-component grouping techniques.

A good review of techniques for machine-component grouping is given by King and Nakornchai (1982), who classified the variety of approaches into similarity coefficient, set theoretic, evaluative and other analytical methods. Moreover, King and Nakornchai observed "that there is a considerable overlap and interrelationship between these methods".

(a) Similarity Coefficient Methods

The similarity coefficient method was first suggested by McAuley (1972) who measured the similarity between machine pairs, and on this basis grouped machines into families using a dendogram approach. The degree of similarity is given by Jaccard's coefficient which is defined for a machine pair as the number of components which visit both machines, divided by the number of components which visit at least one of the machines. King and Nakornchai point out that a drawback of this type of coefficient is "that equal weightings are given to the requirement and nonrequirements of a particular component insofar as the machines are concerned". As King and Nakornchai (1982) indicate the equal weightings given to "requirements and nonrequirements" of components for machines can result in two machines having a low similarity coefficient although they may process a large number of parts between them. The arbitrary setting of the "threshold value" for the similarity coefficient will cause coefficients lower than this value to be ignored in the next stage of the algorithm. Rajagopalan and Batra (1975) attempted to systematise the selection of the threshold value of the similarity coefficient in their graph theoretic method which used cliques of the machine graph as a method of classification. However, King and Nakornchai point out that the arbitrariness has not been eliminated, and that "because of the high density of the graph, a very large number of cliques is usually involved and many of the cliques are not vertex disjointed".

A modified approach of Burbidge's Production Flow Analysis (PFA) was suggested by De Beer et al (1976) and De Beer and

De Witte (1978). A notable step in their technique is the "development of a method of cell formation based on an analysis of operation routings and the divisibility of operations between machines and hence between cells, this divisibility being governed by the numbers of machines of the required types that are available for undertaking specific operations. These categories of machine types are defined as primary or key, where only one such machine is available; secondary where several machines are available; and tertiary, where there are sufficient machines available to be able to assign to each cell if required". The method was extended by De Witte (1980) to take into account the interdependence of machine types in the three classes of machines. In this regard, he introduced three similarity coefficients which are different from Jaccard's.

(b) Set-Theoretic Methods

Techniques based on set-theory were developed by Purcheck (1974) which employed "union operation to build up supersets of machines and components". King and Nakornchai (1982) report that this was extended by Purcheck with a "classification scheme which combines machine requirements and sequences by coding them in the form of strings of letters and digits". However, these code lengths tend to be long and Purcheck (as mentioned by King and Nakornchai) devised various complex mathematical formulations for this purpose.

(c) Evaluative Methods

Production Flow Analysis (PFA) due to Burbidge (1971) is one of the first systematic approaches to machine-component grouping. Burbidge describes his method as a technique of "finding the families of components and associated groups of machines for group layout ... by a progressive analysis of the information contained in route cards ..." However, this relies on one's ability to recognise patterns by careful inspection and can be time consuming. As King and Nakornchai (1982) mentioned "Burbidge's approach consists of a series of subjective evaluations, which require substantial local knowledge in order to make any well informed judgments. It is not surprising, as has been discussed by Edwards and El Essawy, that most of the attempts to apply the procedures have not been entirely satisfactory". However, Burbidge's method did indicate the necessity for demarcating the problem into manageable sizes.

Similar to PFA is Component Flow Analysis as proposed by El Essawy and Torrance (1972). However, unlike Burbidge they do not partition the problem. De Beer and De Witte (1978) extended Burbidge's method to give their Production Flow Synthesis which took into account machine duplication and its different characteristics. King and Nakornchai (1982) have pointed out the absence of a systematic approach to the problem of cell formation in the methods developed so far.

(d) Other analytical methods

A matrix clustering technique has been proposed by McCormick et al (1972) called the Bond Energy Algorithm. It is heuristic in nature and will reveal any block diagonal form if one exists. King (1980) introduced his Rank Order Clustering (ROC) Algorithm which is based on binary ranking of the binary machine-component incidence matrix. However, computational difficulties and limitations exist insofar as the number of parts and machines in the problem and the sorting procedure rapidly increases in complexity. The method was extended by King and Narkornchai (1982) in order to overcome the above mentioned difficulties in their ROC2 algorithm. However, the method still does not consider machine capacity constraints.

1.2.2 FURTHER DEVELOPMENTS

With the development of GT systems into different forms of flexible manufacturing systems, additional developments and/or extension to previous cell formation techniques, from recent literature are now considered. They take into account other aspects and relationships in cellular manufacturing systems.

Green and Sadowski (1983) developed mathematical relationships for machine density and job density for studying the commonality of machines to production cells. Lemoine and Mutel (1983) identified an iterative technique based on the dynamic cluster principle for the automatic recognition of machine cells and part families. The method is based on an algorithm which minimises a criterion based on weights and distances of two points in two subsets representing the machines and parts, using the centre of gravity of sets. The algorithm uses three functions and the criterion decreases as the parts partition and machine partition converge. However, a drawback of the method is that it requires an initial partition of the machines into cell subsets.

Tonshoff et al (1982) used cluster analysis for developing a FMS for rotational parts, based on part similarity and workpiece description. Malik et al (1973) considered various operational characteristics and plant layout alternatives in the formation of cells in group manufacture.

Vanelli and Kumar (1986) noted the necessity of identifying minimal bottleneck cells for grouping part-machine families. This method is a graph theoretic approach which is equivalent to finding the minimal cut-nodes of a graph while partitioning the graph into subgraphs, and then applying a dynamic programming approach to identify bottleneck cells. However, the choice of part subcontracting and machine duplication to decompose a system into non overlapping families is left to the user.

Chandrasekharan and Rajagopalan (1986) used a clustering algorithm to produce part-machine groups in cellular manufacturing. The main features of this technique is the use of an ideal seed to make the clustering non-hierarchical as opposed to the dendogram approach used previously by researchers. However, the selection of the ideal seed relies on informed judgement.

A computerised approach was developed by Waghodekar and Sahu (1984) for machine-component cell formation in group technology. A notable aspect of this technique is that although it is based on a similarity coefficient approach, the authors use coefficients of the product type as opposed to the additive type referred to previously. An extended similarity coefficient method (SCM) has been described by Seifoddini and Wolfe (1986) to form independent machine cells. The method includes duplication of bottleneck machines on the basis of the number of intercellular moves. By manually changing the threshold value of the similarity coefficient alternative solutions may be examined. An interesting departure from the similarity coefficient approach is the use of dissimilarity coefficients by Lashkari et al (1987) who employed an integer programming technique to form part families. However, they identify the need for testing with larger number of parts, different branch and bound, and linearisation strategies. Attempts to evolve the cell formation problem from a GT to an FMS scenario were tried by Kusiak et al (1985) and Dutta (1984). The former considered part-fixture grouping and developed a heuristic algorithm in the light of the scheduling problem in flexible manufacturing systems. The latter investigated the part-tools approach and cell formation by analysis of tooling homogeneity of part groups. These techniques would be of interest in further division into sub-cells after an initial FMS cell formation procedure. Ballakur and Steudel (1987) developed a heuristic for part-machine grouping which considered practical criteria such as within-cell utilisation, workload fractions, maximum number of machines assigned to a cell, and percentage of component operations completed within a single cell. Another heuristic has been proposed by Askin and Subramanium (1987) which took into account costs of work-in-process and cyclic inventory, intra-group material handling, set-up, variable processing and fixed machine costs. This approach uses King's (1980) clustering algorithm.

Recent work forming extensions of previous techniques such as King's Rank Order Clustering (ROC) method are also evidenced in the literature. Chandrasekhar and Rajagopalan (1986) combined the ROC algorithm with a block and slice method, which they call

MODROC (Modified ROC), of obtaining non-intersecting part families and intersecting machine cells. The latter is derived by using a hierarchical clustering method. Chandrasekhar and Rajagopalan (1987) later broadened the scope of their previous non-hierarchical clustering method by introducing different seeding methods initially, to be followed in the last stage by an ideal seeding method. This technique has been termed ZODIAC by the authors.

Leskowsky et al (1987) developed a variation of McCormick's method, and used a class of comparison functions to decide which machines or parts to add to which group. They focused on Vanelli and Kumar's production constraints of the necessity of sub-contracting certain parts. However, their approach was to keep the cell boundaries invariant, since they considered it as a plant layout problem, and sub-contracted parts which did not fit.

1.2.3 REFLECTIONS ON THE APPROACH TO CELL FORMATION

Many of the above methods of machine-part grouping were developed in relation to GT. They ignore the real and practical aspects of flexible manufacturing systems. For example, machine requirement criteria which may depend on multi-shift modes of operation as is the case in most FMS are not considered. Some methods duplicate machines in different cells merely due to the presence of a few "difficult" parts. The machine requirement is likely to be constrained by the tool and fixture management methods adopted in a particular cell. It is necessary to consider also whether these activities occur together or sequentially and the extent of their dependence on manpower resources and the method of allocation of men to machines in the cell.

Additionally, production cells in FMS are not necessarily totally independent of one another, since the FMS concept presumes some degree of integration of the cells in a particular system. This can take the form of intercell automated material handling together with computer integration. Intercell transport systems in many industrial FMS installations access an automated storage and retrieval system (AS/RS). Thus the problem in FMS cell formation is one of minimisation of intercell material handling associated with the degree of cell differentiation. Also, because of the flexibility implied in FMS, the cell formation problem need not be subject to rigid system constraints.

Many of the techniques examined for the derivation of machine-part clusters, ignore some interrelationships which may be important within the part set and machine set. Furthermore, the cell boundaries in real problems are not usually invariant. Thus a consideration of fundamental requirements in cell formation should include:

(a) Machine capacity and requirement analysis;
(b) Systematic examination of part-machine interrelationships;
(c) Consideration of varying levels of cell differentiation;
(d) Level of automation and cell operational characteristics; and
(e) Any other constraints or influences specific to a particular system design.

It should be kept in mind that the level of flexibility incorporated in a cell may be influenced by the corporate strategy set at higher echelons of the management structure in a company. For example, Baer (1988) reported that when Cummins Engines installed a flexible machining line for a new brake product recently, it was looking for a new market to supplement its established diesel engine production. The company went in for a system with greater flexibility in order to lower the risk associated with the new brake. The firm compared the costs of flexible and dedicated automation. The initial costs of flexible automation were reported to be two to five times higher, but the programmable flexible tooling was two to three times cheaper to change. Cummins thus invested in a FMS with AGV transport. The new product (brakes) proved to be an unexpected success from the start with demand increasing further. Subsequently, the company transferred brake production to a higher volume dedicated cell. The installed FMS was then shifted to other products, thereby yielding a return of more than 40%.

1.2.4 LEVELS OF AUTOMATION

In much of the technical and commercial literature there is a preference for a phased implementation of FMS. For example, KTM (1987) recommends a step-by-step automation to FMS approach using its Fleximatic machining centres. Phasing ensures that production of components is maintained while the system is automated in incremental steps. Of no less importance is the fact that this approach helps to smooth out cash flow over a longer period. However, use of standard hardware elements and modular software does require long term commitment by both user and supplier.

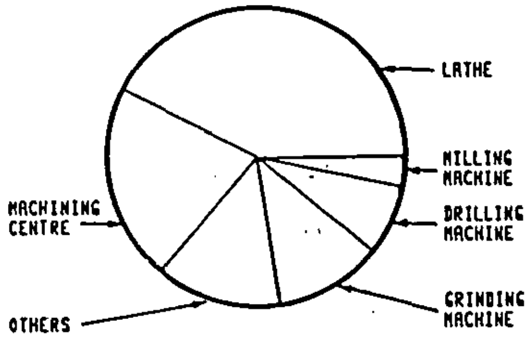
A survey conducted by Edghill and Davies (1985) which examined some 107 FMS installations worldwide, revealed a clear dominance of prismatic component machining and a corresponding dominance of machining centres among the machine tools in the FMS. Figs. 1.1 (a) and (b) gives a breakdown of machine types in the systems studied. Machining Centres are establishing themselves as stepping stones to FMS in the incremental approach to automation, as concluded by McBean (1982) from his experience in industry.

Fig. 1.2 (a) illustrates the various stages in the implementation of incremental automation for the machining of prismatic parts. The diagram draws on the outline by Bullinger (1986) as proposed for turned parts and shown in Fig. 1.2 (b). It may be noted that FMS for machining embrace a wide variety of systems combining various levels of automation in the primary and secondary functions. It is clear that for any FMS having lower levels of automation there is a greater need for manual intervention. Bullinger (1986) notes that for complete unmanned operation, the machine must be able to monitor itself as illustrated in Fig. 1.3. He further observed that a basic condition for the step-by-step increase in degree of automation is that the individual components be compatible among themselves as well as 'upwardly' with regard to their material and information flow interfaces.

1.3 EXAMINATION OF FMS TECHNOLOGIES

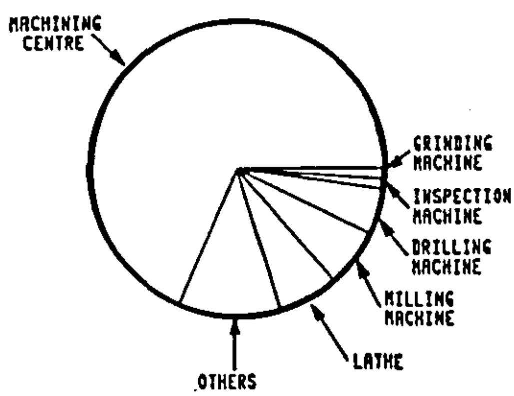
1.3.1 SYSTEM CONFIGURATION

There are many possible ways of configuring Flexible



MACHINE TYPE	NUMBER	%
LATHE	40	42.6
MACHINING CENTRES	20	21.3
OTHERS	13	13.8
GRINDING MACHINE	11	11.7
DRILLING MACHINE	7	7.4
MILLING MACHINE	3	3.2
INSPECTION MACHINE	0	0
TOTAL	94	100

Fig. 1.1a: Proportion of Machine Types in Systems Configured to Produce Rotational Parts
{extracted from Edghill and Davies (1985)}



MACHINE TYPE	NUMBER	%
MACHINING CENTRES	463	68.2
OTHERS	78	11.4
LATHE	46	6.7
MILLING MACHINE	44	6.5
DRILLING MACHINE	34	5.0
INSPECTION MACHINE	8	1.2
GRINDING MACHINE	6	1.0
TOTAL	679	100

Fig. 1.1b: Proportion of Machine types in Systems Configured to Produce Prismatic Parts
{extracted from Edghill and Davies (1985)}

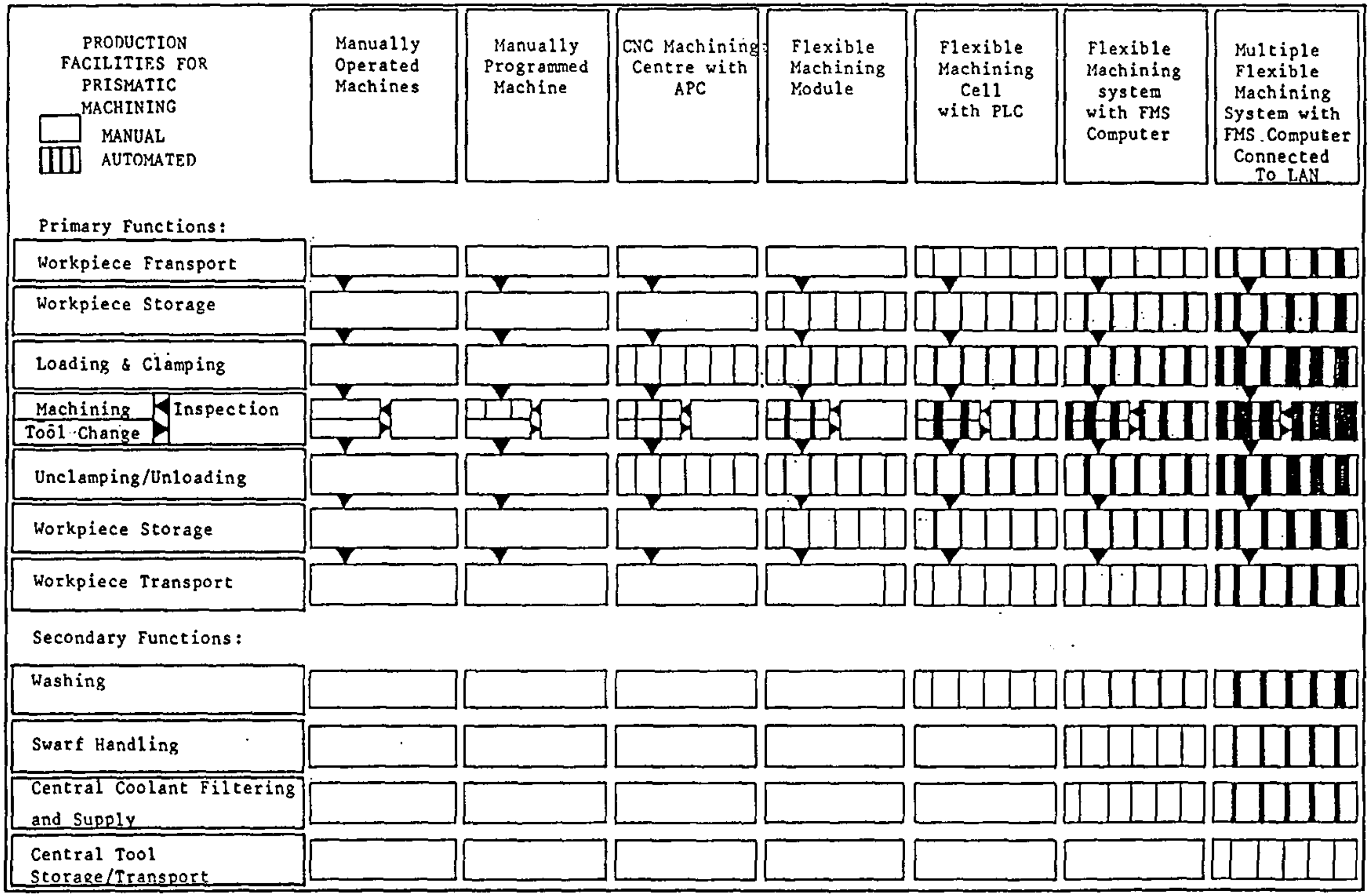


Fig. 1.2a: Incremental Automation of Machining of Prismatic Parts

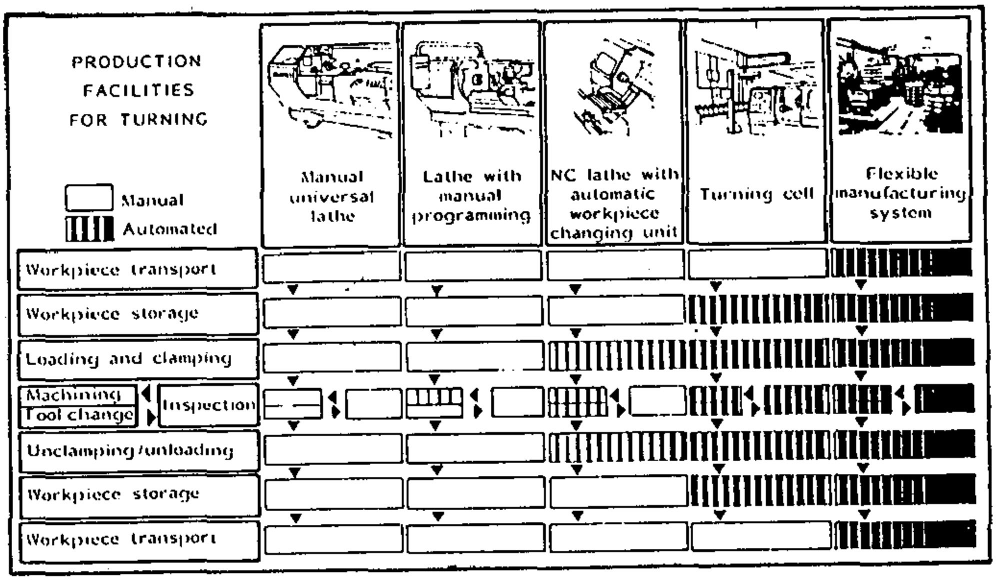


Fig. 1.2(b): Incremental Automation for Machining of Rotational Parts
{Extracted from Bullinger (1987)}

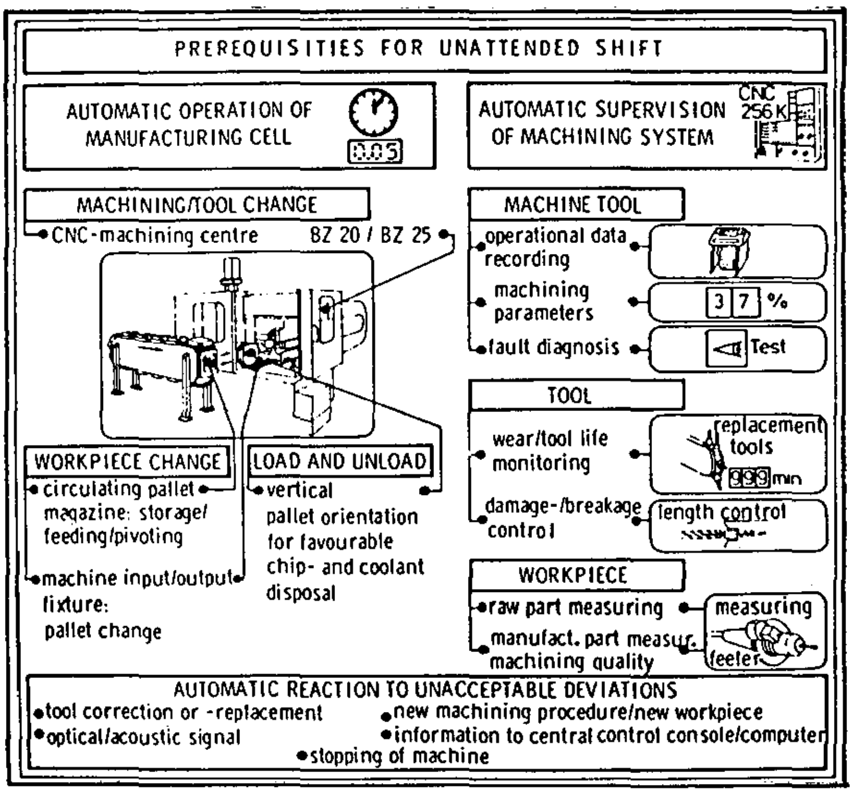


Fig. 1.3: Prerequisites for Unattended Shift on a Machining Centre
{Extracted from Bullinger (1987)}

manufacturing systems. They vary in the way the main subsystems are combined, i.e. the work stations, material handling system, and the computer control system, in a particular FMS structure. Fig. 1.4 shows 12 possible FMS configurations from industry as noted in a Toyoda Machine Works Ltd Technical Bulletin (1983). A brief review of the technology used in FMS is given below.

1.3.2 WORK STATION COMPONENTS

1.3.2.1 Machine Tools

The part spectrum to be produced by a FMS generally determines the type of machine or mix of types of machines to be included in that FMS. Horizontal machining centres are key metal removing machines in some Flexible Manufacturing Systems. However, it is often the case that in such machines the fixtured part is cantilevered away from the table surface aggravating accuracy problems as well as wear and failure mechanisms. For these reasons and particularly machining requirements (e.g. parts requiring precision boring) greater reliance may be placed on vertical machining centres. The need to mount multiple workpieces on a pallet/fixture can lead to the purchase of larger machining centres with suitable work cubes.

Scrase (1987) reviews the state of the art in machining centres and observes that sales for vertical machines are nearly twice that of horizontal machines. However, there appears to be a recent trend towards horizontal machines especially in unmanned and minimal manning applications. This is notwithstanding the higher costs, typically 50% more, for horizontal machines. Since

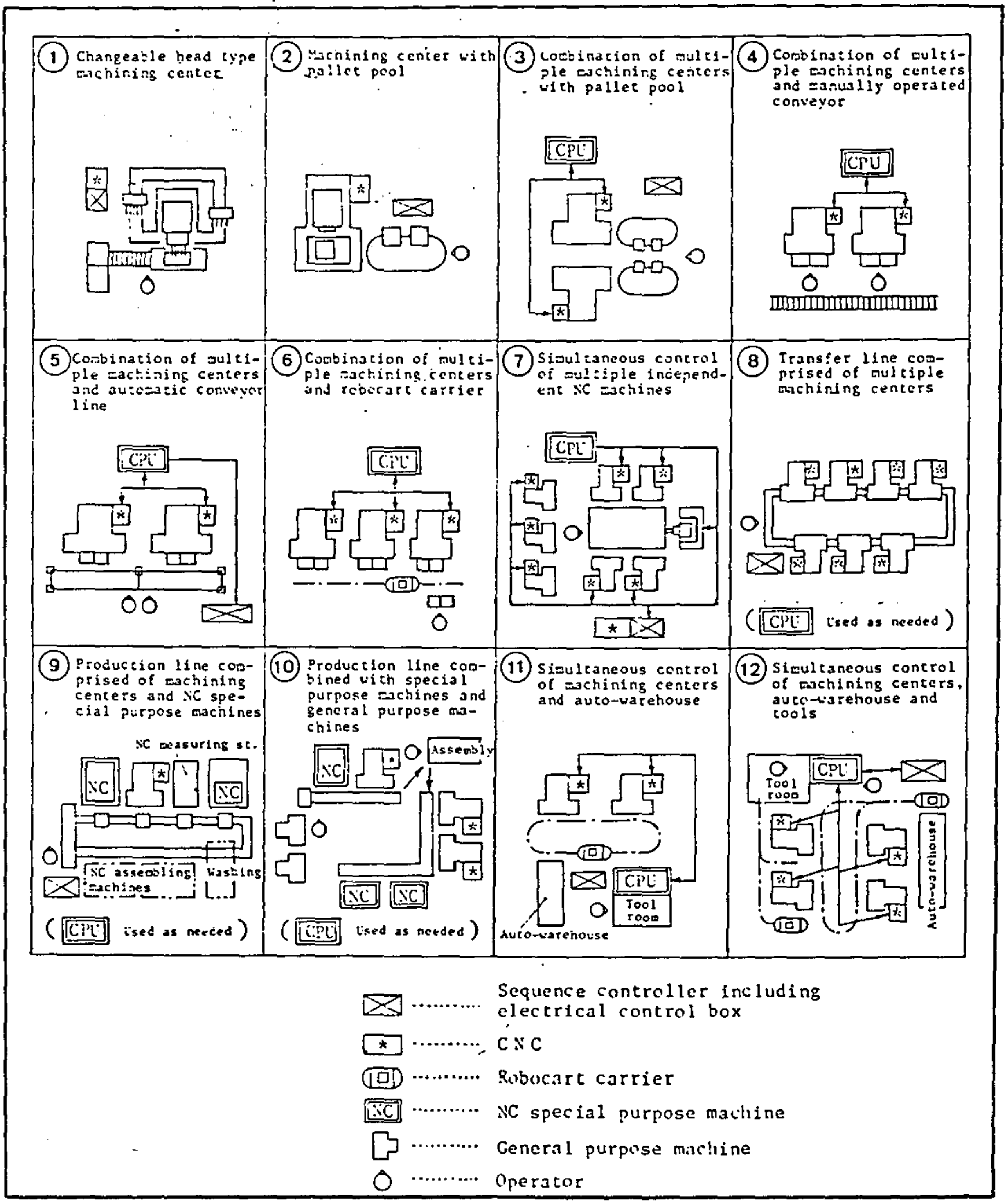


Fig. 1.4: Examples of FMS Configuration
{extracted from Toyoda Technical Bulletin (1983)}

the development of multipallet systems for vertical machines, the advantages of horizontal machines in this area have largely been negated. Fixturing is easier on vertical machining centres. Other features in current machining centres are high metal removal rates, multiple spindles, advanced programming features, tilt and rotation of work surface, modular construction, faster automatic pallet changing, faster and more accurate set-up by semi-skilled operators, and larger pallet pools or carousels.

The trend in machining centres has also been towards larger tool magazines. Sometimes the tool magazine is in the form of an automatic removal drum. Faster tool changing devices and methods are being implemented, as well as tools with erasable identification systems. There is also a move towards standardisation of tool holders and therefore tool pockets in tool magazines. Centralised automatic tool stores serving several machining centres have also been developed as, for example, at Yamazaki as reported by Elmaraghy (1985). In this application a rail guided shuttle transports tool drums between machining centres and tool room.

1.3.2.2 Load/Unload Stations

The principal requirements of load/unload stations are a clean support for the pallet in a position accessible to the material handling system, pallet manoeuvrability or accessibility. The pallet support may consist of fixed stands or have a hydraulically operated table that works in conjunction with the material handling system. This integration is aided with appropriately mounted sensors and status-update systems. Work at the Load/Unload station includes loading and unloading of piece parts onto fixtured pallets as well as mounting and demounting of fixtures after completion of a batch. This function may be performed by robot manipulators for rotational parts with their greater symmetry but it is usually manual for prismatic parts. More often than not prismatic parts and fixtures tend to be heavier than rotational parts.

1.3.2.3 Wash Stations

To prevent interference with system operation and any precision coupling mechanisms on pallets and load/unload stations, the cleaning operation is performed immediately after the machining sequence. Cleaning of prismatic parts consist of washing of the part, fixture and pallet. This is less of a problem for rotational parts as most of the swarf falls away with the coolant.

Typical operation sequence of a washing station is demonstrated by the Fleximatic 700R machine on show at the MACH-1984 exhibition, and developed by CERA of Mitcham, Surrey. It has a work envelope of 700 mm cube and is able to accommodate loads of up to 1 tonne. The washing process is carried out by five Flexi-jets, four mounted at fixed overhead positions within the washing cabinet and the fifth held in the robot arm. The microprocessor controlled robot mounted Flexi-jet is programmed to produce optimum spray pattern and/or pulsation for the particular part. The robot will direct a high pressure pencil jet of fluid into holes, pockets, undercuts and other features to dislodge any swarf particles. Broad faces and surfaces are washed using a full jet pattern, while for larger bores and similar openings a hollow cone jet can be employed.

Following the wash cycle during which the turntable makes indexing motions, a dwell period allows the bulk of the fluid to drain from the component. Drying air is then directed on to the pallet by a fan mounted in the roof of the wash cabinet. At the same time compressed air is directed by the robot held Flexi-jet to disperse remaining fluid in inaccessible areas. Different programmes can be used for the washing and drying cycles.

1.3.2.4 Inspection Systems

Inspection has tended to be done off-line on a co-ordinate measuring machine (CMM). This is because inspection is generally slower than the production rate. Multiple inspection machines may be considered, but there are cost constraints. Off-line inspection introduces time lags due to remote location, part fixturing and locating delays. Although on-line inspection aids in faster identification of manufacturing problems, it cannot rectify all machining errors. It is also difficult to perform complete inspection on-line. Additionally, from their experience at Fujitsu Fanuc in Japan, Kobayashi and Inaba (1984) recommend that "inspection of quality should not be achieved by after-machining inspection, but by quality control before and during machining".

The inspection frequency will be decided by the quality control system adopted, but more importantly it is dictated by the tool and fixture management system employed. Modern CNC machining centres if effectively used can minimise the need for inspection such that wastage is avoided as far as possible. However, this is the traditional method which is termed Post Process Measurement Control by Treywin (1982), as opposed to In-Process Control which he defines as "measurement of the size of a product as it is machined or processed".

In-Process gauging can be performed while the part is in position on the machine and machining is in progress, or with the machine halted and cutting tool withdrawn. However, these systems are generally employed in more computer integrated automated inspections, where In-Process gauging is interfaced onto the FMS control computer system. In recent times there is a trend towards the use of information from In-Process inspection system to perform corrective feedback in an FMS such that In-Process Quality Control is achieved as reported by Veron et al (1986).

1.3.3 MATERIAL HANDLING SYSTEMS

It is the view of some researchers such as Rembold et al (1985) that a special feature of FMSs designed to date is that material handling can be regarded as the central core of the installation. The material handling system consists of part transport system, workpiece handling and transfer units, storages and buffers, and pallets. These elements can be automated to different degrees.

1.3.3.1 Part Transport

With recent advances in microprocessor controlled systems, precision mechanisms, electric drives, sensors and transducers, higher degrees of positional accuracy has been made possible. A wider choice of conveyance methods in FMS is thus available. In addition to systems using manually propelled trolleys, automated transport of parts may be accomplished by the use of powered roller conveyors, stacker cranes, rail guided shuttle, and automated guided vehicles (AGV). Tuchelmann (1987) mentions three important factors in most types of transport systems: flexibility of track route, adaptability to new products and parts, and suitability of computer control.

Powered roller conveyors can move more material between any two points in a given period of time than other methods. Another major advantage is that they can be designed so that individual conveyor units operate only when they contain material. They provide the most efficient method of queueing materials at a work station. The major disadvantage is that they are often not cost-effective for moving relatively small quantities of material long distances. The turning stations (or turnstiles) in conveyor systems are comparatively more expensive and thus their use is minimised. Positioning fixtures may be required at certain points on the conveyor system.

Stacker cranes and overhead gantry cranes generally move along a linear path. Their distinctive feature is that they can access multi-level storage and retrieval systems, which occupy less floor space than other storage systems. Crane transport systems are amenable to computer control, and only changes in the program of the crane's computer control are necessary when machining installations are relocated.

A particular feature of KTM and Scharmann flexible machining systems is the use of the rail guided shuttle. This type of transporter moves to and fro along a floor mounted linear rail track to effect the transport of fixture mounted parts between stations. In case of relocation of production equipment the track has to be appropriately altered.

For the above reason track relocation cost is even greater for AGV systems due to higher floor preparation costs. Most forms of AGVs use a wire guidance system to lead the vehicle along selected routes. A copper wire buried about 120 mm deep in the floor is fed with an alternating current from a central controller. These pulses are picked up by sensors in the front of the AGV and its control system ensures that it follows the route. It is not the vehicle which represents the major part of the investment, but its peripherals. Wylie (1985) reports that Ingersoll Engineers have estimated that up to 30% of the AGV system cost may be required in just preparing the floor. Additionally, battery recharge facilities may be needed to support the AGVs. Daum (1987) notes that AGV application to FMS depends on size and weight of workpieces, and length of machining time.

Transport Systems may also be classified according to work flow as shown in Fig. 1.5, i.e. Line, Loop or Network pattern. The layout selected will depend upon the number of machining stations, the method preferred for materials handling and to a lesser degree on the capacity of the buffer store and load/unload stations. The number of transporters is dictated by the handling task and the size of the FMS.

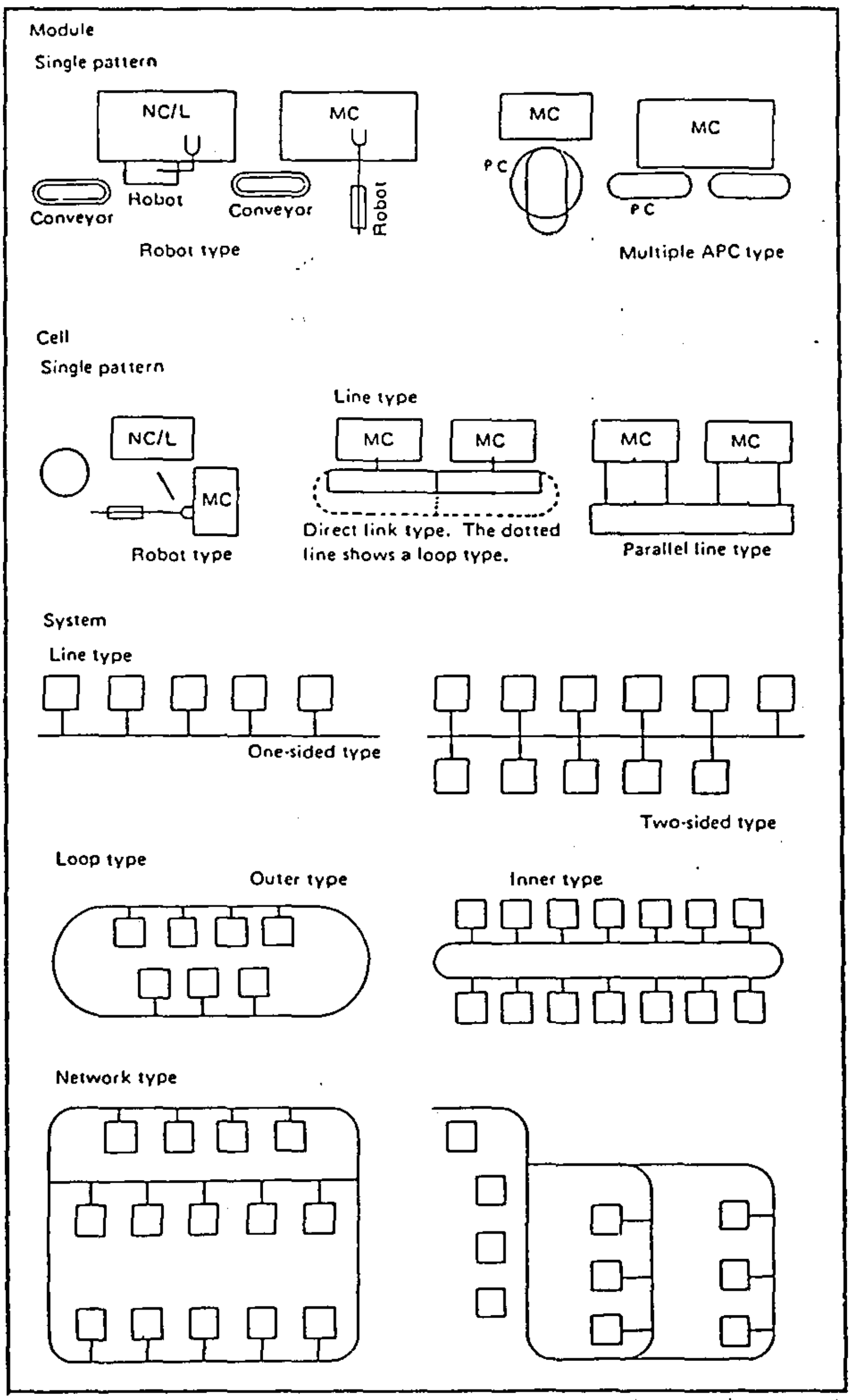


Fig. 1.5: Basic FMS Patterns (Layouts by Transport Systems)
{Extracted from Metalworking, January 1984}

1.3.3.2 Buffer Storage

Buffer storage may take the form of fixed stands with sensor devices arranged linearly in a horizontal plane or in a vertical multilevel automated storage and retrieval systems (AS/RS). The latter is used in stacker crane transport systems while the former is accessed by conveyors, rail guided shuttle, AGV, and manually. In independent machining centre automated islands the buffer storage takes the form of multipallet pool carousel and is integrated with workpiece transfer units. Examples exist of up to 16 pallets being accommodated on such carousels with a fixed position earmarked for the load/unload operation. A guide to the capacity requirements of intermediate buffer stores may be guided by simulation results.

1.3.3.3 Workpiece Transfer Systems

In order to obtain better machine utilisation, it is desirable that machined workpieces can be automatically loaded and unloaded to and from the machining station quickly. This function is accomplished by an automatic pallet changer (APC) which handles the pallet mounted with the fixture holding the workpiece. An important feature of APC is the possibility of fixturing a pallet station that is not being used while the machine is operating on a previously loaded component. The APC is available in many forms listed by Ishikawa (1985) in Fig. 1.6.

The robot type automatic workpiece changer (AWC) is generally used for loading and unloading rotational parts from a

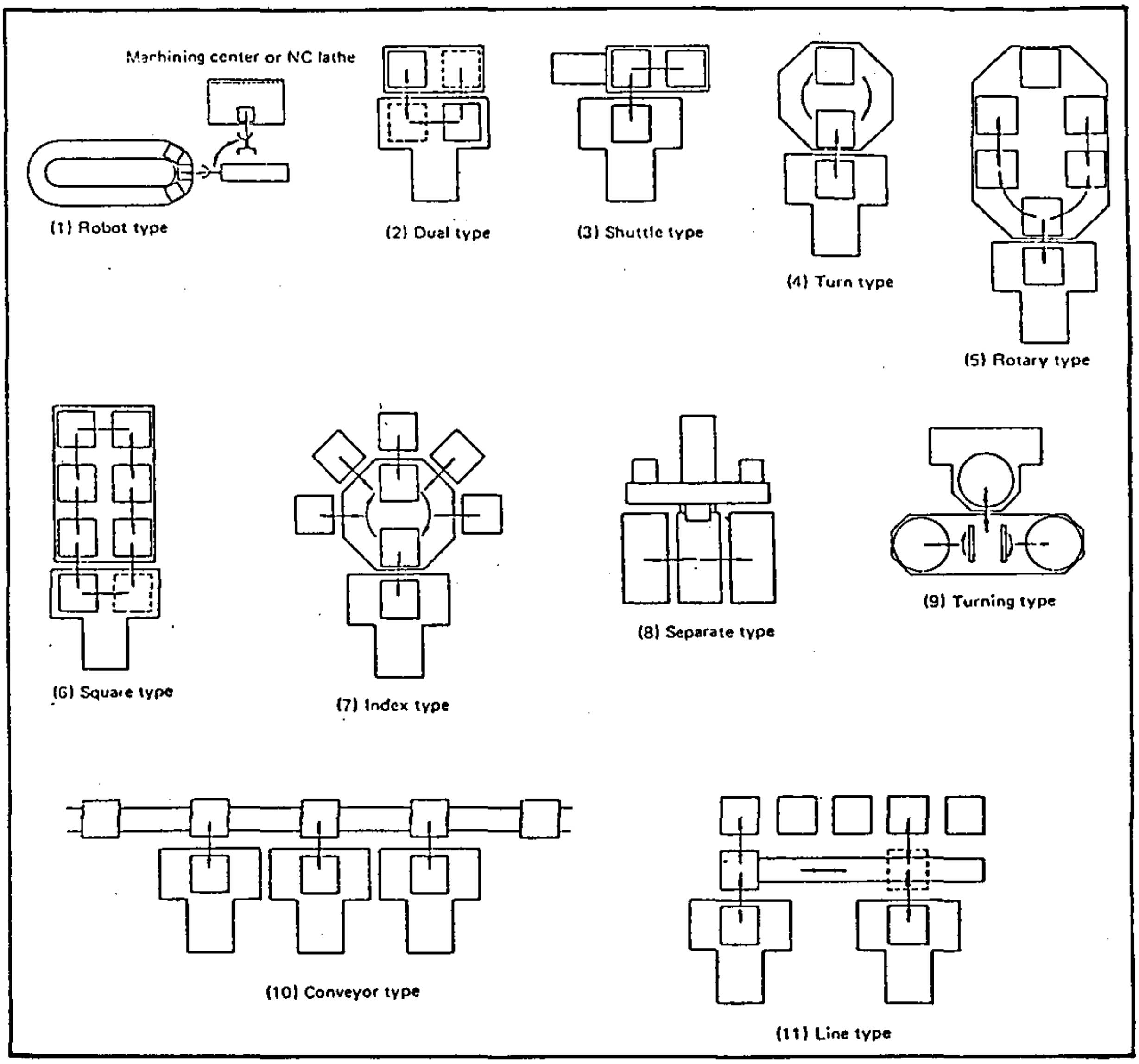


Fig. 1.6: Types of APCs
{Extracted from Ishikawa (1985)}

loop conveyor onto compact machining centres and NC lathes. This type is not suitable for prismatic parts which sometimes can be very heavy. Other types of automatic pallet changers are considered for such parts.

According to Ishikawa, the effective utilisation of APC may be enhanced by the use of common fixture base plates, adequate supply of workpieces, use of APC for other functions (such as transferring tool racks) and incorporation of clamp units in vertical machining centres. Large workpieces require large APC's which are expensive and have greater space requirements. For large parts, Ishikawa points out that the twin pallet APC may be adequate for most purposes.

In machining systems where workpiece setting takes place at the APC, overhead electric hoists and/or forklift trucks may be required for heavy parts. In flexible manufacturing systems with automated transport similar workpiece handling equipment would be required at the Load/Unload Stations. In practice, it is possible that choice of APC is determined by the selection of machining equipment.

1.3.3.4 Pallets

Pallets used in a FMS must be compatible with transport systems and load/unload stations. Precision grade locations can orient the pallet on the machine. Different pallet sizes can be accommodated provided an appropriate selection of machines and handling facility have been undertaken. With conveyorised forms of transport suitable pallet positioning fixtures may be required. Trolleys will be needed in flexible manufacturing systems using manual transport.

1.3.4 OTHER ELEMENTS

1.3.4.1 Fixtures

Fixtures vary in complexity and are largely determined by the part to be fixtured. High quality fixturing and workholding is as important to the finished part's accuracy as other high technology components of FMS systems. Parts with complicated shapes generally require dedicated fixtures. However, modular fixtures are capable of being adapted to a group of parts. One systematic approach towards a modular fixturing system (MFS) is described by Yingchao et al (1983). (Fig. 1.7). It is a modular, universal fixture which is assembled from a set of ready made, reusable, standardised elements and combined units. To avoid low machine utilisation when using modular fixtures it would be necessary to have fixture platens that locate quickly on machine beds or pallets.

One of the problems with such fixturing is the apparent difficulty of recording a modular fixture before it is broken up, since quite complex fixtures may be built up from modular system components. In a review on workholding, Capes (1985) mentions the use of polaroid cameras for keeping records of fixture mounts prior to strip down, and even the development of a CAD fixture data library. A checklist of important steps necessary before assembling modular fixtures has been outlined by Horie (1988).

Gandhi and Thompson (1985) in the USA observe that in addition to modular fixture kits, flexible fixtures for FMS include the use of programmable conformable clamps, and use of materials with biphase characteristics. Their ongoing research

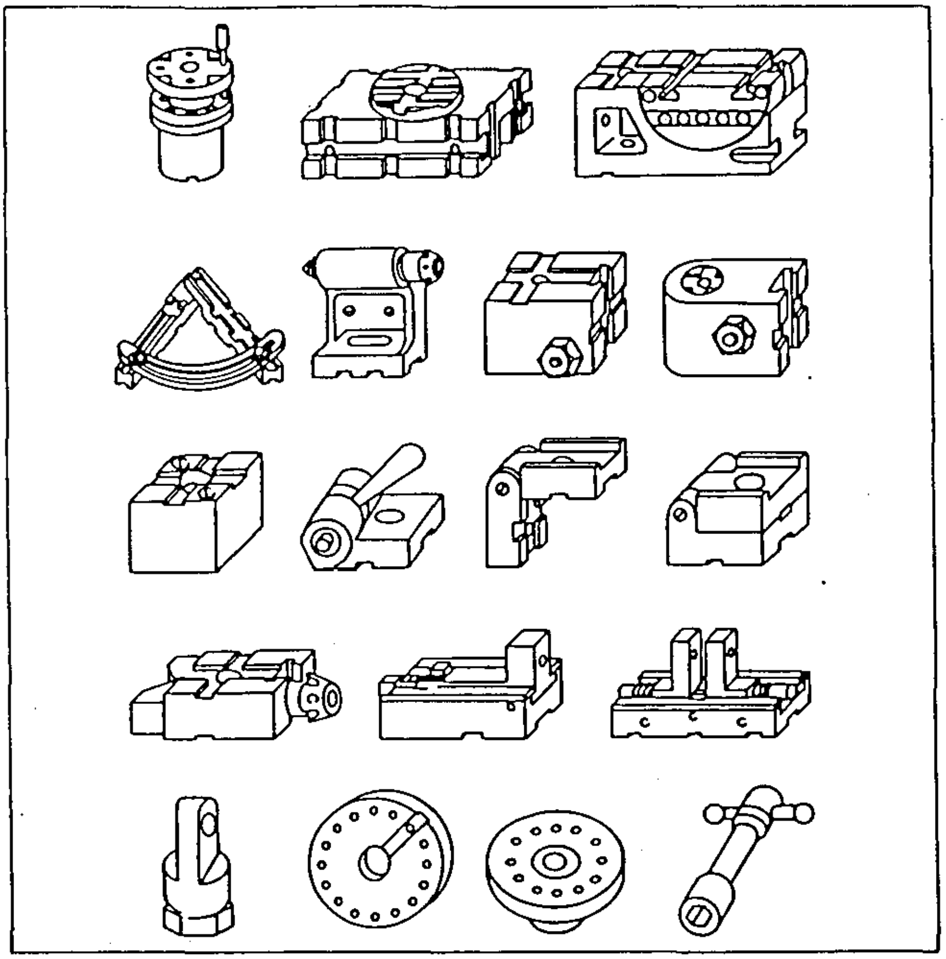


Fig. 1.7: Examples of Modular Fixturing System Units
{Extracted from Yingchao (1983)}

includesthe investigation of temperature induced and electrically induced phase change between liquid and solid for flexible fixtures. They note the use of temperature induced phase change (TPF) materials such as low melting point bismuth alloys as an encapsulating medium for the milling of turbine blades. Investigations are continuing into the use of electrically active polymeric materials such as polyacrylnitrile for application in electrically induced phase change fixturing (EPF). Gandhi and Thompson observe the need for rapid, uniform and reversible phase change in such materials and low fixture operating costs.

1.3.4.2 Tooling

Apart from the appropriate choice of replaceable tool inserts, toolholders must be selected that are capable of making full use of the power, accuracy, rigidity and productive capacity of the machine. Fig. 1.8, illustrates some of the main classes of tools and toolholders generally used for prismatic part machining. Toolholders are selected so that the distance between spindle bearings and tool cutting edges is minimised. For example, minimum tool projection on drills will reduce tool wander, and improve hole positioning accuracy, tool life and production rates. Similarly, tool life and workpiece accuracy is improved in end milling operations when tool overhang is minimised.

Modern machining centres are being equipped with increasingly large tool magazines that can store large numbers of tools. They are also equipped with Automatic Tool Change (ATC) facility to minimise tool change time between spindle and tool magazine. Trajkorski (1987) classifies tool magazines, and lists six types of

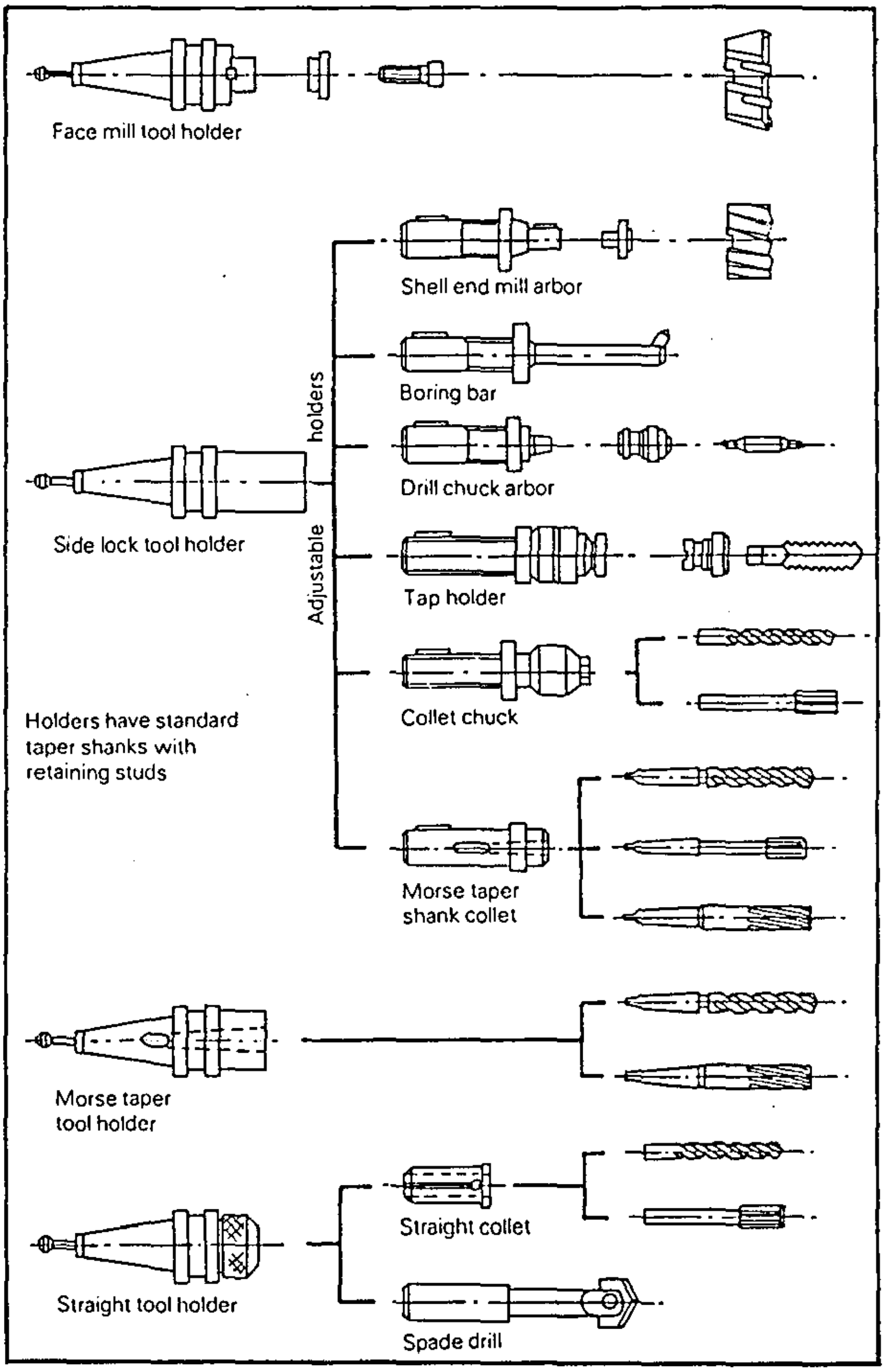


Fig. 1.8: Tooling for Prismatic Parts
{Extracted from Gibbs (1984)}

ATCs:

(a) ATC - without tool changing arm

(b) ATC - with tool changing arm pivoting in one axis,

(c) ATC - with tool changing arm pivoting in two axes,

(d) ATC - with tool changing arm and a parking station,

(e) ATC - with tool changing arm and a transport system,

(f) ATC - with tool changing arm, transport system and parking stations.

In many machining centres, tools may be loaded manually and locked automatically. There is a recent trend towards the use of automatic tool gauging facility and acoustic or piezoelectric tool breakage sensors. In fully automated ATC, there are centralised tool stores connected to tool magazines by an automated tool transport system so that tools may be loaded and unloaded automatically. Tool recognition and coding depend on the ATC being manual, semi-automatic or fully automatic. A system for continuous tool failure monitoring for semimanned and unmanned NC and CNC machines has been developed by PERA (1984).

1.3.4.3 Part Recognition

In highly automated manufacturing systems, identification of parts mounted on pallets may be performed by computer control of pallet position and appropriate software. Use may also be made of bar codes and optical sensors or other types of transducers. Additionally, there is a recent trend towards the development of intelligent computer controlled vision systems for automated recognition of parts. The goal is the correct selection of part program when the pallet is loaded onto the machining centre. Separate part programs need to be created for various combinations of parts on pallets mounted with multiple fixtures. In manually operated flexible manufacturing systems, the operator keys in the required part program selection on the machine controller console.

1.3.4.4 Coolant and Swarf Disposal

In many FMS installations there is a move towards automatically controlled central coolant filtering, storage and supply system. New all-plastic coolant hoses with a variety of clip on nozzles are beginning to replace copper and aluminium hoses on machine tools according to Spirax Sarco Ltd. of Cheltenham. Browne (1986) reported the development of coolants with better characteristics, such as lubrication, long emulsion life and biostability, reducing the frequency of application by up to 90% and costs up to 66%.

Attention is also being focussed on chip disposal problems which is more acute on vertical machining centres. This has resulted in the development of conveyorised swarf handling systems installed below machines, and slanting machine structure surfaces when possible. Vacuum techniques are also being considered, as well as cleaning air blast systems. However, in many small and medium sized FMS, swarf disposal is performed manually at regular intervals.

1.4 CONTROL AND OPERATION OF FMS

1.4.1 CONTROL SYSTEM ELEMENTS

In flexible machining systems with manual transport the level of control is localised at the machining station. However, with the introduction of automated material handling, the transport system controller needs to be co-ordinated with the machine controllers of machining centres, intermediate storage systems and status of load/unload stations. This is only possible with a well planned control system consisting of controllers, sensors, transducers, communication links (e.g. Infra Red and Fibre Optic links) interfaces and microcomputers, or even mainframes (depending on the size of the task). These hardware elements are generally arranged in a hierarchical manner to reflect the various control levels. With the availability of more flexible and powerful programmable logic controller (PLC) the microcomputer task may be adequately performed by a PLC for systems with, for example, conveyor transport.

Generally, the control system consists of the Host system and Process Control system. The latter performs Sector Control and has two subsystems, Work Station and Move control. The Host system may have three elements as shown in Fig. 1.9, i.e. Scheduling system, the Optimiser, and Data Processing. The scheduling system prepares the daily load to be processed from the weekly requirements, and the optimiser allocates the loads to machines on a shorter timespan using different priority rules which vary from system to system. Finally, the Data Processing aspect is performed on-line on a continuous basis, and may form

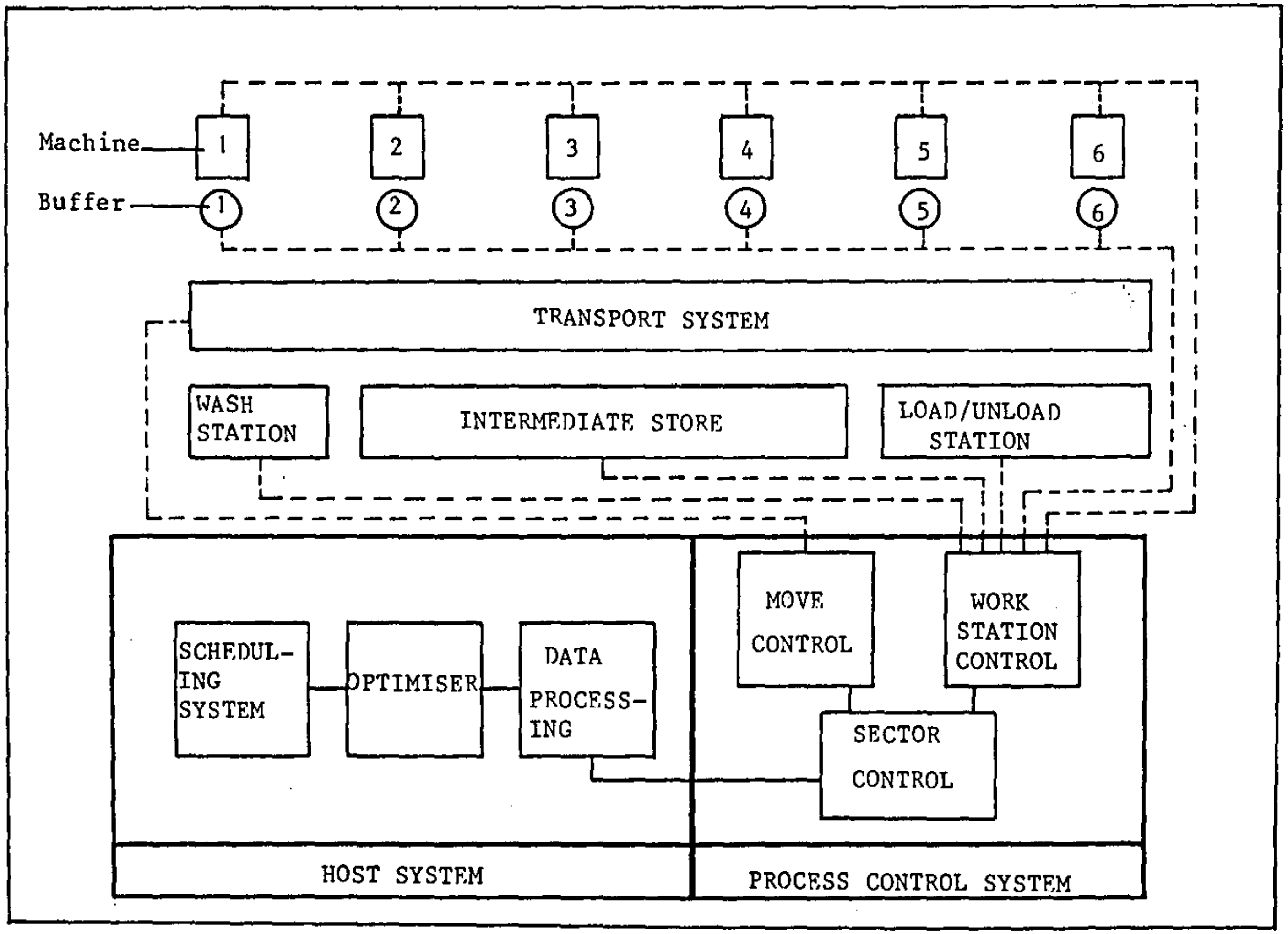


Fig. 1.9: FMS Control System Elements

part of the Management Information system (MIS). The scheduling and operational aspect will be considered separately in Section 1.4.5. However, with advances in Local Area Networks (LAN) and development of manufacturing protocols, this method of interconnection of system elements is replacing the hierarchical mode of linking the system hardware. Implementation of LANs in large flexible manufacturing systems helps to link up different flexible cells that make up the larger system. For increased flexibility Chandler et al (1984) have proposed a Machine Interface Terminal (MIT) and associated software for interfacing different types of machine controllers to a DNC system.

The more flexible and all-embracing the management task is specified to be, the more complex the control system that is required. It is therefore necessary that the system logic representing the flexible cell operation should be kept as simple as possible without sacrificing system efficiency.

1.4.2 CONTROL SOFTWARE

Computer control software should be structured to ensure control management and monitoring functions which enable the system to achieve high utilisation. For greater flexibility, the software is written in modular form, for example, as advocated by Dato et al (1983). According to well established practice the control system architecture is typically hierarchical as described adequately in handbooks, and is illustrated in Fig. 1.10. The control software has access to the various distributed components of the FMS Database as described by Ranky (1982,85).

The flow of material through a flexible manufacturing system

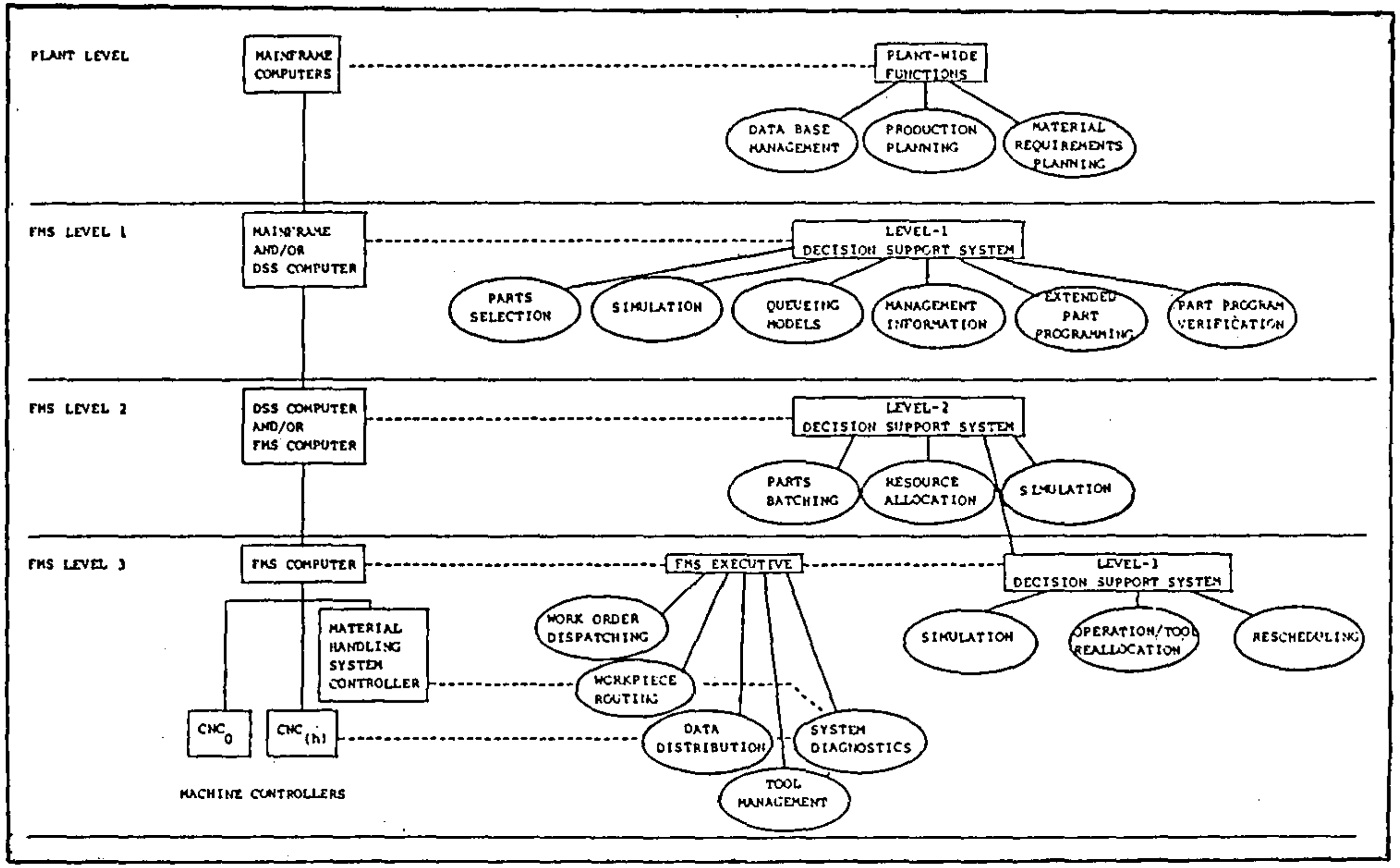


Fig. 1.10: Hierarchical FMS Control System Architecture

{Extracted from FMS Handbook (1986)}

is determined by the operational aspects of the FMS. Thus attention must be directed at tool management systems, fixturing policy, and scheduling of parts inside the cell.

1.4.3 TOOL MANAGEMENT SYSTEM

The introduction of CNC machines and the trend towards smaller batches has made tool management an increasingly important issue within machining operations. Automatic tool changing between tool magazine and machine spindle is now available and provided by machine tool companies on most machining centres. Although increasingly reliable equipment and probes to aid tool breakage detection are available commercially, breakage may be reduced and excessive tool wear avoided by careful selection of tool offsets, tool inserts, spindle speeds and feeds, and tool life limits.

Elmaraghy (1982) indicates that automation of tool flow requires some essential elements such as tool transfer system, tool storage facilities, tool replacement facilities, automated tool loading and unloading mechanisms and control logic for managing tool replacement and transfer activities. Ber and Falkenberg (1985) point out that a tool control system in a FMS must be able to follow tools as they enter the system and along their path through the factory. The system must be able to divert tools from their predesigned path to a new one if necessary. The control system must also keep track of changing conditions of the tools.

Tomek (1986) mentions three basic tooling strategies:

(a) a batch of parts processed by a group of tools,

(b) several batches of parts processed by a group of tools,

(c) a common tool inventory shared by a group of machines.

He adds that the FMS must be supported by appropriate system software where tools flow must match parts flow. However, much needs to be done in refining automated tool management procedures by simulation studies.

1.4.4 FIXTURING POLICY

In manually operated cell configurations fixtures are mounted on the grid plate on the machine bed or on the fixture platen or pallet on an APC. In the former case if a batch of parts require more than one fixture set up, they may be mounted on the same grid plate if it is large enough. In this case no other batch may be machined during the processing of a particular batch. In systems with APCs, without automated tool magazine loading systems, fixtures for different batches may be set up on the various stations provided the tools required are present in the tool magazine.

In FMS with automated transport, it is preferable to hold all fixtures premounted on base plates ready for usage in a fixture storage area. According to the FMS Handbook (1986) this approach reduces the fixturing time to between 6 and 15 minutes. The fixturing policy adopted would then depend on the scheduling procedure and tool management strategy.

1.4.5 SCHEDULING AND OPERATIONAL CONTROL

Production scheduling in a FMS must take into account the system structure, interrelationship between system elements and various flexibility aspects. The effectiveness of different scheduling rules need to be considered in relation to objectives sought which themselves depend on company policy. In developing a scheduling model for an FMS, Iwata et al (1982) observes the following requirements in a realistic schedule; the capability to handle different FMS configuration and stations, selection of system entities, routing of parts, and consideration of buffer storage constraints. Some researchers such as Murotsu et al (1983) view production scheduling as a hierarchical structure of decision making for the selection of machine tools, transport devices, operators and scheduling rules. Others, such as Onari and Kobayashi (1986) see the scheduling system as a planning problem consisting of a hierarchical loading sequence with decreasing time horizon.

In FMS both approaches need to be considered in establishing a viable scheduling system. Scheduling thus consists of loading and sequencing parts through the system as well as decision rules for selection of entities such as machines, tools, fixtures and operators. Additionally, disturbances to the system schedule in the form of short term priority changes have to be reckoned with. Fig. 1.11 illustrates this complex interrelationship in a highly automated flexible machining system showing the main operational control links. Furthermore, it is necessary to take into account particular system requirements. For example, the presence of certain tools or prefixtured pallets may influence the loading of particular parts and thus affect the determination of any feasible schedule.

Carrie and Petsopoulos (1985) concluded that each FMS has

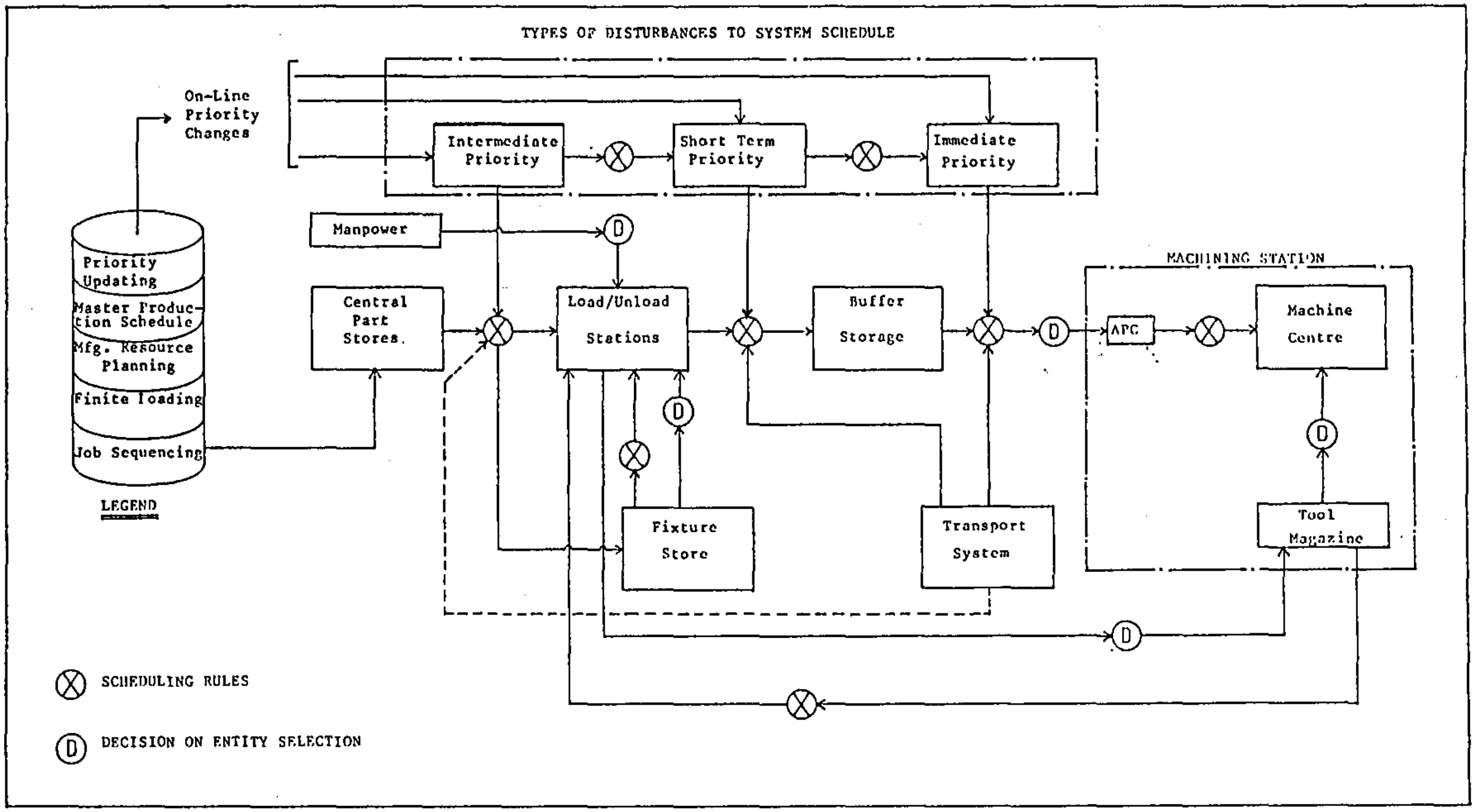


Fig. 1.11: Scheduling and Operational Control Elements in Flexible Machining Systems

special requirements and features, so that scheduling methods related to one system may not be universally valid. Carrie and Perera (1986) considered work scheduling in FMS under tool availability constraints using a tooling post-processor for a simulation model. In their particular study they showed that with high product variety tooling availability constrains scheduling decisions. Escudero (1987) proposed a hierarchical approach for generating alternative schedules which consisted of loading of parts, execution of operations on parts, and processing route of each part. He concluded that due to the higher flexibility of FMS, a computer based methodology to narrow the set of alternatives was necessary. His algorithm attempted to minimise production and transport costs and achieve better load balancing. A similar approach was adopted by Dagli (1987) in his mathematical programming model. Sriskandarajah et al (1987) examined a scheduling algorithm based on a job matching principle using the minimisation of Finish Time criterion for FMS with a loop conveyor system. It was found that good results were obtained for low conveyor speeds. Nakamura and Shingu (1986) also examined a two stage algorithm consisting of machine route selection and load sequence determination in relation to a loop type conveyor FMS.

Bell and Bilalis (1983) studied a three level control algorithm which consisted of prerelease planning phase, input control to determine timing and sequence of job release using five decision rules, and an operational level controlling part movement between machine tools and central store using three simple rules. This is better suited to multistage systems, and the various combination of the decision rules were studied on a hypothetical cell for rotational parts.

A Fast Scheduling scheme for on-line production control was examined by Onari and Kobayashi (1986). They used a two stage heuristic algorithm for a near optimal solution with a short processing time, and was investigated by application to a Flexible Assembly Line and FMS. The first stage of initial ordering was followed by an order improvement stage using a partial branching method. Gershwin et al (1984) formulated a short term production scheduling algorithm and conducted simulation tests on an automated printed circuit assembly facility. Their algorithm was an extension of Kimemia and Gershwin's (1983) on-line hierarchical scheduling scheme for FMS.

However, scheduling of parts in a flexible machining system should be related to the part spectrum and other features such as production control and other operational aspects like tool management and so on. Thus the scheduling rules incorporated in FMS operational procedures should be tested in relation to specific manufacturing conditions. The effectiveness of rules is likely to depend to a great extent on the spread of workpiece machining times, numbers of various types of machines, and possibly other resources in a cell, as well as considerations such as buffer storage, fixturing methods and tooling constraints.

CHAPTER 2

FMS EVALUATION AND SELECTED AREAS OF STUDY

2.1 EVALUATION OF FMS

2.1.1 INTRODUCTION

In relation to required system objectives and after deriving alternative design conceptions for a particular FMS application from the various combinations of selected equipment and control under consideration, a final selection of configuration requires systematic evaluation. The FMS Handbook (1984) prepared by Charles Draper Laboratories at M.I.T., USA, recommends the consideration of the following criteria: cost, system throughput and availability, flexibility, precision and accuracy, tool capacity, inspection and surge capacity.

Some reseachers, for example Ito et al (1985) have considered flexibility to be a more important feature, and proposed a flexibility evaluation vector to achieve this. Because of the abstract and theoretical basis of these mathematical formulae, this method of evaluation is limited in scope. Primrose and Leonard (1988) note that increased flexibility of production from FMS is a frequently quoted example of an intangible benefit, but they point out that "flexibility itself is not the benefit". However, the relative weighting assigned to the different criteria for selection is likely to depend on the particular FMS application. A more systematic approach is the use of various modelling concepts to study FMS system performance in relation to a defined range of manufacturing requirements.

In this endeavour, Stecke (1984) mentions various FMS modelling techniques such as simulation, queuing networks, perturbation analysis, mathematical programming, and timed Petri nets. Queuing networks require average inputs, such as average processing time at a machine and average frequency of visits to a machine. The outputs are also average values, for example, mean queue lengths and machine utilisations. This approach may be useful for initial system analysis, although these models are based on many assumptions.

Simulation remains the most popular method of evaluating FMS, and enables the dynamic behaviour of the system to be examined. However, the results of the simulation depend to a great extent on the model specification and the degree of realism integrated into the simulation program. An approach combining mathematical queuing models with user specified simulation graphics has been reported by Bell et al (1986) which they term "emulation". It has attempted to make "modelling and simulation transparent to the user", and draws on information obtained through industrial collaboration. It is based on user specified menu driven file development which is manipulated to drive a graphical simulation on a VDU terminal. The system may be used for designing a range of FMS using AGVs, and may be extended to a broader range of transport systems.

2.1.2 PERFORMANCE MEASURES

In mathematical models developed by Buzacott and Shanthikumar (1980) production capacity has been used as a measure of system performance. The production capacity is calculated from departure rates from the system, or maximum arrival rate for a stable system, or the job feedback rate for the closed system case. Other researchers like Maione et al (1986) have developed closed-form analytical expressions for evaluating the performance of FMS based on the product of visit ratio and mean service time. Balanced and nearly unbalanced systems may be considered.

However, in appropriately developed simulation models meaningful performance measures based on deterministic or stochastic data inputs may be attained in relation to chosen constraints and resources. Variations in performance within the timespan simulated can also be identified. Some of the more common system performance measures are utilisation (of machines, pallets, manpower, etc.), output, work-in-progress levels and throughput times.

2.1.3 ECONOMIC JUSTIFICATION OF FMS

The last stage in FMS evaluation is the economic analysis. Most published accounts relating to the final justification of FMS use traditional approaches to project appraisal such as payback period, return on investment (ROI), net present value (NPV) discounted cash flow (DCF), life cycle costing, and breakeven point. The effect of government grant, taxes and inflation also need to be included. All the methods of appraisal are based on probability of future events, thus sensitivity analysis may have to be performed. However, the traditional approaches have their shortcomings in application to investment in FMS as for example the inability to quantify the intangible benefits of FMS, such as improved delivery performance, effect on sales and contribution to overhead recovery from increased sales. It may be noted that these intangible benefits should not be overestimated and must have some regard to the type of product and product life. With regard to the intangible effects of FMS, Hundy (1984) observed that greater consideration must be given to the potential reduction in lead time. The resulting effect on Work-in-Progress and stocks can be easily assessed. However, beyond the cost evaluation of a particular FMS section in a company, Finnie (1986) noted that any final investment decision must be viewed and evaluated in relation to the entire system and not on a 'stand alone' basis.

Primrose and Leonard (1985) have proposed a framework for evaluating these intangible benefits, and incorporated them in a comprehensive computer program using the DCF technique. They point out that most of the information required exists "in-house" while the remainder may be generated from technical design simulations. Choobineh (1986) classified the intangible benefits into strategic and tactical benefits. Tactical benefits are those that accrue from benefits attributable to cellular organisation of FMS and programmability of the cell, while strategic benefits are tied to the strategic plan of the firm. He recommends the use of the NPV method for the tactical justification and a ranking technique for the final strategic justification.

Approaches to investment appraisal of FMS, by Airey (1983), Primrose and Leonard (1984, 85, 86) and others, have used project evaluation techniques such as Internal Rate of Return, Net Present Value and Discounted Cash Flow in comparing NC and CNC machining systems. Potts (1985) reports that these evaluation techniques have been used by Primrose and Leonard at UMIST in their computerised evaluation program called IVAN (Investment Analysis Computer Program). The software costs £600, and is marketed by Organisation Development Ltd. It runs on IBM compatible systems. However, these analyses do not identify cost per unit of production created in comparing alternative forms of Flexible Manufacturing Systems.

However, identification of production costs are complementary to a financial analysis based on, for example, a net present value approach. A clearer view of alternative FMS configurations may be ascertained by using a differential cash flow basis. Results from simulation testing (e.g. cycle times, output and manpower levels, machine and manpower utilisation) are inputs into the above economic analysis. Such investigations must take into account investment and operating costs, and may well have regard to intangible benefits.

2.1.4 SIMULATION OF FMS

Various applications have been reported dealing, for example, with scheduling rules, buffer stocks, work-in-progress, and machine utilisation. Contributions have been made to various aspects of appraisal by researchers such as Chan and Rathmill (1978), Spur (1983), Clementson and Hutchinson (1985), Carrie (1986) etc. Spur has pointed out that the time and cost of a simulation study can be costly as it is determined by:

"(a) Data preparation for modelling;
(b) Modelling depending on required degree of detail and model complexity;

(c) Simulation runs to be performed depending on number and range of parameters to be varied and the timespan to be simulated;

(d) Evaluation and documentation of simulation results".

Commercially available software for discrete simulation offers a quick and less expensive way of studying real-time control systems as in FMS. Clementson and Hutchinson (1985) pointout that an explicit discrete event simulation model of the control system and physical equipment enables detection of logical errors at an early stage, as well as complex dynamic relationships of control decisions. A comprehensive description of available software packages for manufacturing simulation has been produced by Miller (1987). The wide range of programming languages includes the simulation package known as ECSL (Extended Control Simulation Language) developed by Clementson (1982). This system has been widely used in the UK and is available at Loughborough University of Technology. ECSL is a high level FORTRAN based language that adopts an activity based three phase approach to discrete simulation.

2.2 SELECTED AREAS FOR STUDY

The scope and justification for further research in the field of FMS is apparent, as for example in the determination of forms and their appropriateness to a wide spectrum of manufacturing requirements. Further work to assist industry in the analysis of work flow and cell formation would also enlarge industrial application. The need remains for refining methods for advancing the technological and organisational aspects in the control of tooling. Fixturing is also a field which would be fruitful for further study especially in less automated systems.

Two aspects have been selected in this study in relation to particular industrial requirements. These are:

(i) cell formation for FMS, and,

(ii) performance evaluation and cost effectiveness of selected alternative flexible machine systems.

2.2.1 BACKGROUND

In order to take account of real industrial conditions the research study has sought to draw on the requirements applying, and the developments which could be considered in a particular factory. The study, it is considered, would thus benefit from industrial realism through the use of data relating to actual production requirements and take note of important constraints.

The previous review of techniques of cell formation indicated a need for a more explicit procedure for the final stages of cell formation in FMS taking into account also any particular needs of Flexible Manufacturing Systems. Preliminary work in cell formation in the company used the Burbidge PFA approach. Limitations in using this method led to an exploration of the possible advantage of using a graph-theoretic method. Hence, it was found helpful to draw on the method developed by Rajagopalan and Batra (1979) but to appraise the advantage of adding an analytic treatment which would strengthen the final stages of the analysis. Such addition can be seen as necessary to provide a more explicit treatment of the process of cell differentiation for an FMS application to a real problem.

The topic of appraisal of alternative configurations bears on a fundamental question that all companies face, viz., choosing a form of FMS which shows to both technological and economic advantage. Again it was sensed that the use of actual data would be helpful in making such an appraisal. It is noteworthy that little research has been reported in regard to such studies which seek to compare the effectiveness and relative costs of alternative forms of FMS.

For this research study, data was obtained from a firm manufacturing lifting equipment such as handchain and electric hoists. In recent years, the firm has updated its product range by introducing developments which enhance their potential for lower unit cost manufacture. The reorganisation of the manufacturing function is proceeding along the principles of Flexible Manufacturing. An internal company report identifies the overall goal to provide major benefits in:-

(a) the ability to respond to fluctuations in demand levels and mix;

(b) shorter manufacturing lead times;

(c) smaller batches, lowering levels of work-in-progress (WIP) and inventory;

(d) efficient utilisation of high capital machine tools and skilled operators.

The first stage which the company has pursued is that of developing a CNC machining facility to meet the demand from the assembly section for sufficient high quality, high value components concentrating on those produced in-house. Towards this end the company initially created a list of 207 parts with the following shape characteristics: Cuboid, Flat Plate, Plain Disc, Multi-diameter Disc, Disc Gear, Shaft Gear, Multi-diameter Shaft and Plain Shaft.

Early in the course of this research study, the company purchased five new vertical machining centres which together with an existing horizontal machining centre formed an autonomous machining cell. This development in no small measure complemented this research. This embryonic CNC machining cell is operated as a Flexible Machining System. Later, in an attempt to increase the flexibility of this cell, three of the new machining centres were fitted with automatic pallet changers.

The first stage of this study was to examine the initial total list of 207 parts, their machining data and annual demand in order to perform a manufacturing flow synthesis. A method of performing this has been developed in the following chapter, which derived the various FMS cells required to process the parts.

A prismatic cell was one such independent cell. Seven alternative forms of FMS to process an expanded prismatic part spectrum of 147 parts have been conceived. This aspect forms the second stage of this study. The seven alternative FMS configurations for the above application have been modelled in the ensuing chapters and their performance examined in regard to system output, average process time, manpower utilisation, machine utilisation and levels of unmanned operation. The performance evaluation has been conducted by computer simulation experiments. The comparison of economic justification of alternative configurations is seen as of major importance. The study aims at appraising the comparative costs of manufacture by each of the configurations in order to complement a financial investigation based on a NPV approach.

CHAPTER 3

MANUFACTURING FLOW SYNTHESIS IN FMS DESIGN

3.1 INTRODUCTION

With the development of more flexible manufacturing systems in recent times and the recognition of the cell system as a more efficient method of batch production, the problem of machine-component grouping has to be viewed as a fundamentally important consideration in the design of many manufacturing systems. Increasing equipment costs and higher levels of integrated automation necessitate a systematic analysis, design and planning of the cell structure.

3.2 STATIC CAPACITY-LOAD REQUIREMENT ANALYSIS

Planning of manufacturing systems is generally made on the basis of sales forecasts, and the commonality of parts in the various products. The policy on spare parts production may be considered. Thus the first step has been to establish a product range and demand database together with a part-product matrix.

3.2.1 PRODUCT LINE AND DEMAND

This study is based on a company manufacturing material lifting equipment. The product range consists of five classes of equipment. These product classes in some cases consist of sub-assemblies and are further divided into product types that vary in their performance characteristics. Each product may thus be coded by a four digit number ($N_1N_2N_3N_4$), where N_1 is the product class, N_2 is the subassembly if any, and N_3N_4 denotes the product characteristics. Appendix A1 gives the actual product classification and the expected annual demand. The part-product matrix gives the product types in which the part exists and the quantity of that part required in the particular product. Thus the total part requirement may be computed by adding the respective quantities required for each product type. The total part demand may then be entered into the part-machining data file. Table A2 in Appendix A gives the part-product matrix.

3.2.2 PART-MACHINING DATA FILE

The computed part-machining data file is given in Appendix A4, showing the part machining sequence and the cutting time for each operation. The part demand shown has been computed as explained above. The maximum number of machining operations on any one part in this part spectrum is four. On this basis a machine requirement analysis can thus be performed.

3.2.3 MACHINE REQUIREMENT ANALYSIS

The machine requirement depends on the shift system employed and the total available working days, here assumed to be 240 days per year. Thus, for single, double and three shifts per day systems the total available machine hours are 1920, 3840 and 5760 hours respectively. The total machining hours for the part spectrum for each machine type can be obtained from the part machining data file referred to previously. Table 3.1 gives the minimum estimated machine requirement below.

Machine Type	M/C Code	Different Types of Parts	Total No. of Parts	Total M/C Hrs	Minimum No. of Machines Required		
					1 Shift	2 Shift	3 Shift
1	2	91	56380	8286	5	3	2
2	4	47	15380	3200	2	1	1
3	5	17	11730	400	1	1	1
4	6	14	5010	836	1	1	1
5	7	70	43180	7216	4	2	2
6	8	48	28910	2316	2	1	1

Table 3.1 - Machines Required on Annual Basis

3.3 FLEXIBLE CELL FORMATION

3.3.1 INTRODUCTION

The machine requirement for a specific system is influenced by several factors as shown in Fig. 3.1, such as type of cell operation and cell organisation aspects as well as the level of automation built into the manufacturing system. The main considerations for cell formation in FMS have been enumerated in the previous chapter. The level of automation integrated into the Flexible Cell is naturally dependent on the investment made in the system. However, this is appraised in relation to system performance of the cell and is the subject of a later chapter. Nevertheless, at this initial stage there is a need for performing this front-end section of the analysis of the manufacturing system by a quick and practical method that is preferably amenable to computerisation. A possible way of doing this is investigated in this section.

If the machines are unavailable due to the method of loading and unloading of machines or operational characteristics of machine set-up, this may have to be considered in a detailed machine requirement analysis. For example, machines may be loaded and unloaded manually or by automated pallet changers. Additionally, the effect of machine setting up activities and their degree of parallelism, (depending upon manpower resources), may have to be taken into account. Fig. 3.2 illustrates some of these possibilities.

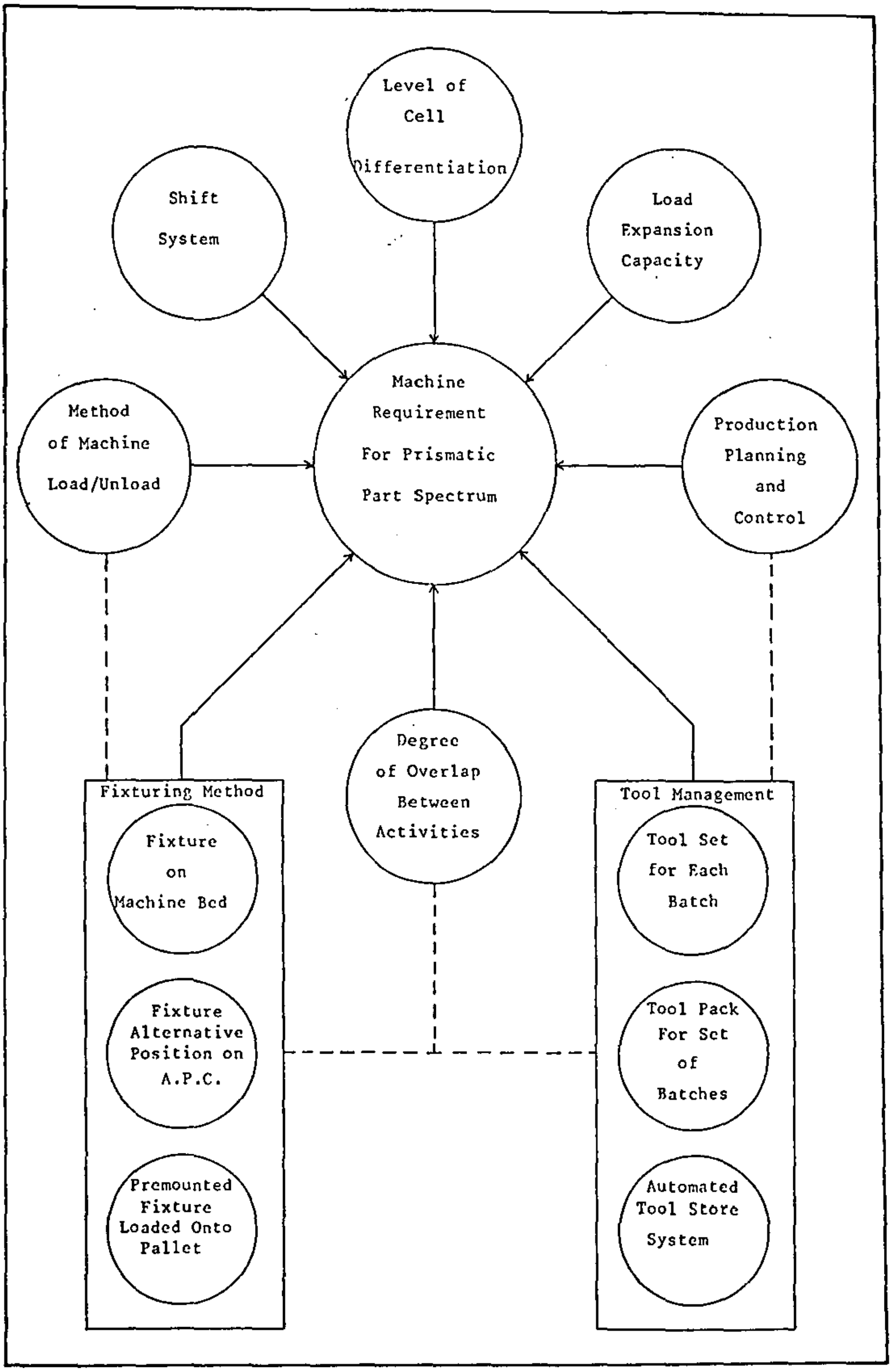
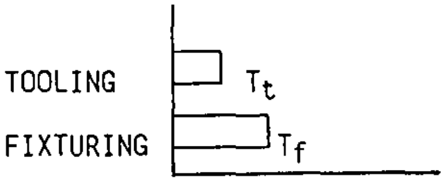


Fig. 3.1: Factors Influencing Machine Requirement

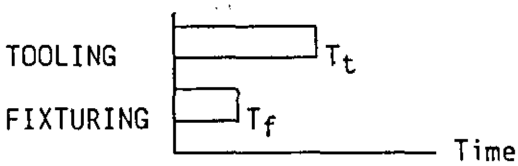
(i)



<u>$T_t < T_f$</u>

Setting up Time, $T_s = T_f$

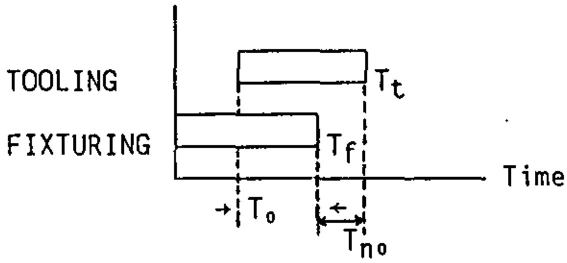
(ii)



<u>$T_t > T_f$</u>

Setting up Time, $T_s = T_t$

(iii)

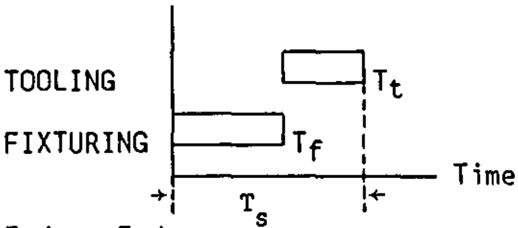


<u>Partial Overlap</u>

Overlapping Time, $T_o = \alpha\, T_t$ $(\alpha < 1)$

Setting up Time, $T_s = T_f + T_{no}$
$= T_f + (1-\alpha)T_t$

(iv)



<u>End to End</u>

Setting up Time, $T_s = (T_f + T_t)$

<u>Fig. 3.2: Overlapping of Setting-up Activity Times</u>

3.3.2 FEATURES OF PART SPECTRUM

It should be noted that many of the parts go out of the system altogether before returning for further processing, for example, parts to be heat treated before grinding. Other parts return to the load/unload stations for a fixture set up to reorient the part before further machining. A few rotational parts may require machining in another cell for additional operations such as slotting. Some parts that require a final operation such as gear deburring are performed outside the environ of the FMS.

3.4 DESCRIPTION OF FLEXIBLE CELL SYNTHESIS METHOD

The method developed here is based partly on Rajagopalan and Batra's graph theoretic method with the addition of one important modification to remove the arbitrariness in the selection of the 'threshold value'[(1)]. Rajagopalan and Batra obtained their threshold value by plotting the graph edges against threshold levels. This method was applied to the industrial study conducted herein. However, the plot obtained had no well-defined minimum in which case the choice of the machine-graph edge variable for a particular threshold level is left to individual judgement. In applying Rajagopalan and Batra's approach the choice of threshold level would be in the region of minimum negative gradient. This yields a rather sparse machine graph which appears to be rather unsatisfactory for the purpose of cell partitioning.

However, in the method developed in this thesis this drawback has been avoided by treating the similarity-threshold binary matrix as an ordinary information set.

(1) The value for the similarity coefficient below which machine graph edges are ignored.

This ordinary information set is considered to consist of different subsets for each threshold value. From the plot of Shannon information measure against threshold level, the threshold value is chosen at the point of maximum Shannon information content. In this study a clear maxima was observed and the machine graph obtained was less sparse than that obtained by Rajagopalan and Batra's method. This enabled a better flow analysis and system synthesis to be performed.

The procedural steps of the complete method are now outlined:

Step 1 - Preparation of Part-Product Data File

For i number of parts and j products, the part-product array (Pp) is given by,

$$\underline{Pp} = \begin{vmatrix} P_{11} & P_{12} & --- & P_{1j} \\ P_{21} & P_{22} & --- & P_{2j} \\ \vdots & \vdots & & \vdots \\ P_{i1} & P_{i2} & --- & P_{ij} \end{vmatrix}$$

where, $P_{qr} = 0$ or 1

Step 2 - Obtain Annual Sales/Production Forecasts

The product line with j products, column array ($\underline{D}$) for annual demand for product types is given by,

$$\underline{D} = \begin{vmatrix} d_1 \\ d_2 \\ \vdots \\ dj \end{vmatrix}$$

Step 3 - Compute Annual Part Requirement

The annual part requirement array ($\underline{R}$) for i parts is given by,

$$\underline{R} = \underline{Pp} . \underline{D} = \begin{vmatrix} r_1 \\ r_2 \\ \vdots \\ ri \end{vmatrix}$$

Step 4 - Set up Part Machining Data File

The machining data file for i parts consists of a part route array ($\underline{Nr}$) which gives the machine type visited during the series of operations for each part, and the machining time array ($\underline{Mt}$) which has the process time for each operation on the part.

For i parts with k operations, the arrays are given by,

$$\underline{Nr} = \begin{bmatrix} n_{11} & n_{12} & \cdots & n_{1k} \\ n_{21} & n_{22} & \cdots & n_{2k} \\ \vdots & \vdots & & \vdots \\ n_{j1} & n_{j2} & \cdots & n_{jk} \end{bmatrix}$$

where, n_{qr} = machine type number (integer value) for the rth. operation on the qth. part. In this study, $1 < n_{qr} <$ S, where S = no. of machine types.

$$\underline{Mt} = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1k} \\ m_{21} & m_{22} & \cdots & m_{2k} \\ \vdots & \vdots & & \vdots \\ m_{j1} & m_{j2} & \cdots & m_{jk} \end{bmatrix}$$

where, m_{qr} = processing time for rth. operation on the qth. part.

The total annual processing time ($\underline{T}$) for each part may be computed from this file for the static machine requirement analysis, and is given by

$$\underline{T} = \begin{bmatrix} r_1 m_{11} + r_1 m_{12} + \cdots + r_1 m_{1k} \\ r_2 m_{21} + r_2 m_{22} + \cdots + r_2 m_{2k} \\ \vdots \\ r_j m_{j1} + r_j m_{j2} + \cdots + r_j m_{jk} \end{bmatrix}$$

Step 5 - Formation of Relation Matrix

From the part flow between machine types, the Relation matrix ($\underline{F}$) based on the annual demand is given by,

$$\underline{F} = \begin{bmatrix} f_{11} & f_{12} & --- & f_{1s} \\ f_{21} & f_{23} & --- & f_{2s} \\ | & | & & | \\ f_{s1} & f_{s2} & --- & f_{ss} \end{bmatrix}$$

where, f_{xy} = Total no. of parts using both machine type x and y; (x < y). For x > y, the elements are zero giving a triangular array.

f_{xx} = Total no. of parts using machine type x.

s = Total no. of machine types.

The triangular array for the Relation Matrix obtained in this study is shown in Table 3.2.

Step 6 - Calculation of Similarity Coefficient Matrix

Using the similarity function, S(f), the similarity coefficient array ($\underline{S}$) is set up. S(f) is given by,

$$S_{xy}\,(f) = \frac{f_{xy}}{f_{xx} + f_{yy} - f_{xy}}$$

where, f_{xy} = No. of parts using both machine types x and y;

f_{xx} = No. of parts using machine type x;

f_{yy} = No. of parts using machine type y;

For x = y, $S_{xy}(f)$ is set to zero.

The triangular array for the Similarity Coefficient Matrix obtained in this study is shown in Table 3.3.

Table 3.2: Relation Matrix Obtained in this Study

$$\underline{F} = \begin{bmatrix} 56380 & 1910 & 10930 & 4860 & 43180 & 26460 \\ 0 & 15380 & 0 & 800 & 800 & 0 \\ 0 & 0 & 11730 & 1340 & 9590 & 510 \\ 0 & 0 & 0 & 5010 & 800 & 1010 \\ 0 & 0 & 0 & 0 & 43180 & 18970 \\ 0 & 0 & 0 & 0 & 0 & 28910 \end{bmatrix}$$

Table 3.3: Similarity Coefficient Matrix for this Study

$$\underline{S} = \begin{bmatrix} 0 & 0.027 & 0.191 & 0.086 & 0.766 & 0.450 \\ 0 & 0 & 0 & 0.041 & 0.014 & 0 \\ 0 & 0 & 0 & 0.087 & 0.212 & 0.013 \\ 0 & 0 & 0 & 0 & 0.017 & 0.031 \\ 0 & 0 & 0 & 0 & 0 & 0.357 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Step 7 - Set up Similarity/Threshold binary portrait

For various threshold values for the similarity coefficient the binary portrait[2] ($\underline{B}$) is obtained for the similarity coefficient matrix.

$$\underline{B} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1s} \\ b_{21} & b_{22} & \cdots & b_{2s} \\ \vdots & \vdots & & \vdots \\ b_{s1} & b_{s2} & \cdots & b_{ss} \end{bmatrix}$$

For a threshold value, T_h, then for $x < y$;

$b_{xy} = 1$, for $S_{xy} \geq T_h$, and

$b_{xy} = 0$, for $S_{xy} < T_h$.

All other values are set to zero. The binary table obtained in this study for various threshold values is given in Table 3.4.

Step 8 - Compute Shannon Information Measures for each threshold level

The total number of graph edges (N_T) for each threshold level is obtained from array $\underline{B}$. It is given by,

$$N_T = \sum_{x=1}^{s} \sum_{y=1}^{s} b_{xy} \quad ; \quad \text{Max. } N_T = \tfrac{1}{2}(S^2 - S)$$

[2] The binary portrait is the total group of binary sets in Table 3.4 for the subsets of machine graph edges for each threshold value.

Table 3.4: Threshold Binary Table

Th	0.010	0.025	0.05	0.1	0.2	0.3	0.4	0.5
S_{12}	1	1	0	0	0	0	0	0
S_{13}	1	1	1	1	0	0	0	0
S_{14}	1	1	1	0	0	0	0	0
S_{15}	1	1	1	1	1	1	1	1
S_{16}	1	1	1	1	1	1	1	0
S_{23}	0	0	0	0	0	0	0	0
S_{24}	1	1	0	0	0	0	0	0
S_{25}	1	0	0	0	0	0	0	0
S_{26}	0	0	0	0	0	0	0	0
S_{34}	1	1	1	0	0	0	0	0
S_{35}	1	1	1	1	1	0	0	0
S_{36}	1	0	0	0	0	0	0	0
S_{45}	1	0	0	0	0	0	0	0
S_{46}	1	1	0	0	0	0	0	0
S_{56}	1	1	1	1	1	1	0	0

Table 3.5: Graph Edges and Information Measure

Th	0.010	0.025	0.05	0.1	0.2	0.3	0.4	0.5
NT	13	10	7	5	4	3	2	1
Hs	0.567	0.918	0.997	0.918	0.834	0.722	0.567	0.093

where, N_T = total number of graph-edges at a threshold level,

S = total number of machine types.

The corresponding Shannon Information measure for each threshold level is given by the expression,

$$H_S(p_1,p_0) = - p_1 \log_2 p_1 - p_0 \log_2 p_0$$

$$\text{where, } p_1 = \frac{N_T}{Max.N_T}, \text{ and } p_0 = \frac{(Max.N_T - N_T)}{Max.\ N_T}$$

Table 3.5 gives the values of total machine graph edges (N_T) for each threshold level and the corresponding Shannon information level (H_S). The derivation of H_S (p_1,p_0) is given in Appendix B.

Step 9 - Derive the optimal machine type sub-graph

From the plot of information level (H_S) against the threshold level (T_h) as shown in Fig. 3.3 the maximum value of H_S at the corresponding level of T_h is noted. In this study the maximum value of H_S is 0.997 at threshold level of 0.05. The total number of graph edges for the optimal machine graph is 7 (Table 3.5).

The nuclear machine type graph is drawn in Fig. 3.4 from the binary table (Table 3.4). Fig. 3.5 shows the plot of graph edges vs. threshold level according to Rajagopalan and Batra.

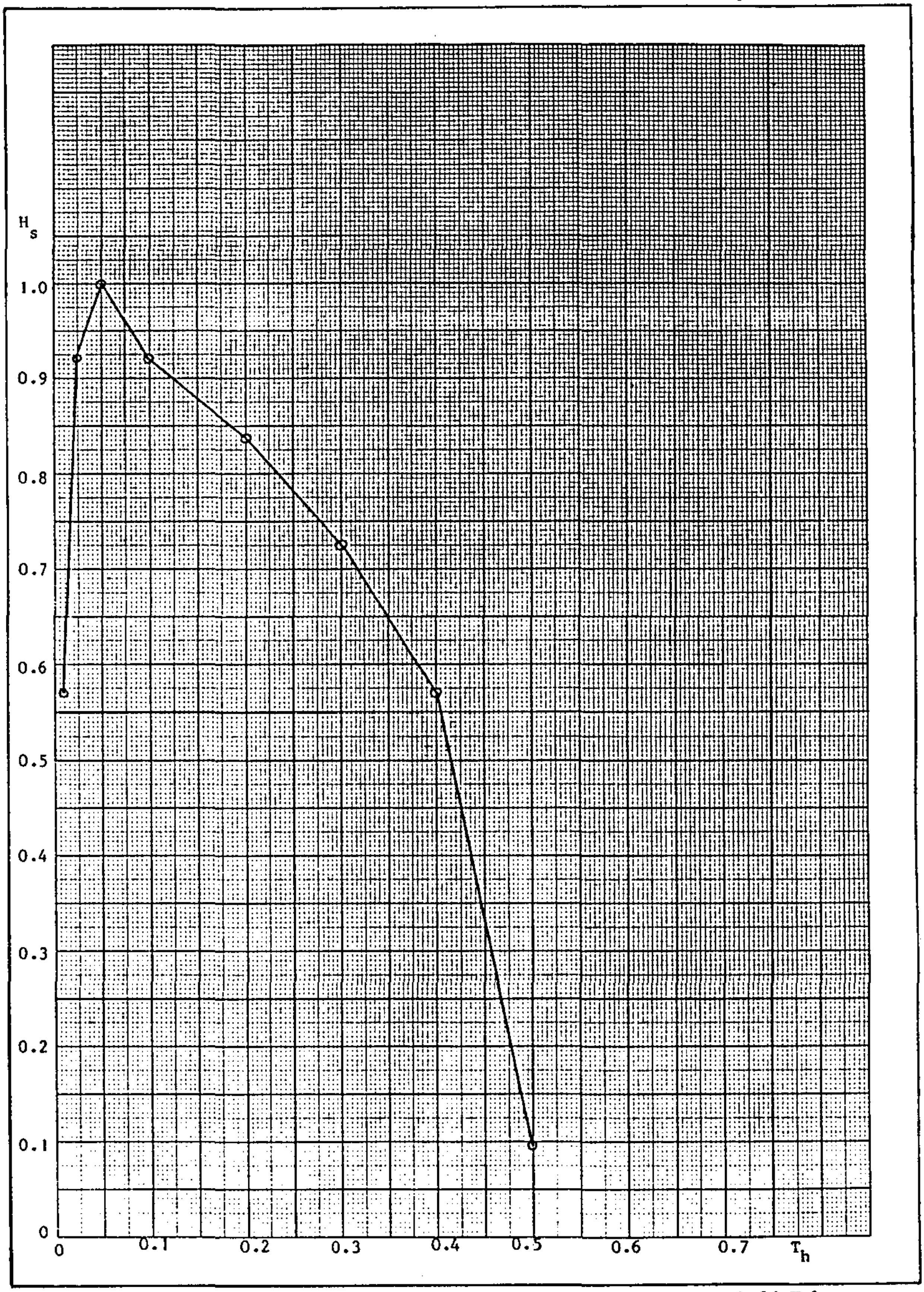
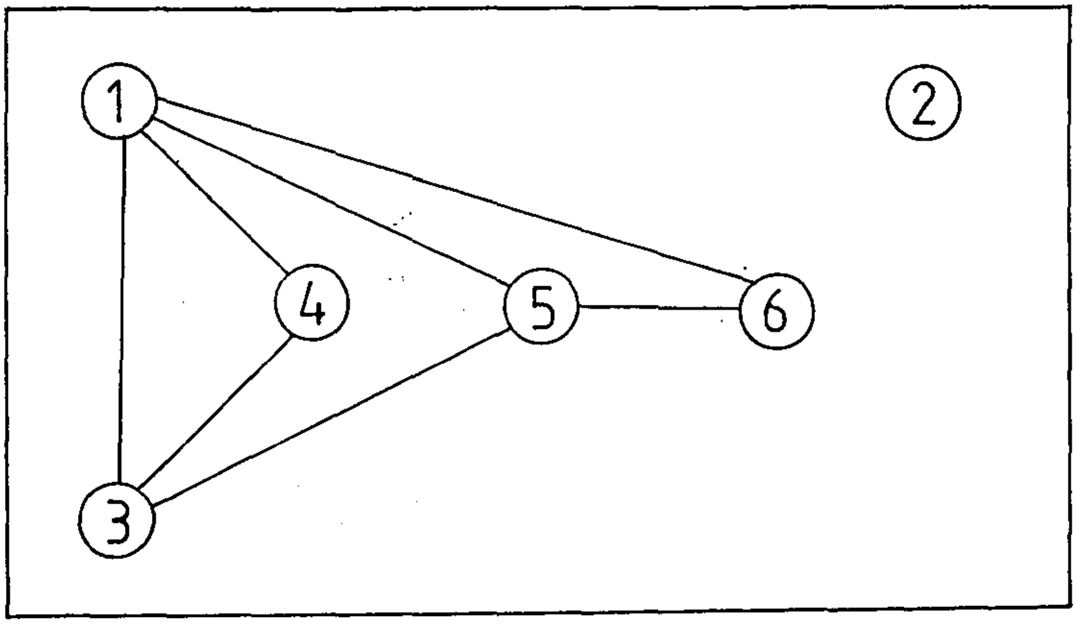


Fig. 3.3: Information Measure of Machine Graphs v.s. Threshold Value

Fig. 3.4: Optimal Machine Sub-Graph.



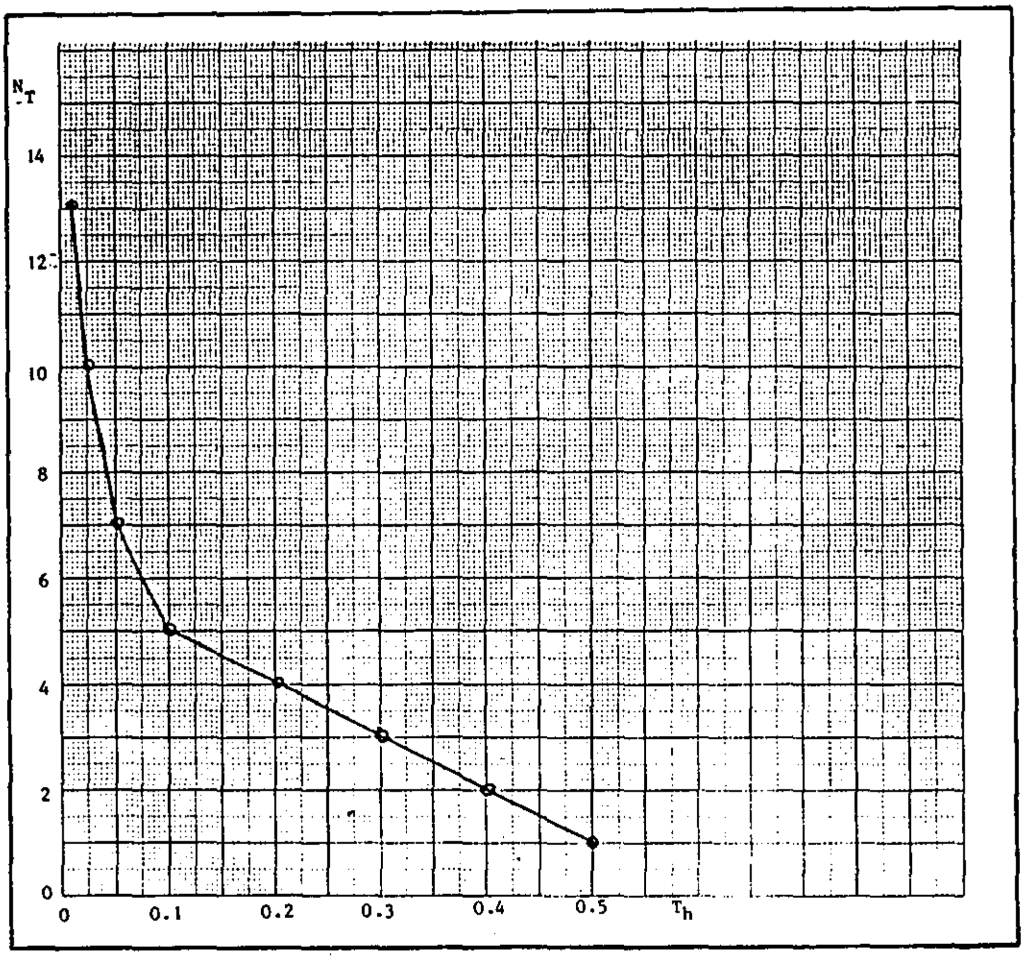


Fig. 3.5: Machine Graph Edges v.s. Threshold Level

Step 10 - Partition machine graph derived

The machine type graph obtained is now partitioned for the formation of cells. This is done in accordance with an established basis. In this study this is performed by considering intercell movements and part flow together with the minimum machine requirement analysis. Other operational conditions may be considered after cell formation depending on the particular system requirements. The formation of cells is now explained in the following section.

3.5 DERIVATION OF MACHINE CLUSTERS IN CELLS

The cell formation will depend primarily on the numbers of each type of machine needed according to the static requirement analysis, and on operational conditions such as shift system, scheduling methods and so on. The partitioning into nearly independent machine clusters seeks to minimise intercell movements. Thus intercell material handling problems are eschewed as far as possible. However, the directionality in part flow through a particular cell does not necessarily have to be considered, since the transport system integral to the cell is usually capable or designed to accommodate this. It is possible that for cost consideration, for example, a fixed conveyor tree network has to take into account direction of flow. This problem can be surmounted by employing a conveyorised loop network.

3.5.1 PARTITIONING OF MACHINE CLUSTERS

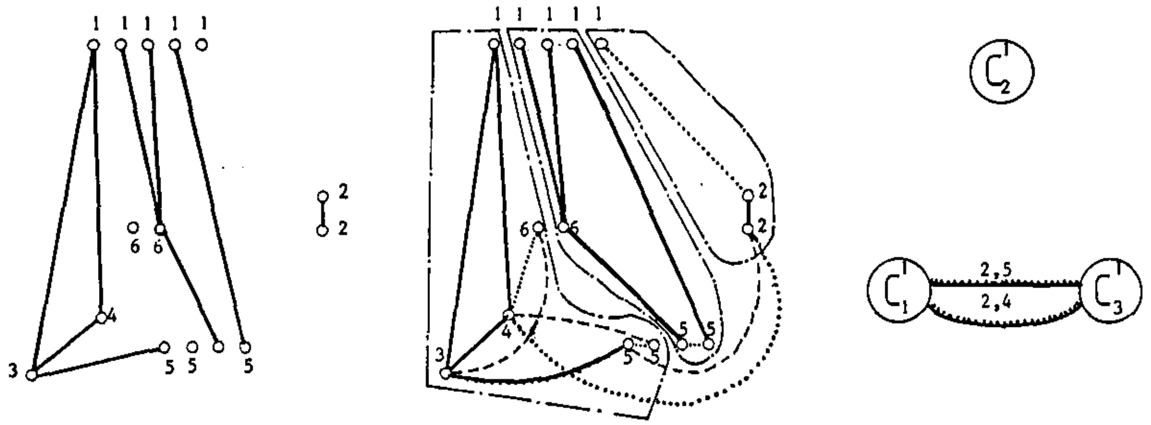
Any completely disconnected vertex of the optimal machine graph is considered to be the nucleus for a cell. If there are more than one vertex they may be agglomerated into one cell depending on the basis they are grouped together. For example, in this study, vertex (2) is nearly independent as shown in the machine graph in Fig. 3.4.

The next stage is to consider all the machine clusters for the shift system used. Figs. 3.6a, 3.6b and 3.6c illustrate the machine clusters with the inter-machine linkages suitably connected for various threshold levels showing the transformation into flexible cells with their intercell linkages. Table 3.6 shows the total annual processing hours on each machine for each operational stage.

For the single shift system, because of the multiplicity of certain machine types, three nearly independent cells have been formed. Only two weak intercell links are present.

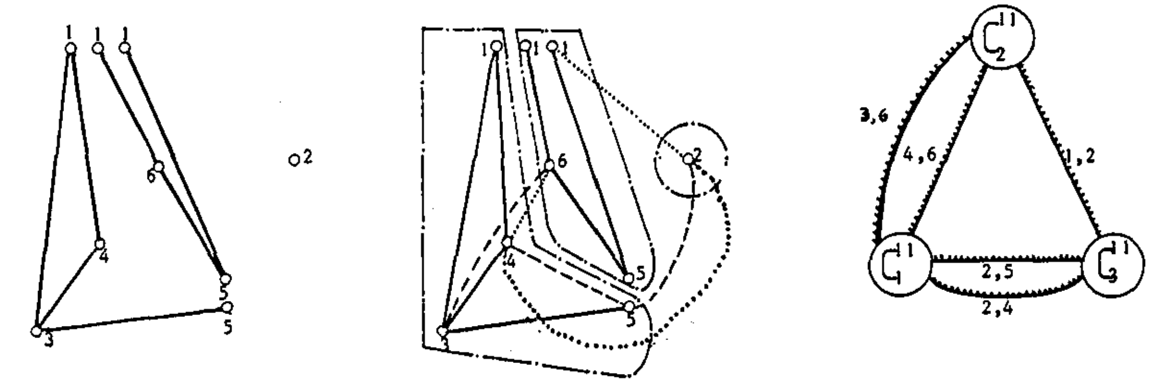
However, for the double shift system the number of machines from the static requirement analysis for each machine type is less. Thus a problem arises in the agglomeration of machines into cells. For example, as shown in Fig. 3.6(b) there are two machines of type (5). This machine type is required in Cells (1) and (2) to be followed by operations on machine types (3) and (6). From Table 3.6 it is observed that the total processing time for each case is less than the time available on one machine. Thus one of each machine type (5) is allocated to cells (1) and (2), as shown in Fig. 3.6(b). The same applies to the three shift system as shown in Fig. 3.6(c). However, due to the lesser number of machines in the two and three shift systems more intercell

(a) SINGLE SHIFT



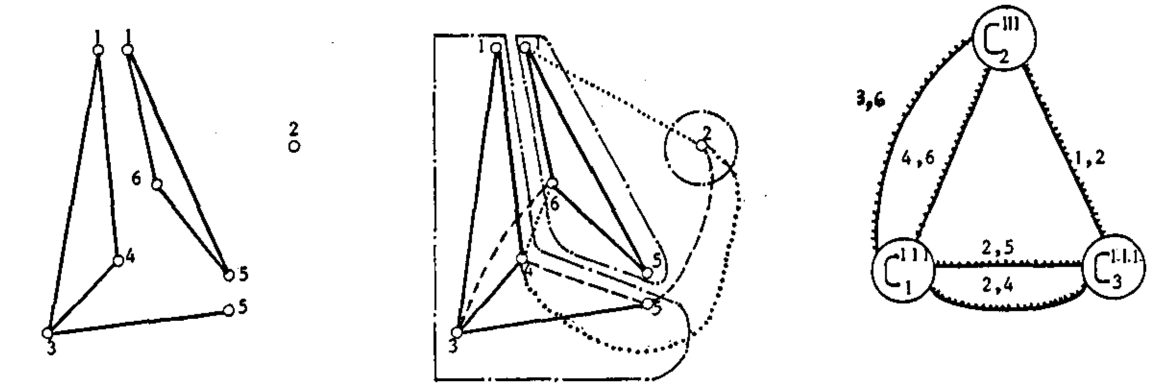
(i) Threshold = 0.050 (ii) Threshold = 0.025 (iii) Threshold = 0.0

(b) DOUBLE SHIFT



(i) Threshold = 0.050 (ii) Threshold = 0.025 (iii) Threshold = 0.0

(c) THREE SHIFT



(i) Threshold = 0.050 (ii) Threshold = 0.025 (iii) Threshold = 0.0

LEGEND

- (solid line) Optimal Machine Graph Edges for Threshold = 0.050
- (dotted line) Machine Graph Edges in addition to optimal graph for Threshold = 0.025
- (dashed line) Remaining Graph Edges to complete machine graph for Threshold = 0
- (dash-dot line) Cell boundary
- (hatched line) Intercell Linkages
- C_n^s Machining Cell (s = shifts/day, n = cell no)

Fig. 3.6: Machine Graphs for Different Shifts and Threshold Levels

Table 3.6: Annual Processing Time[3] (hrs) Array for each Operational Stage

Operation	Machine Hrs on Machine Type / When next Machine Type is	1	2	3	4	5	6
1	Nil	88(2)	3237(47)	0	0	0	0
	2	49(1)	0	0	0	0	0
	3	1541(11)	0	0	0	0	0
	4	242(8)	0	0	0	0	0
	5	3194(40)	0	0	0	0	0
	6	3311(27)	0	0	0	0	0
2	Nil	0	37(1)	0	90(3)	2622(22)	620(7)
	3	0	0	0	0	359(11)	0
	4	0	78(1)	113(3)	0	0	47(1)
	5	0	158(1)	0	179(1)	0	1188(16)
	6	0	0	0	98(4)	735(17)	0
3	Nil	0	566(2)	16(3)	371(2)	2600(26)	768(17)
	5	0	0	94(3)	0	0	0
	6	0	0	0	0	0	213(2)
4	Nil	0	0	26(3)	0	0	79(2)

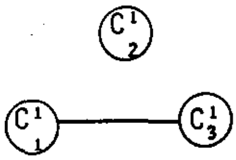
(3) Number in brackets denotes number of parts.

movements are required as illustrated in Figs. 3.6b(iii) and 3.6c(iii). The linkages between machine types between the cell groups are noted on the cell graph edges. For example, in Fig. 3.6a(iii) there are 2 linkages between $c^1{}_1$ and $c^1{}_3$. One represents part flow between machine type 2 and 5, and the other between machine type 2 and 4.

The cells formed with their machine clusters are noted below. A cell flow synthesis for the three groups is performed in the following section.

Single Shift operation

Cell Graph



Machine Clusters

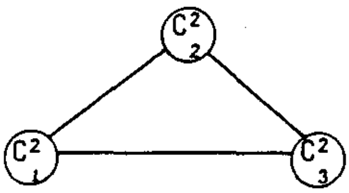
Cell (1), C^1_1 = [1,3,4,5,5,6]

Cell (2), C^1_2 = [1,1,1,5,5,6]

Cell (3), C^1_3 = [1,2,2]

Double Shift operation

Cell Graph



Machine Clusters

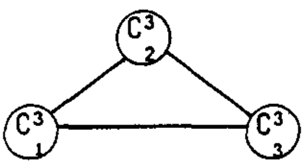
Cell (1), C^2_1 = [1,3,4,5]

Cell (2), C_2 = [1,1,5,6]

Cell (3), C^2_3 = [2]

Three Shift operation

Cell Graph



Machine Clusters

Cell (1), C^3_1 = [1,3,4,5]

Cell (2), C^3_2 = [1,5.6]

Cell (3), C^3_3 = [2]

3.6 CELL FLOW SYNTHESIS

The nature and relation between the cells formed will now be considered for the different operational conditions. This is done with the results obtained in this industrial study. The part flow is shown in Table 3.7 for the three stages. It is worthwhile noting that for GT systems Tilsley et al (1977) observed that "rearranging machines into cells does not by itself improve utilisation". However, he suggests that low machine utilisation may be due to:

(i) cells designed on the basis of exclusive shape families,

(ii) cells being too small, and

(iii) system not being designed to allow job assignment to cells.

Additionally, it is preferable that technologically incompatible processes should be kept apart.

3.6.1 INTERCELL MOVEMENT

The flow of parts and part types between the cells are given by the cell graph array below for the single, double and three shift mode of operation. The subscript stands for cell group, and superscript denotes shifts per day.

Single Shift

To / From	C^1_1	C^1_2	C^1_3
C^1_1	0	0	1600(2)
C^1_2	0	0	0
C^1_3	0	0	0

Double Shift

To / From	C^2_1	C^2_2	C^2_3
C^2_1	0	200(1)	1600(2)
C^2_2	810(4)	0	310(1)
C^2_3	0	0	0

Three Shift

To / From	C^3_1	C^3_2	C^3_3
C^3_1	0	200(1)	1600(2)
C^3_2	810(4)	0	310(1)
C^3_3	0	0	0

Table 3.7: Component Flow Array

First Stage Flow (OP1 → OP2)

From \ To	1	2	3	4	5	6
1	0	310(1)	9530(11)	3030(8)	9340(31)	17090(29)
2	0	4270(12)	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0

Second Stage Flow (OP2 → OP3)

From \ To	1	2	3	4	5	6
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	9590(11)	0
4	0	800(1)	520(3)	0	0	200(1)
5	0	800(1)	0	800(1)	0	11170(16)
6	0	0	0	810(4)	7950(18)	0

Third Stage Flow (OP3 → OP4)

From \ To	1	2	3	4	5	6
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	800(1)	0	0	0
5	0	0	0	0	0	800(1)
6	0	0	0	0	0	0

(Note: Integers in brackets denotes number of distinct types of parts).

3.6.2 LEVEL OF CELL INDEPENDENCE

It is instructive to note the fraction of the total number of parts flowing through a system which has to be moved between cells, and thus the degree to which the cells in the manufacturing system are independent. This may have to be considered from an economic viewpoint, before a decision is taken to invest in additional transport systems for intercell handling required to integrate the cells into a combined network. Since intercell movement is minimised for maximum cell independence, intercell handling should be combined with transport betwen central stores and cells.

If the intercell movement matrix is $\underline{C}$, so that for a system with l cells,

$$C = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1l} \\ C_{21} & C_{22} & \cdots & C_{2l} \\ \vdots & \vdots & & \vdots \\ C_{l1} & C_{l2} & \cdots & C_{ll} \end{bmatrix}$$

then, the total intercell flow (F_T) in the system, is given by,

$$F_T = \sum_{r=1}^{l} \sum_{q=1}^{l} C_{qr}$$

In this study the values for $F^1{}_T$, $F^2{}_T$ and $F^3{}_T$ corresponding to single, double and three shift operation are respectively,

$F^1_T = 1600$,

$F^2_T = 2920$,

and $F^3_T = 2920$.

The level of cell independence (I_C) may then be defined as the total number of parts independently processed in the various cells expressed as a percentage of the total parts flowing through the manufacturing system. Thus,

$$I_C = (1 - \frac{F_T}{N_p}) \times 100 \%$$

where, F_T is the total intercell flow, and N_p is the total parts flowing through the cells. From the results of this study the corresponding values for the operating modes are,

$I^1_C = 96.3\%$, (single shift),

$I^2_C = 93.3\%$, (double shift) and and,

$I^3_C = 93.3\%$, (three shift).

3.6.3 CELL UTILISATION

The cell utilisation for each cell is the total machining time expressed as a percentage of the total available machine hours. The overall system utilisation is the average utilisation for the various cells. The values are tabulated below in Table 3.8 for the different operational modes.

The slight variation in average system utilisation is because when the number of shifts is increased it is not accompanied by a corresponding equal discrete decrease in the total integral number of machines.

Table 3.8: Cell and System Utilisation

Shift/Day	Cell Machine Utilisation(%)			Overall System Utilisation (%)	Total No of Machines
	1	2	3		
One	56.2	72.7	61.1	63.3	15
Two	38.2	79.0	83.4	66.9	9
Three	16.2	88.1	55.6	53.3	8

3.7 IDENTIFICATION OF CELL FOR FURTHER STUDY

From the analysis in this chapter, the most suitable candidate for the initial implementation of a flexible cell appears to be Cell (3). It has the least number of different machines. The industrial concern where this study was based operates on a two shift system and it is interesting to note that this cell has the highest cell utilisation level for this condition. The level of cell independence is over 90%, so that this cell can be the starting point for the development of a larger manufacturing system. Although the cell machine utilisation for a three shift operation is nearly 28% lower, more parts that would otherwise have been subcontracted were identified for processing in the cell.

Cell (3) is a prismatic cell as observed from the part data in this study. With the identification of more parts the prismatic part spectrum was increased from 47 to 147 part types. Due to the increased total machining time and higher sales forecasts for the period 1987 and beyond, the size of the prismatic machining cell in the Company was increased from one to six machines comprising one horizontal and five vertical machining centres. This cell was targetted by the firm for initial investment and attention as a forerunner for longer term development.

3.8 SUMMARY

The technique in this method of cell formation treats the machine and part sets as a combination of ordinary subsets. It determines the machine graph subset with the maximum information content. This determines the nuclear machine graph, the nodes of which (representing different machines) are divided into machine cluster nodes depending on the different operational conditions. The machine graph and the cluster of vertices are partitioned and thus extended to the formation of cells according to various criteria such as degree of cell differentiation, intercell movement and cell independence.

The method of deriving the machine subgraph as developed in this study appears to offer advantage by comparison with Rajagopalan and Batra's method and lends itself to computerisation. It avoids the arbitrariness and adopts a more systematic approach. After having derived the cells of machine groups, the part set is decomposed into subsets to be allocated to each cell. Each flexible cell with its appropriate part spectrum may then be examined with regard to system performance by simulation modelling. Fig. 3.7 illustrates diagramatically the connection of the first stage of cell formation with the subsequent stages of system evaluation.

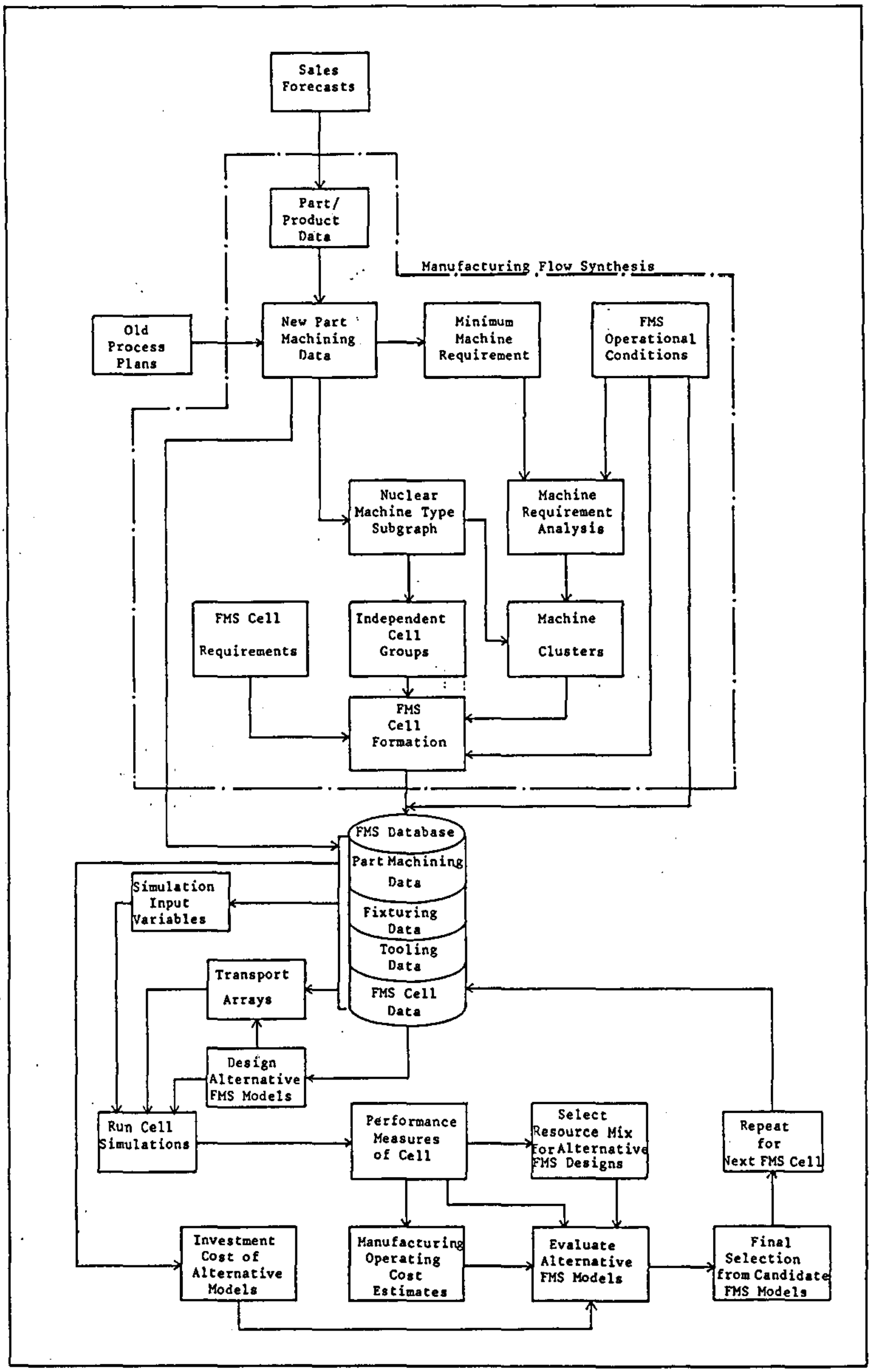


Fig. 3.7: Stages for Cell Formation and System Evaluation

CHAPTER 4

DESCRIPTION OF SELECTED ALTERNATIVE FMS CONFIGURATIONS

4.1 GENERAL INFORMATION

The part spectrum for the prismatic cell consists of 147 different parts. The machining data for the parts is given in Appendix C.1, with batch sizes varying between 1 and 98 components to meet the company's two week period batch control requirements.

Maximum and minimum component machining times for the part spectrum are 460 and 2 minutes respectively. The spread of machining times and batch sizes are shown in Figs. 4.1 and 4.2. However, 12 different parts require two visits to machining centres. An indication of some of the types of components from the part spectrum is given by Figs. 4.3 to 4.8.

The particular volume of output required is processed on six CNC machining centres consisting of 3 different machine types. The one KTM horizontal machining centre has a built in twin pallet linear shuttle pallet changer of the turning type, and may be retrofitted with a four station pallet changer. The other five vertical machining centres considered have zero, two or four pallet stations of the dual type depending on the configuration to be examined. Some 23 components are processed on the KTM whereas 41 parts are processed on either of the 2 Wadkin V4-6, and 88 parts on any one of the 3 Wadkin V5-10 machines.

Seven forms of Flexible Machining Systems have been conceived with characteristics summarised in Tables 4.1 and 4.2:

(i) FMS A - CNC machines;

(ii) FMS B - CNC machines with 2 station APC;

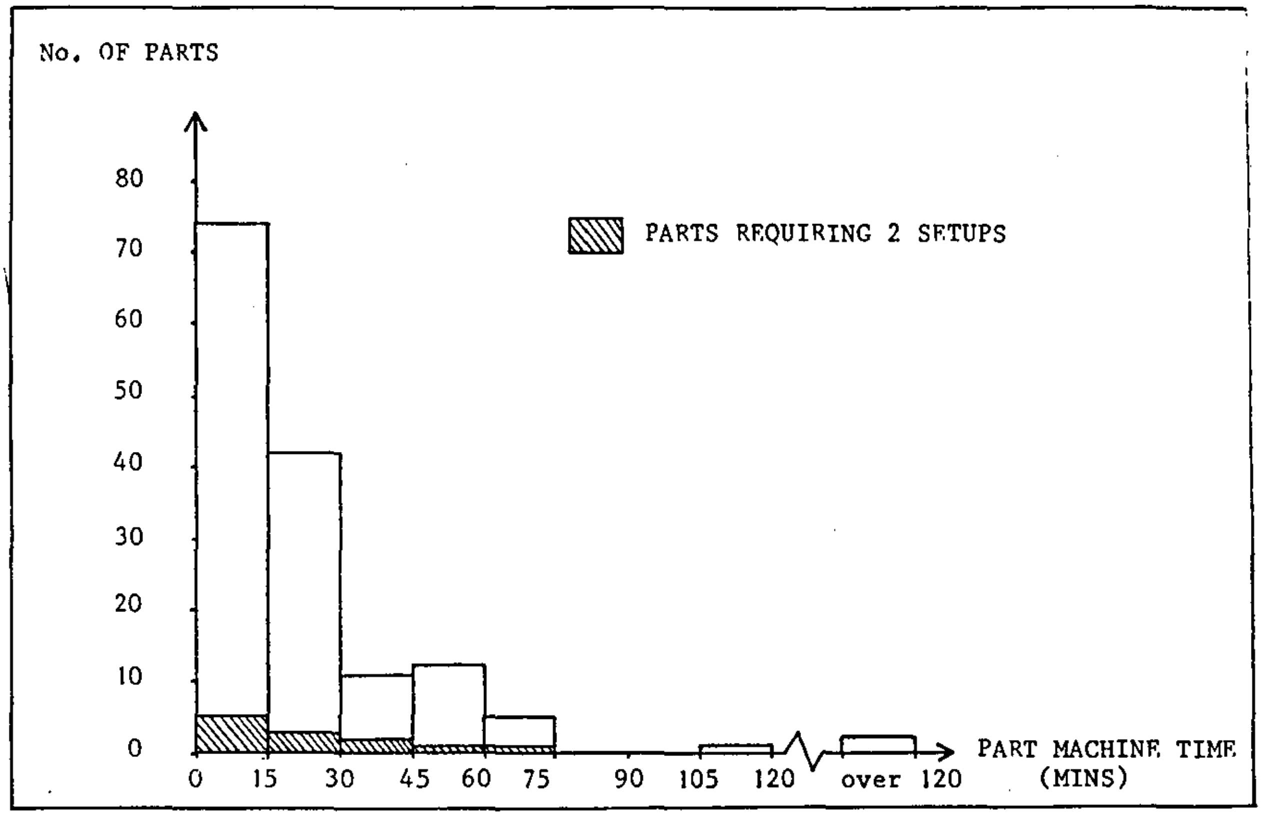


Fig. 4.1: Machining Times of Part Spectrum

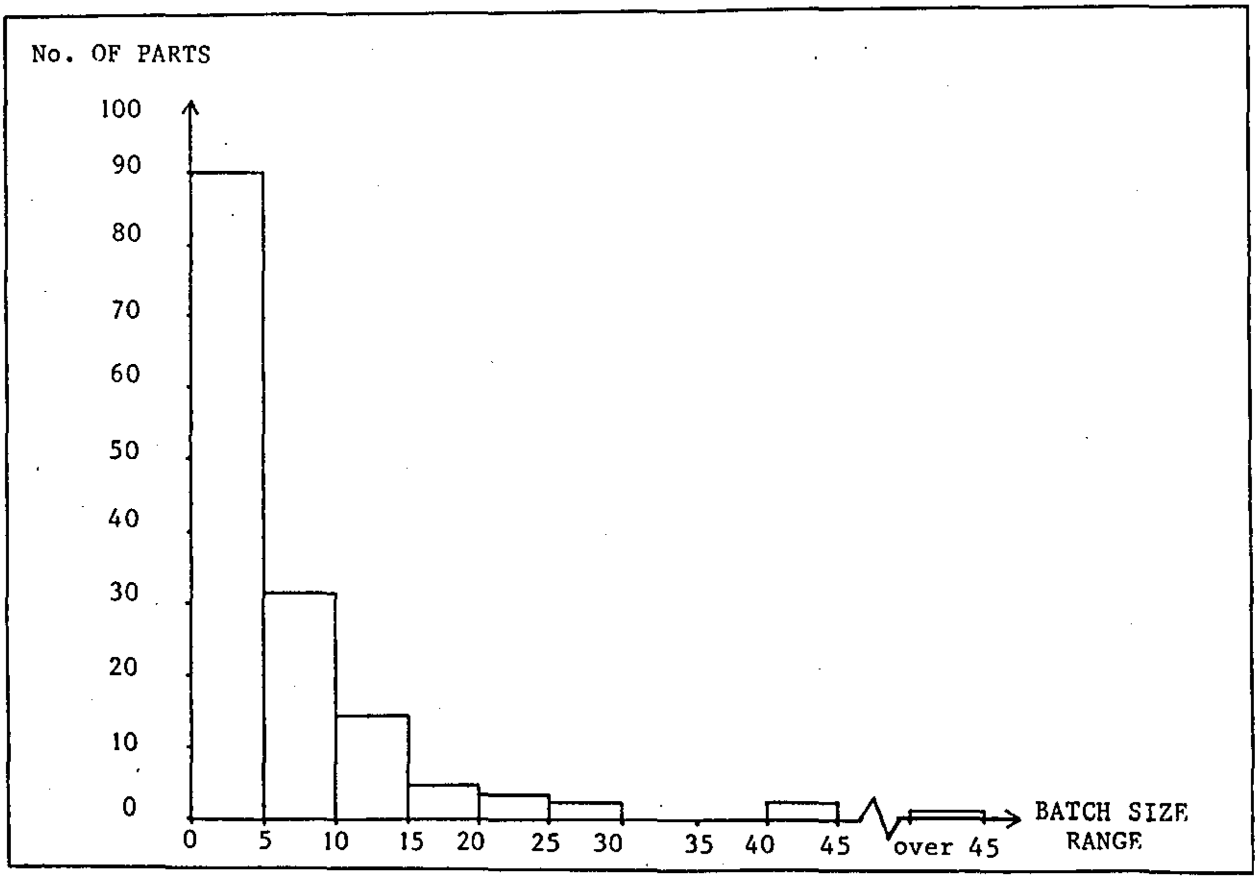


Fig. 4.2: Batch Sizes of Parts

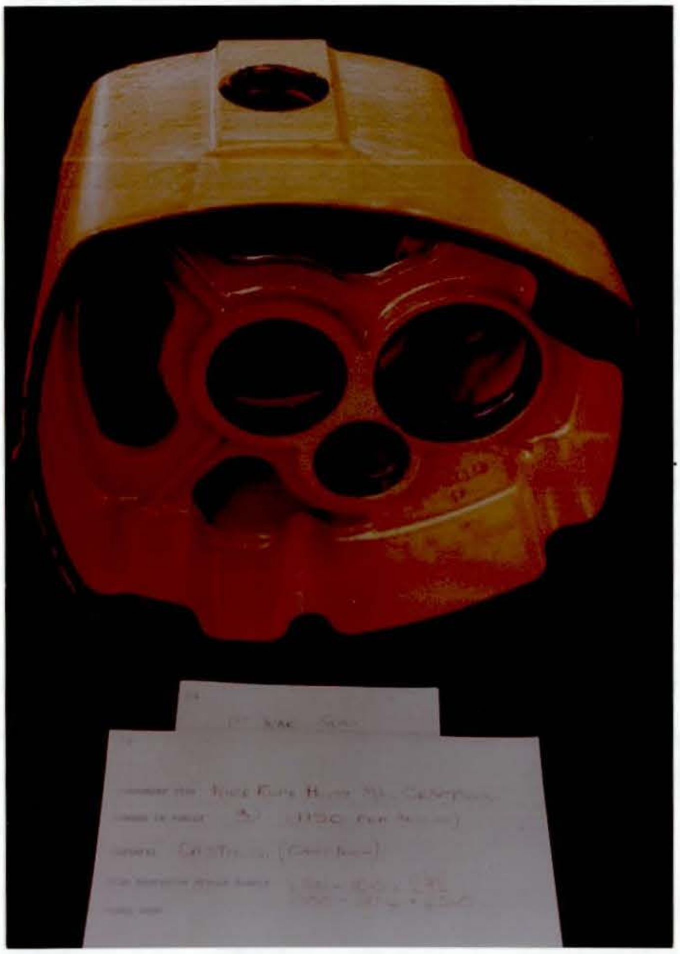


Fig. 4.3: Gear Box

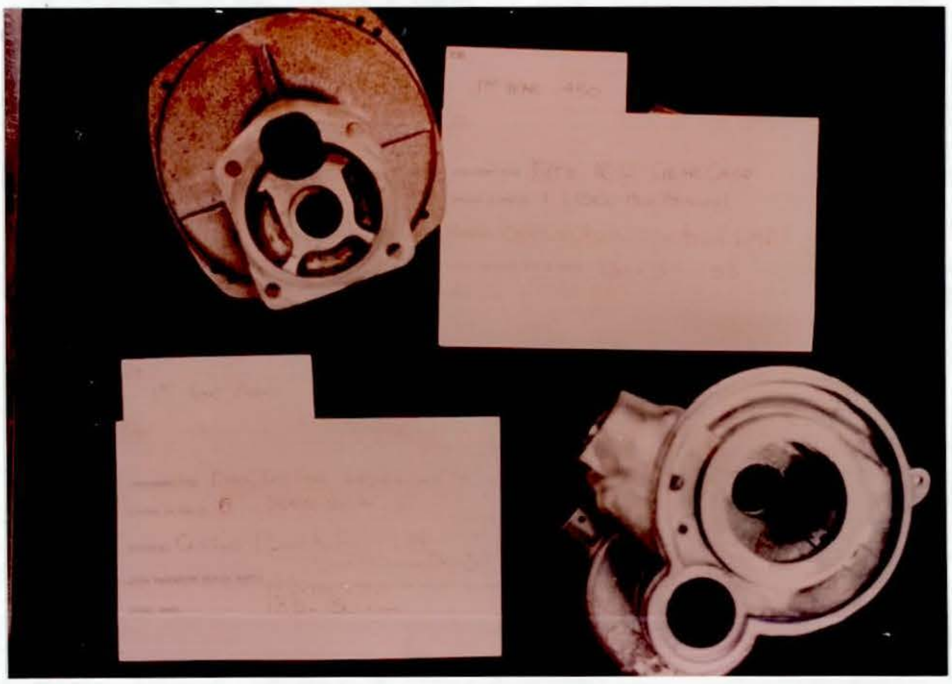


Fig. 4.4: Gear Case (top) and Body Casting

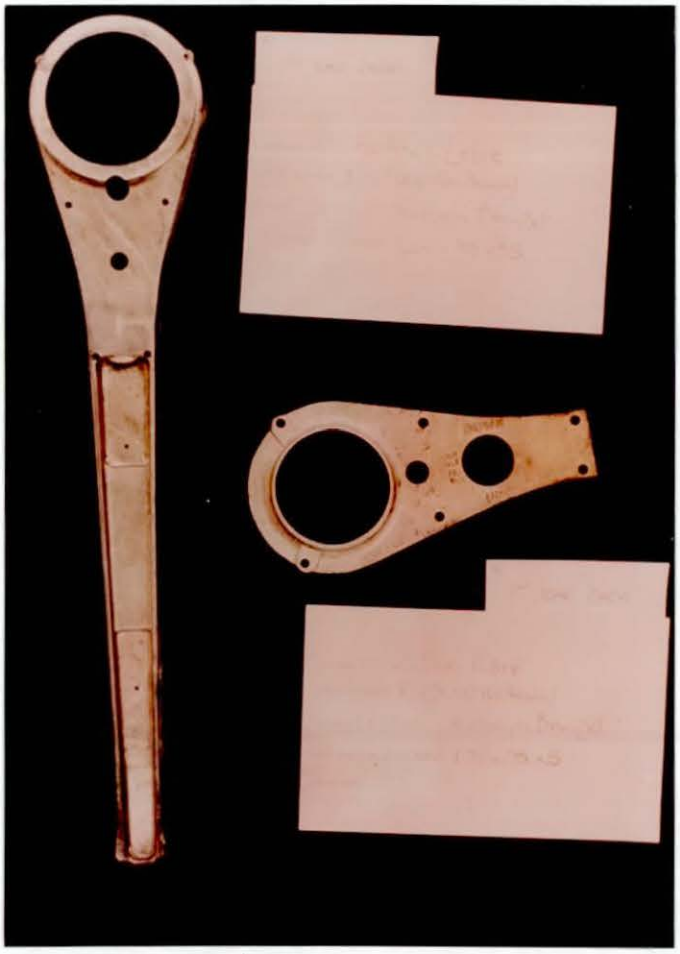


Fig. 4.5: Operating Lever (left) and Cover Plate

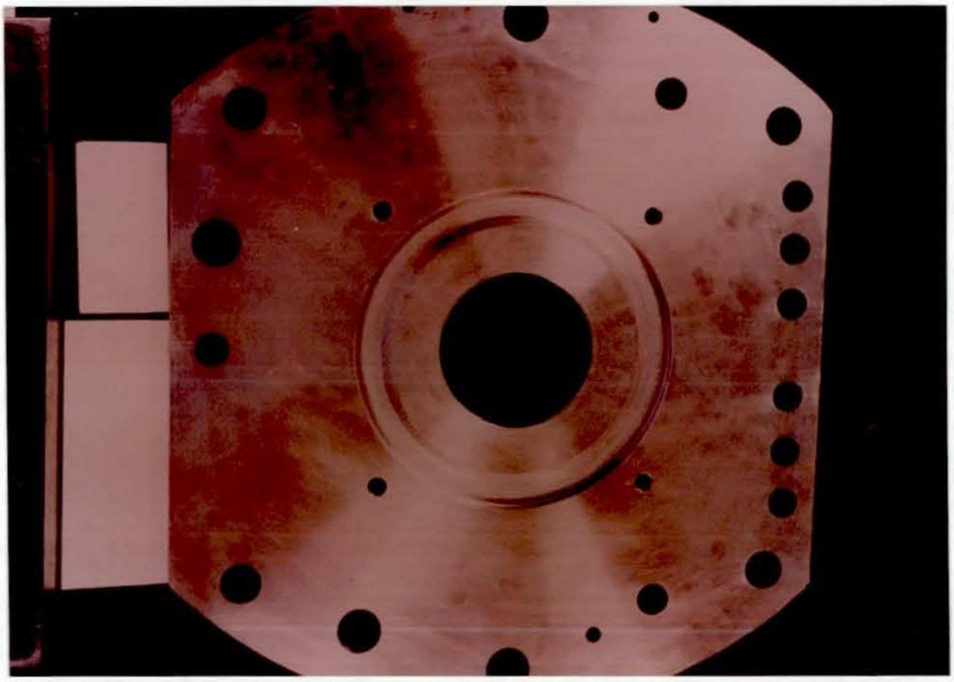


Fig. 4.6: Gear Box Side Plate

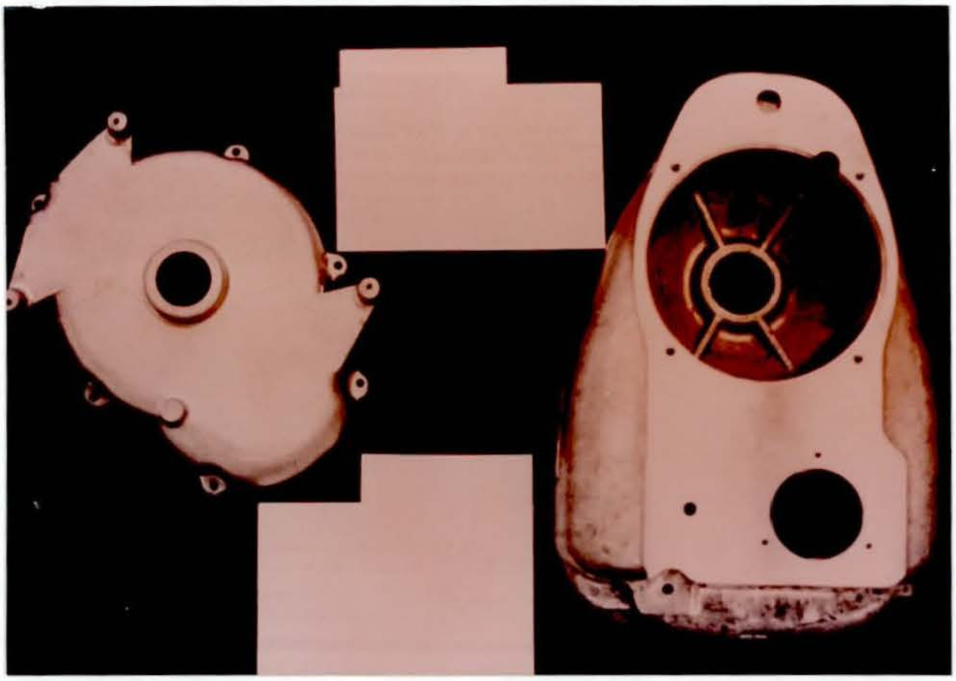


Fig. 4.7: Gear Case Cover (left) and Body Casting

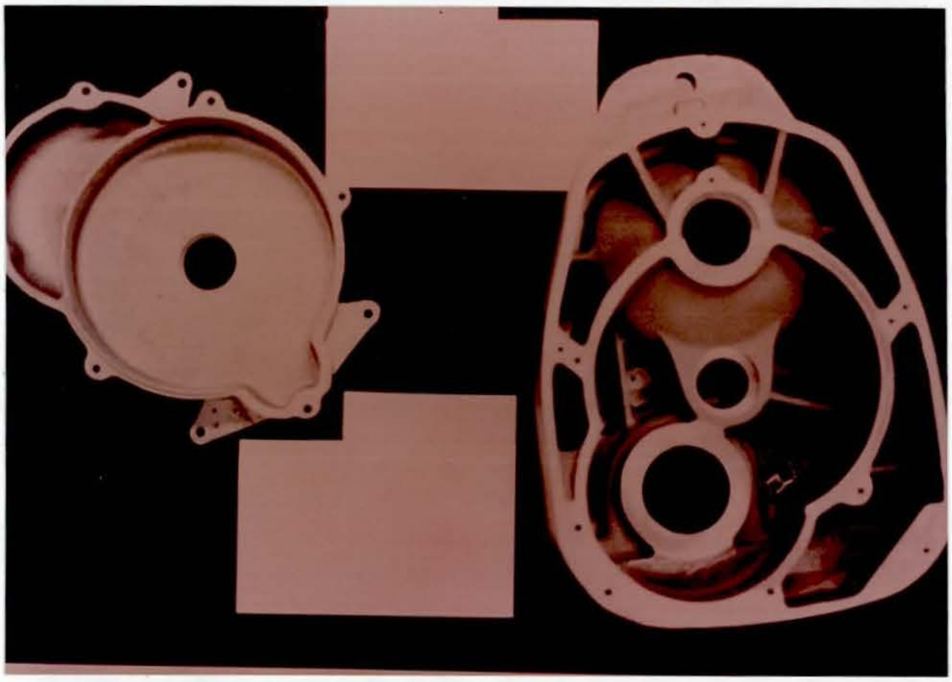


Fig. 4.8: As in Fig. 4.7 (reverse view)

Table 4.1: Description of Machining Centres

Model	Type of Machine Centre	No. of Machines	Tool Mag. Capacity	Spindle Drive	No. of Different Parts Machined	Machine Cube(mm)	Pallet Table (mm)
K.T.M.	Horizontal	1	40	7.5 KW	18	750x500x500	560 dia.
Wadkin V4-6	Vertical	2	30	11.5 KW	41	600x460x525	750x500
Wadkin V5-10	Vertical	3	30	18.0 KW	88	1000x500x600	1150x600

Table 4.2: Profile of Alternative Configurations

Features	APC Pallet Stations	Fixture Loading	Part Loading	Transport to & from Load Stns.	Intermed. Storage	Transport to & from Machine	Tool Mag. Load/ Unload	Swarf Disposal	Part Programme Selection
FMS A	Nil	M	M	M	M	M	M	M	M
FMS B	A(2)	M	M	M	M	M	M	M	M
FMS C	A(4)	M	M	M	M	M	M	M	M
FMS D	A(2)	M	M	A	A	A	M	M	A
FMS E	A(2)	M	M	A	A	A	M	M	A
FMS F	A(2)	M	M	A	A	A	M	M	A
FMS G	A(2)	M	M	A	A	A	M	M	A

(Note: Integers in brackets denote number of pallet stations on APCs)
(A = Automated)
(M = Manual)

(iii) FMS C - CNC machines with 4 station APC;

(iv) FMS D - CNC machines, 2 station APC, and powered conveyor transport;

(v) FMS E - CNC machines, 2 station APC, and Stacker Crane transport;

(vi) FMS F - CNC Machines, 2 station APC, and Rail Guided Shuttle transport;

(vii) FMS G - CNC Machines, 2 station APC, and AGV transport.

The common features in the seven configurations are:

(a) Tooling - All tool requirements are organised into 17 tool packs with 30 tools each so that one tool pack can be used for machining several batches of parts,and shown in Appendix C.2. Twelve trolleys with the required tool packs, according to the production schedule, are delivered and positioned behind the machine. Loading and unloading of tools to and from the tool magazine is accomplished manually by the machine operators and the cell supervisor. Tool selection from within the magazine is automatic as controlled by the machine part program.

(b) Pallets - There are 3 different pallet sizes associated with the three different types of machine centres.

(c) Load/Unload Stations - The configurations with automated transport have 3 load/unload stations to accommodate the 3 pallet types, Station A for machine 1, Station B for machines 2 and 3, and Station C for machines 4,5 and 6. (See Figs. 4.13, 4.14, 4.15 and 4.16).

(d) Material Handling - Raw parts in trolleys are kitted outside the cell and delivered to a central buffer area. They are subsequently taken by machine operators to the machines for unautomated systems. In automated systems trolleys with parts are placed near to the load/unload stations. Heavy parts are loaded and unloaded to and from the fixtures with the aid of an overhead hoist located at each machine. A manually operated fork lift truck assists loading at pallet stations.

(e) Auxiliary Equipment - All tools are preset by toolsetters using a presetting machine located outside the immediate FMS area. Inspection is carried out using a co-ordinate measuring machine. A wash station is located alongside the cell area.

(f) Fixtures - There are 38 dedicated and 28 modular fixtures. All fixtures are stored in the fixture store near to the FMS area. Dedicated fixtures are mounted on fixture platens and modular fixtures are set up on a grid plate. All fixtures are mounted manually by locating directly on the machine bed in manually operated systems. In automated systems preset fixtures are mounted manually on a pallet. There is no duplication of fixtures.

(g) Computer and Control - Each FMS configuration is equipped with a suitable microcomputer system, (including keyboard, printer, VDU and floppy disc and/or hard disc drive). A computer and control system for management and control of the cell is shown in Fig. 4.9. In manually operated systems, the material handling section and machine controller to computer links are non existent, and the computer system is used for production planning and control tasks. In automated transport configurations it is used for both production management and system operation and control.

(h) Cell Management - Long term production planning and period batch control and scheduling is performed by the cell planner in conjunction with other departments. The raw parts accompanied with the required fixtures are sent from central stores together with cards bearing information on parts, batch quantities, due dates and tool file requirements. This data is entered into the computerised information section. A work list is distributed by the cell supervisor to the machine operators.

(i) Manpower - The number of machine operators in the cell may be varied. Other manpower is drawn on for tool presetting, preparation, and transport of tool trolleys, parts washing, swarf removal, cell supervision and planning. However, the work of these men is not included in the system simulation.

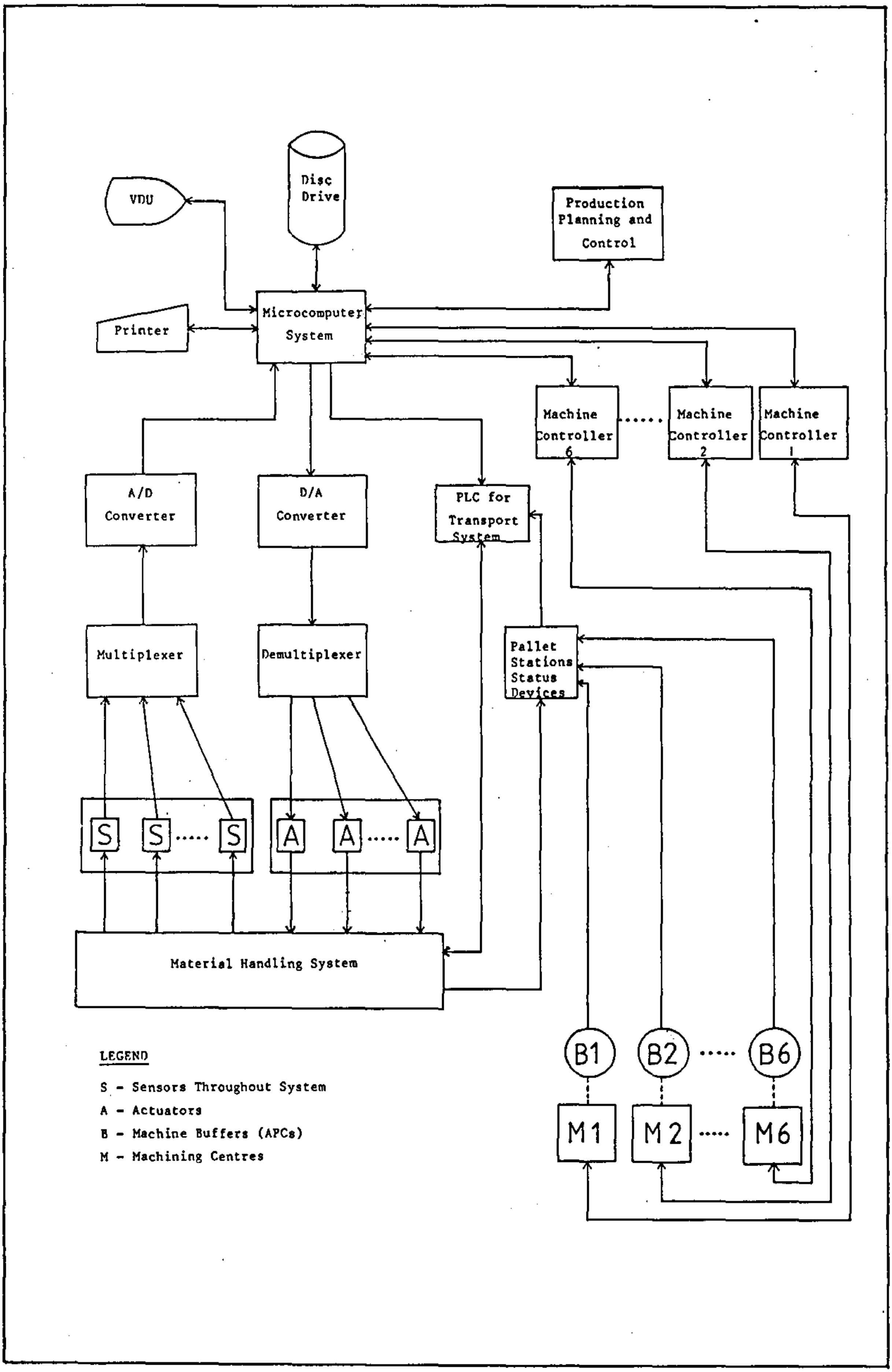


Fig. 4.9: FMS Control System for Machining Cell

4.2 FMS A WITH CNC MACHINES (See Fig. 4.10)

This manually operated cell has two rows of 3 machining stations, with a central buffer storage area accommodating upto 36 trolleys. Parts and fixtures in trolleys are delivered to the central buffer area. They are then collected and the trolley with the batch to be processed is positioned next to the appropriate machine. After the fixture is set up on the machine bed, the complete batch of parts is processed after which the finished parts and fixture are taken by trolley to the central buffer area for subsequent movement to the wash station. Parts and fixtures are cleaned by the cell attendant before returning them to the staging area.

Part programs are selected, entered and initiated on the machine controller by the machine operator at the start of processing of a batch.

4.3 FMS B WITH CNC MACHINES, 2 PALLET APC (See Fig. 4.11)

This configuration is similar to FMS A, but differs by the machine centres being equipped with twin automatic pallet changers for loading and unloading of parts to and from the machine bed. Grid plates are permanently fixed to the APC pallet stations. Fixtures are located and clamped manually on to the grid plate. When one pallet station on the APC is being used for machining parts, the other station, if available, is fixtured. When one pallet station is being unloaded the other stations loaded with parts are transferred for machining. When setting up pallet stations, priority is given to a mounting of fixtures which will

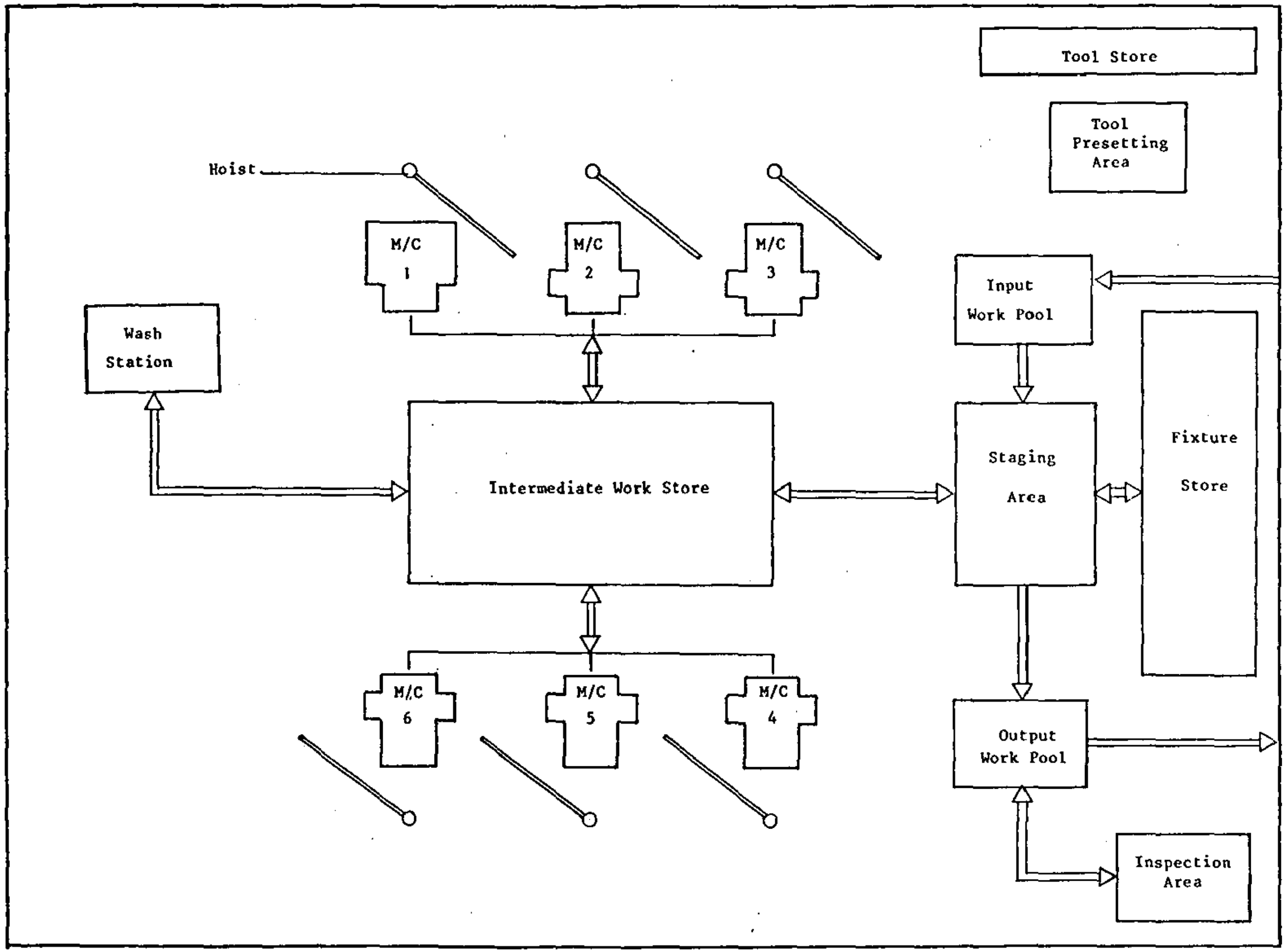


Fig. 4.10: FMS A with CNC Machines

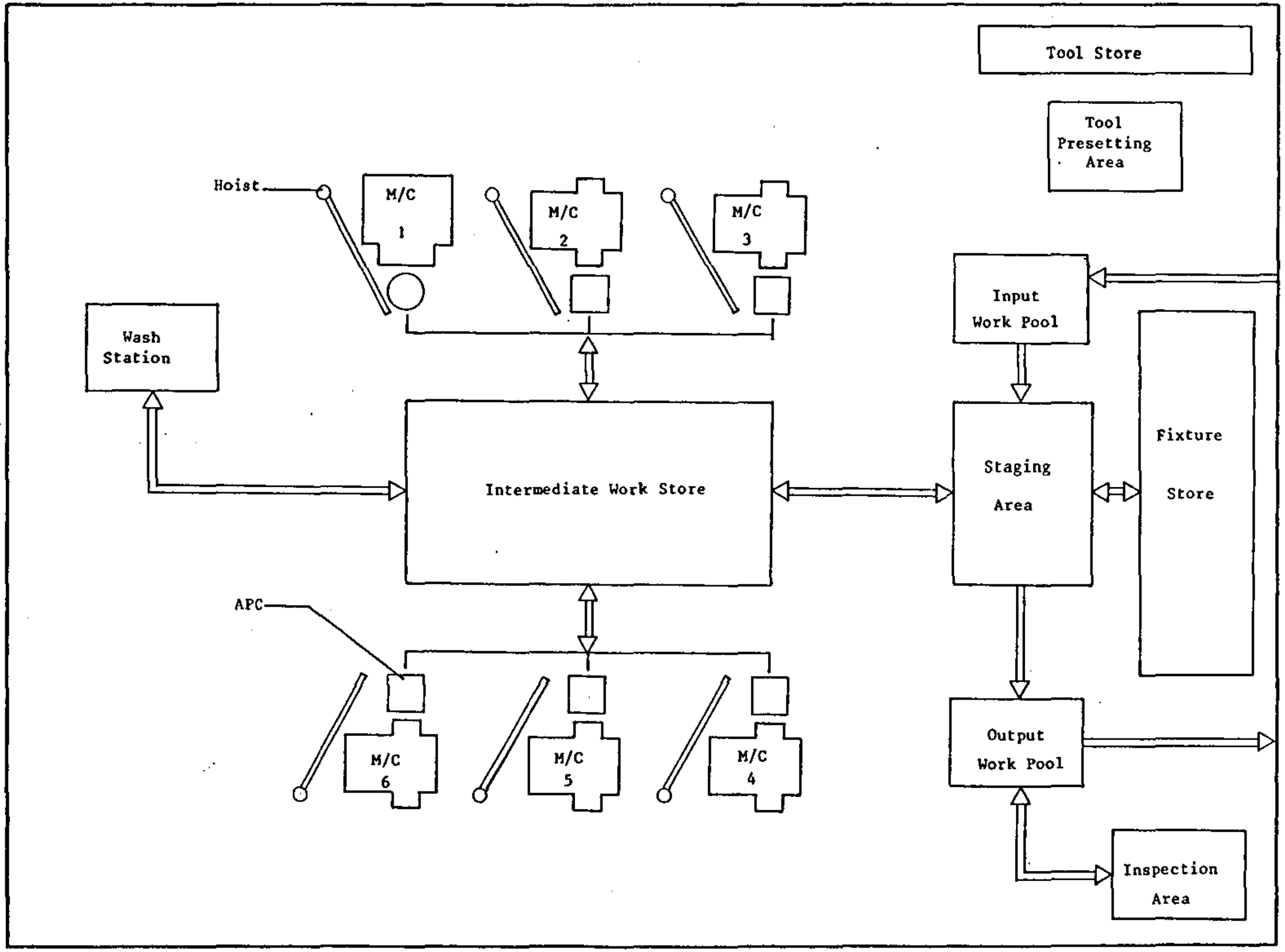


Fig. 4.11: FMS B with CNC Machines, 2 Pallet APC

complete the processing of a particular batch of parts. The flow of parts in all other respects is the same as that in FMS A.

4.4 FMS C WITH CNC MACHINES, 4 PALLET APC (See Fig. 4.12)

This layout is the same in all respects as that of FMS B with the exception of the vertical machining centres having two twin pallet shuttle APC giving an automatic pallet changing capacity of 4 stations. Each of the two APCs is positioned at either end of the machine table. It is noted that the Wadkin machines are conceived in this form although they are not commercially available currently.

4.5 FMS D WITH CNC MACHINES, 2 PALLET APC, CONVEYOR SYSTEM (See Fig. 4.13)

This configuration is equipped with powered roller conveyor for transporting fixtured parts on pallets. The conveyor system connects the load/unload stations to the APCs, and fixtured part transfer is effected by telescopic fork sets at the APC. Because different pallet sizes are employed for the different machines appropriate positioning fixtures are mounted on the conveyor near the turnstiles at the machine centres.

Fixturing is performed at fixturing tables A, B and C, whence the first part in the batch is loaded and transferred to a vacant Load/Unload station. When parts on a pallet have been machined at the machining centre, the fixtured parts return to the appropriate load/unload stations for unloading of the part.

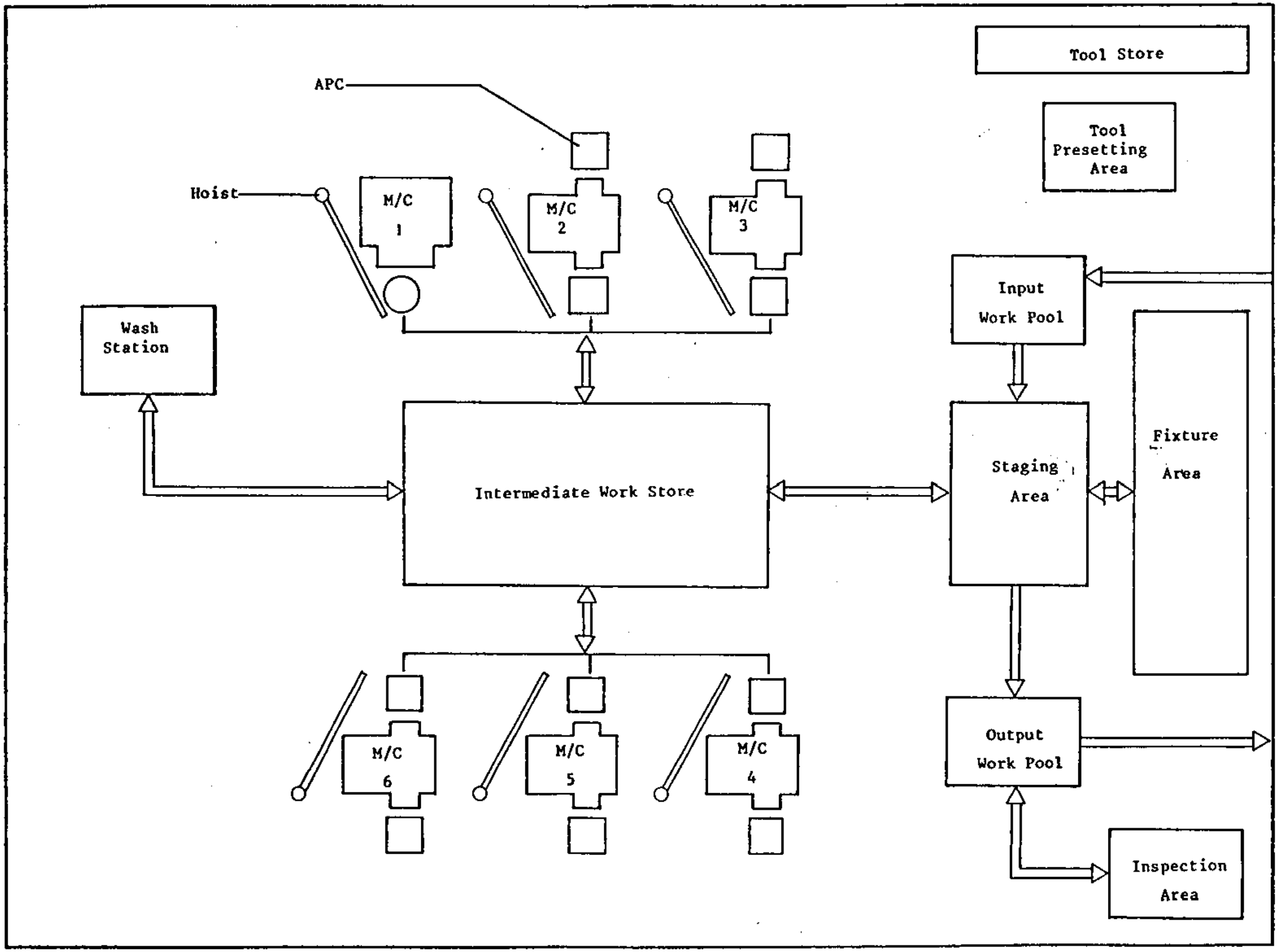


Fig. 4.12: FMS C with CNC Machines, 4 Pallet APC

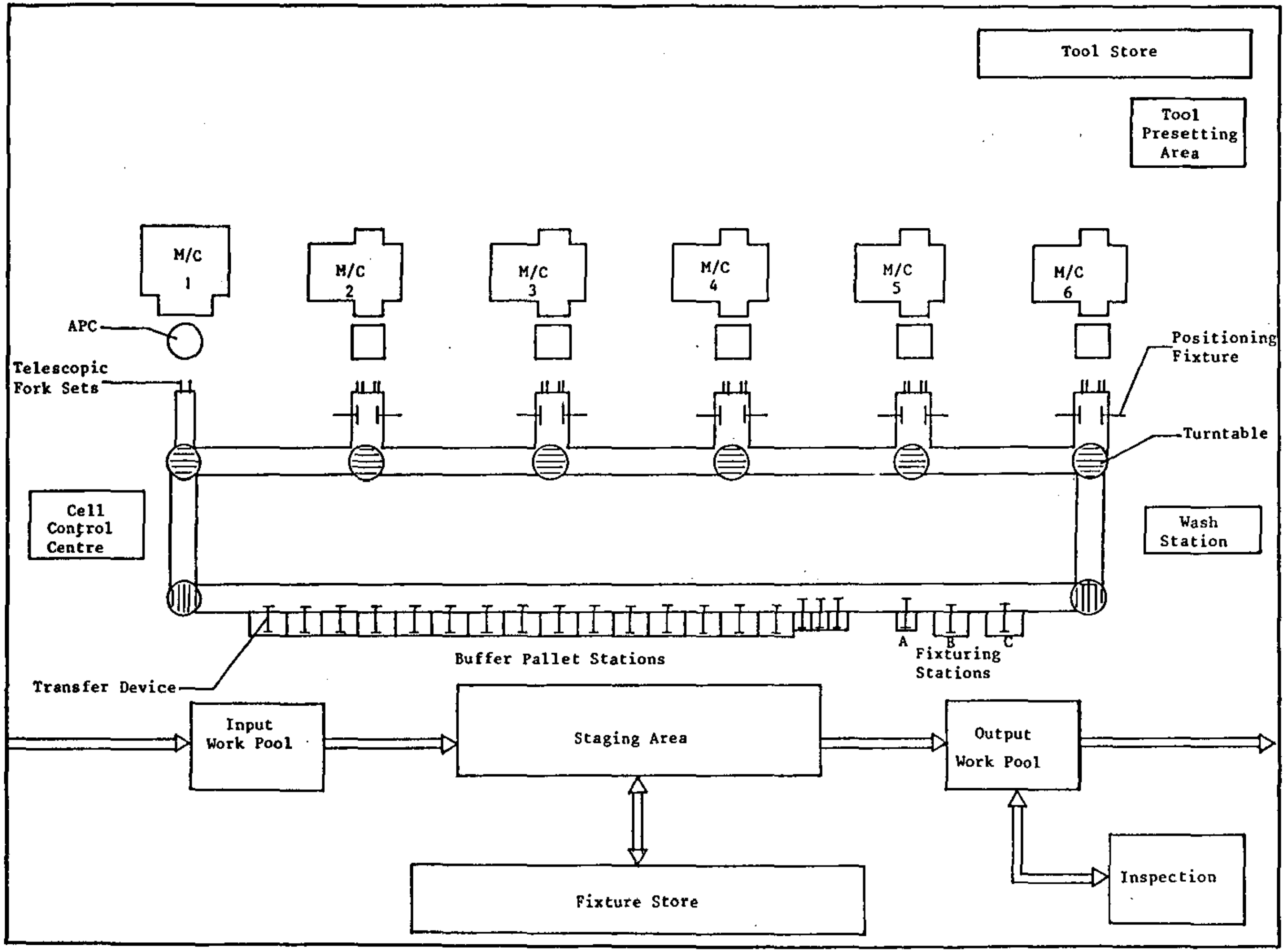


Fig. 4.13: FMS D with CNC Machines, 2 Pallet APC, Conveyor System

The fixture is loaded with new parts for machining and sent to the appropriate APC for processing. This process is repeated until the batch is completed. In this way each machine is able to handle 2 batches, (using the existing tool pack), at any one time.

4.6 FMS E WITH CNC MACHINES, 2 APC AND STACKER CRANE

(See Fig. 4.14)

The APCs at the machining centres are served by a stacker crane moving along a linear path. The main feature of this configuration is a six level intermediate store with a capacity of 30 pallets. The load/unload stations have free roller conveyor tracks on which fixture mounting, part loading and removal take place. The stacker crane is controlled by a programmable logic controller and is interfaced to the computer control system. Parts are loaded onto fixtured pallet plates and are stored at addressable locations in the intermediate store. From this store the appropriate palletised parts are moved onto the APC at the machining centre when available and according to the production schedule. After completion the pallets with parts are returned to the store. They are recalled to the load/unload station by the machine operator interactively via the control system for unloading and loading of fresh parts from the particular batch. (This assists unmanned working).

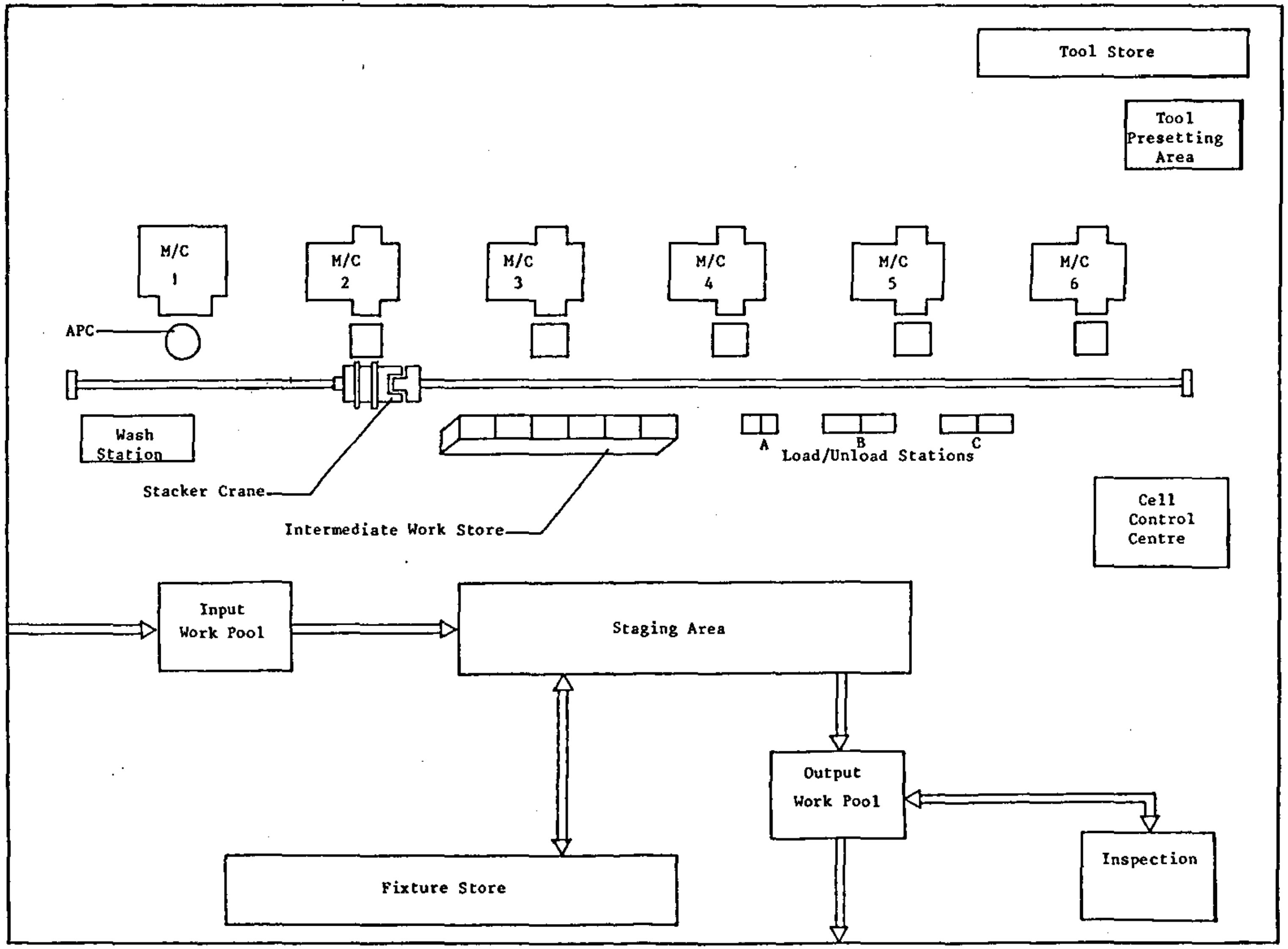


Fig. 4.14: FMS E with CNC Machines, 2 Pallet APC, Stacker Crane

4.7 FMS F WITH CNC MACHINES, 2 PALLET APC AND RAIL GUIDED SHUTTLE (See Fig. 4.15)

This is similar to the stacker crane configuration (FMS E) except that the intermediate store is a single level row of pallet stations, and part transport is performed by a rail guided shuttle mounted on a linear rail track. Fixtures and the first part in a batch are mounted onto pallets at the three fixture stations. Further loading and unloading of parts from fixtured pallets takes place at the pallet stations of the intermediate store directly. Thus there is less movement of parts than in the stacker crane system. The rail guided shuttle is also controlled by a PLC and linked to the computer system.

4.8 FMS G WITH CNC MACHINES, 2 PALLET APC AND AGV (See Fig. 4.16)

This single loop transport network is the most flexible of the automated form of transport, connecting the machine centres, load/unload stations and intermediate buffer store. The AGV track is unidirectional, and has 2 AGVs in the system. There are three load/unload stations each with an input and output station. Parts and fixtures are loaded onto pallets which are transported by AGVs and offloaded into computer identified locations in the 30 station intermediate buffer store. The intermediate store is filled starting from station (1) to station (30). The AGVs are controlled by the computer network. Battery recharge facilities and wash stations are also provided.

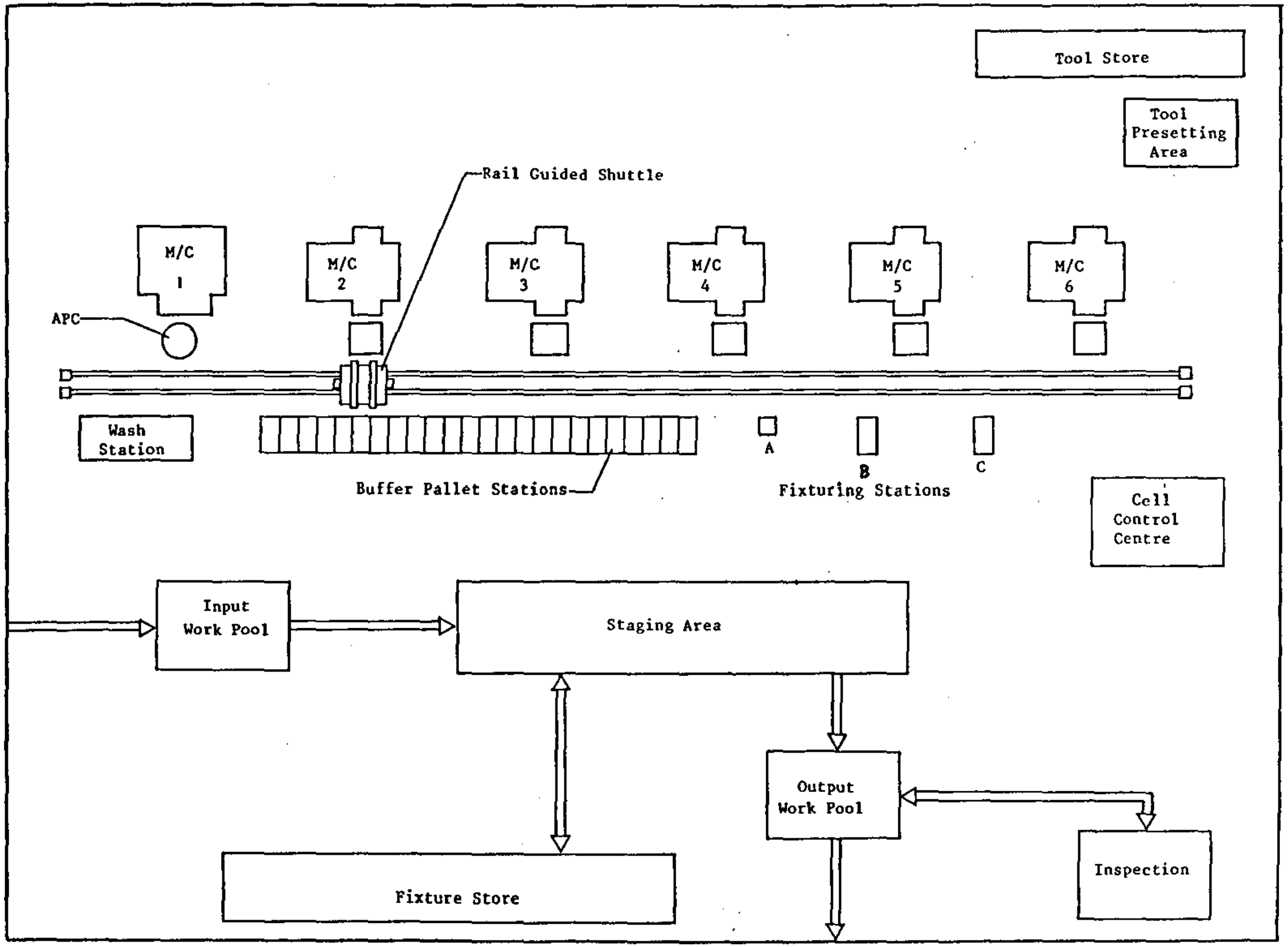


Fig. 4.15: FMS F with CNC Machines, 2 Pallet APC, Rail Guided Shuttle

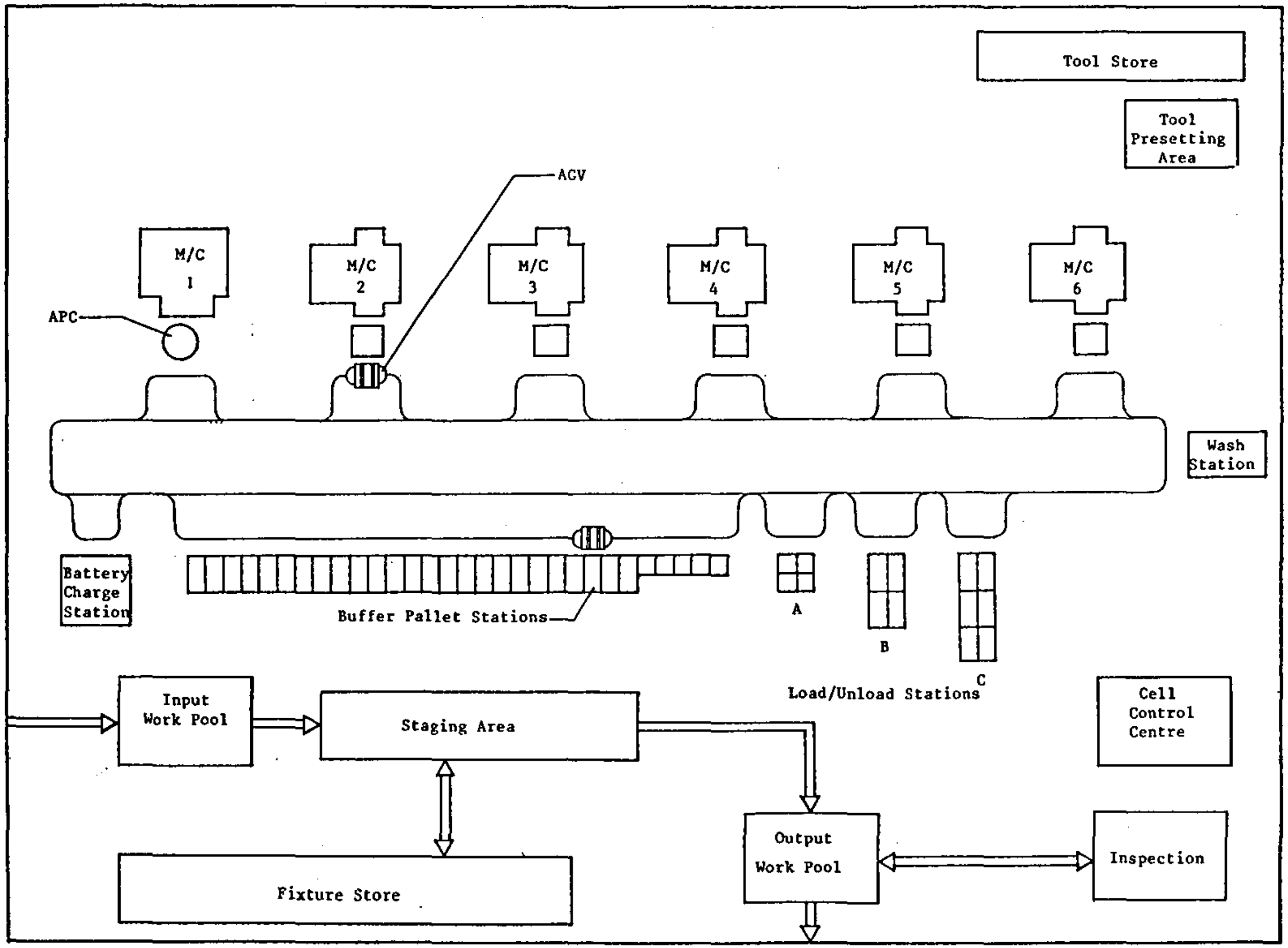


Fig. 4.16: FMS G with CNC Machines, 2 Pallet APC, and AGVs

CHAPTER 5

SYSTEMS MODELLING AND SIMULATION EXPERIMENTS

5.1 INTRODUCTION

The simulation models for each of the seven configurations encompass time dependent activities for updating variables, entity states and attributes. The final output activity processes the simulation data to give the performance measures. Each entity in the simulation models, (such as pallets and machines), has different attributes which are fixed by the data entered into the model or changed during the simulation run. Initial data pertaining to each model and values of selected variables are entered before each simulation run.

ECSL has been used for the simulation. Seven programs of just under 2000 lines of source code have been written. The diagram in Fig. 5.1 shows the overall normal flow of an ECSL program. The coding is for the steps in the left hand column. The basic logic, activities, entities and variables are described later by reference to flow charts and activity cycle diagrams.

The programs developed are lodged in the Department of Manufacturing Engineering. The selection of a 15 sec. simulation time unit has required the total simulation time span to be limited to one week.

5.2 SYSTEM SCHEDULING IN MODELS

The programs enable the use of different scheduling methods

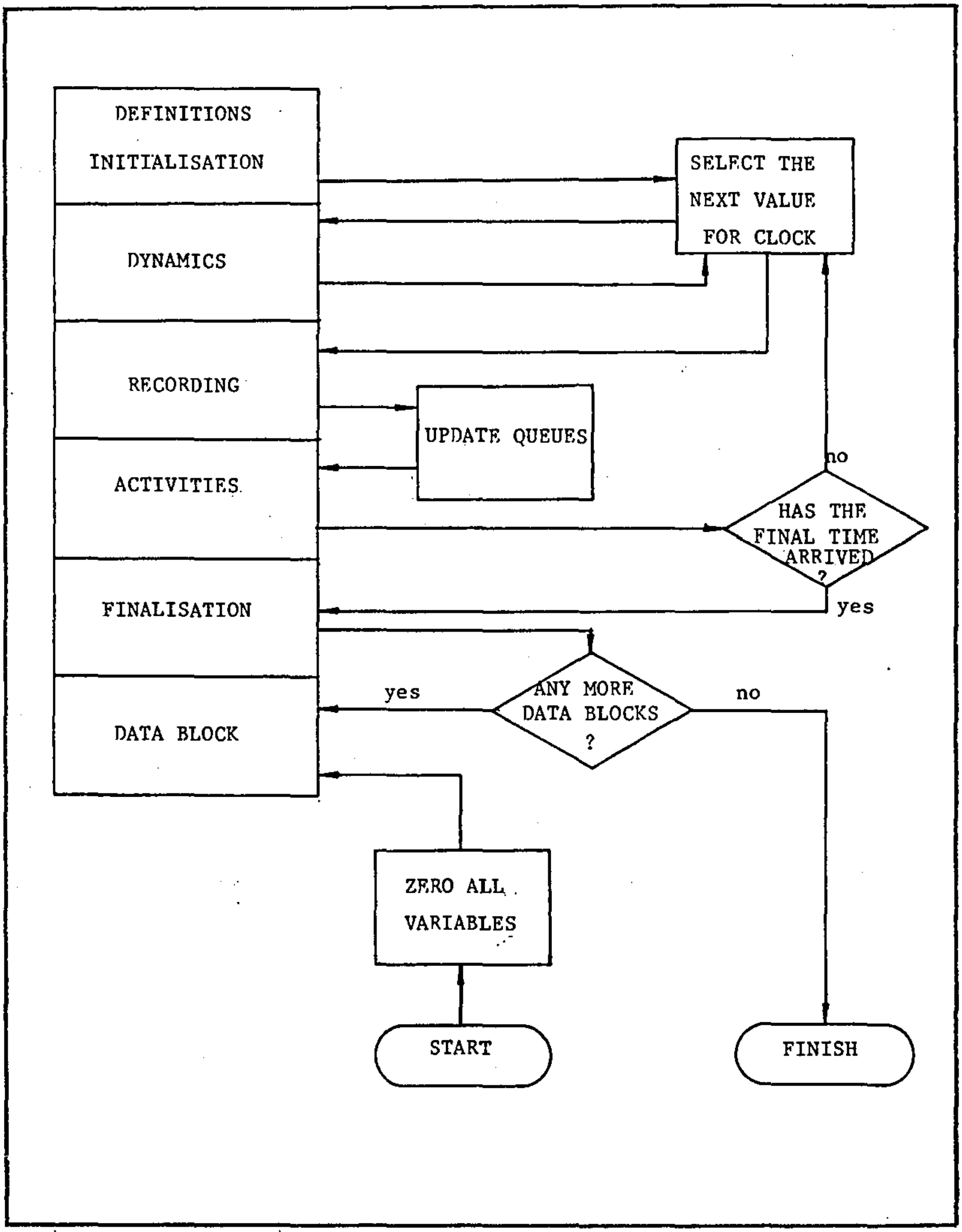


Fig. 5.1: ECSL PROGRAM FLOW
{extracted from, Clementson (1977)}

namely: First Come First Serve (FCFS), Shortest Machining Time (SMT), Longest Machining Time (LMT) and a rule using a combination of two or more of these methods for routing parts to machines (i.e. dedicated parts to fixed machines and parts that may be routed to alternative machines). However in this study a mixed scheduling approach has been adopted, because of the particular mix of machine types.

Since there is ample capacity on machine 1 (KTM) to process all the 18 parts requiring this machine, the scheduling of parts to this machine is on a FCFS basis. However, priority is given to the parts using the tool pack already loaded into the tool magazine.

A different approach has been adopted for the remaining five vertical machining centres. One each of the Wadkin V4-6 and V5-10 machines has been reserved for parts with long machining times (LMT) in order to have them processed without undue delay. Parts for the remaining machines are selected according to the SMT rule so that a high proportion of parts in the overall requirement may be processed quickly. Since there are two V5-10 machines for this purpose, there is a choice of machines for parts requiring this type of machine. However, after selecting parts according to the above rules, parts requiring an existing tool pack in these machines are given priority. Thus the number of tool pack changes is kept to a minimum.

The number of batches selected at one time for each machine is determined by the number of fixture set ups required for the batch and the number of pallets or trolleys in the system. Equal numbers of pallets or trolleys and intermediate storage pallet stations are allocated to each machine in order to keep the queues balanced. For example, if there are 18 pallets and thus 18 pallet storage stations, each machine is allocated 3 pallets and 3 storage stations. Thus three batches requiring single fixture set-ups may be processed. If one batch requires 2 fixture set-ups, two batches are entered into the system by the scheduling activity.

5.3 OPERATION OF COMPUTER MODELS

The operation of manually operated configurations (i.e. FMS A, B and C) with manual transport is illustrated by the flowchart in Fig. 5.2. A particular difference is that in the model without APCs, only one fixture, which may be for several small parts, may be loaded at any one time onto the machine.

In models with one APC, work takes place on two single set-up batches or one double set-up batch per machine taking advantage of the tool pack existing in the machine tool magazine. Thus unmanned operation is possible to some extent outside normal manned shifts until palletised components have been finish machined .

After machining, fixtured parts are returned to the APC pallet stations to be called up on the next manned shift for parts removal and continuation of batch. If a batch is completed the fixtures are also removed from pallets.

Systems with automated transport (i.e. FMS D, E, F and G) function are shown in Fig. 5.3. In the FMS D model, the conveyor is considered to be able to receive work without delay so that transport of pallets between stations takes place without hindrance. Thus the transport activity is not modelled separately

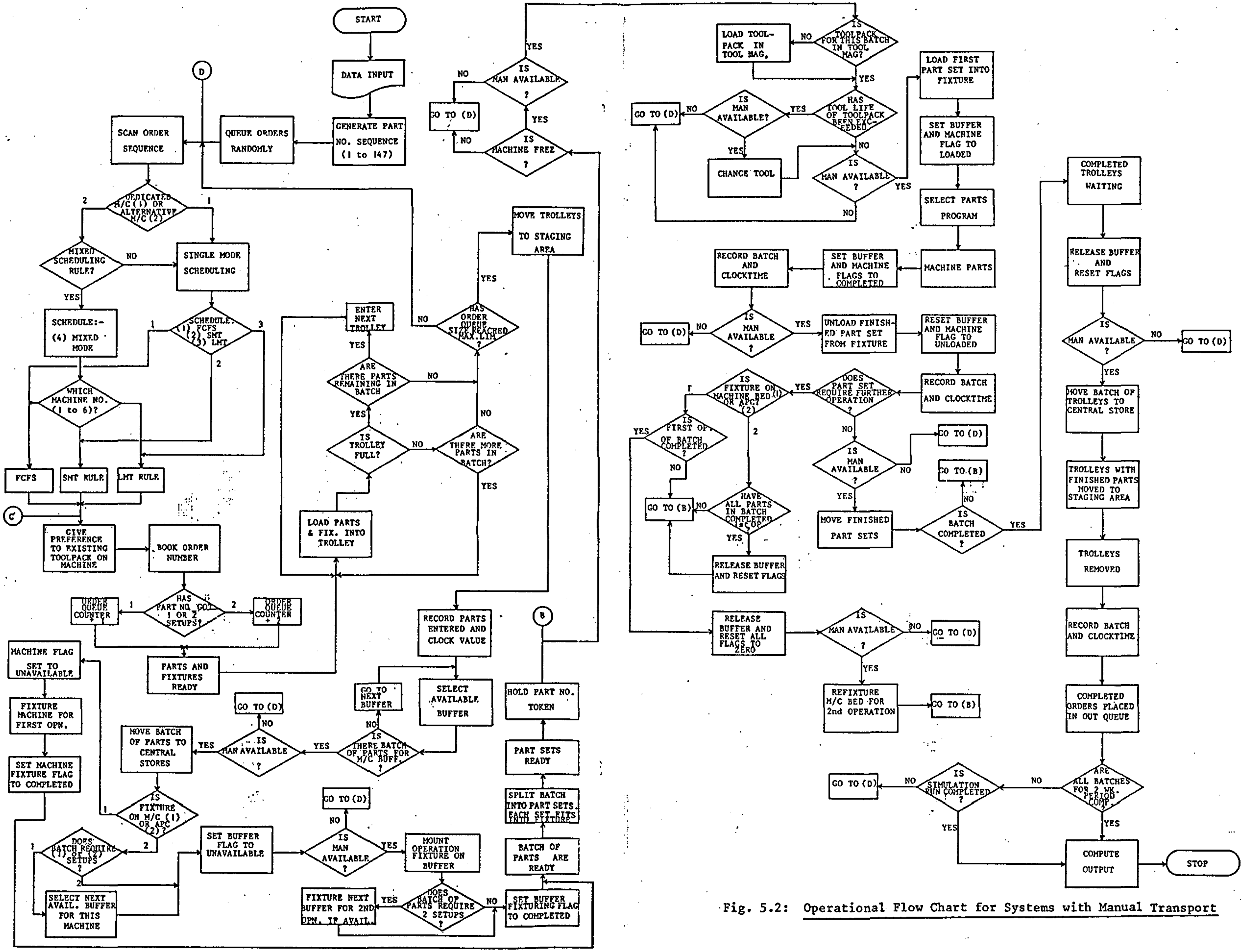


Fig. 5.2: Operational Flow Chart for Systems with Manual Transport

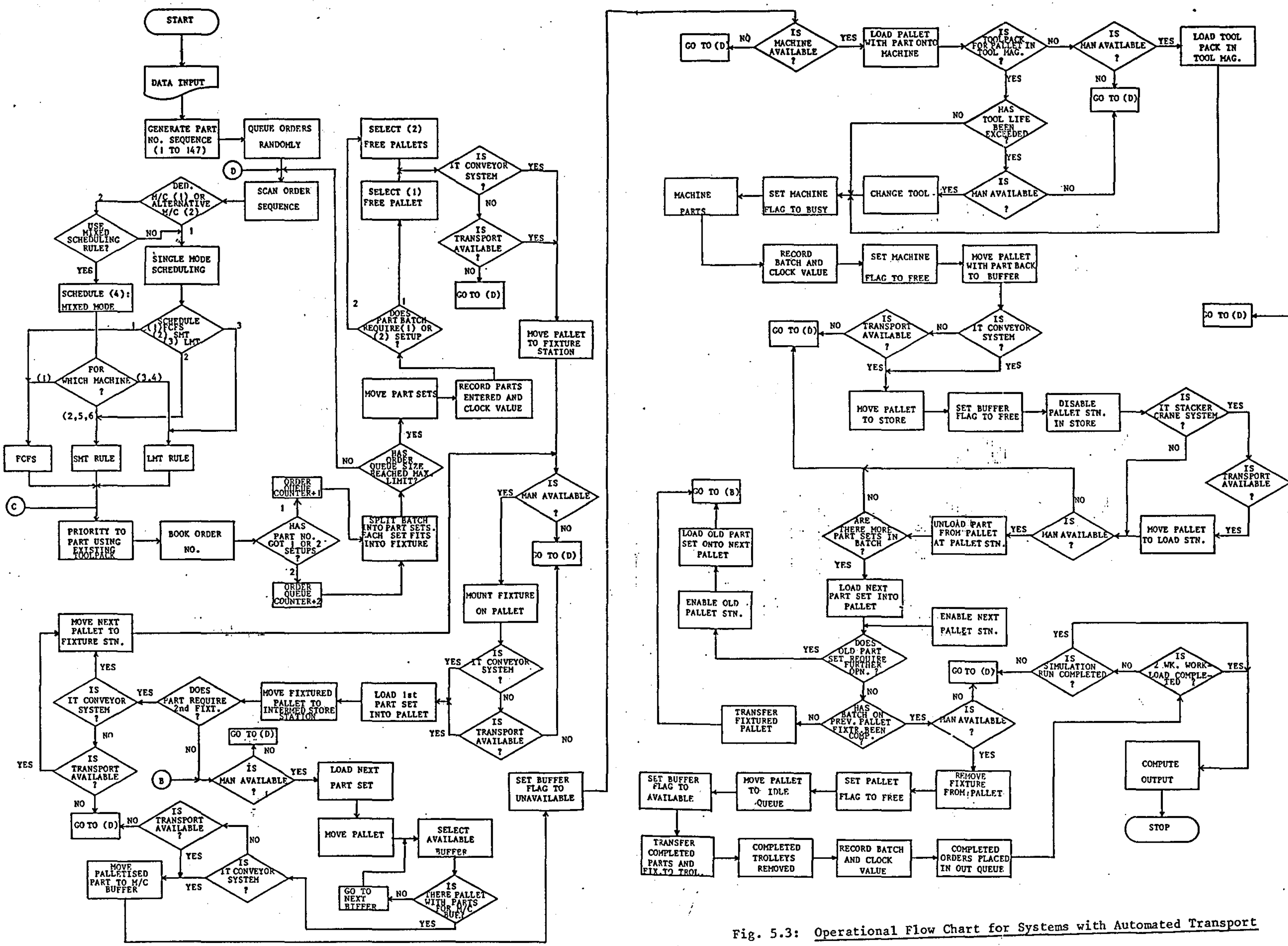


Fig. 5.3: Operational Flow Chart for Systems with Automated Transport

as in the other automated models. The duration of the transport activity is computed in the input to buffer and output from buffer activities (i.e. INBUF and EXBUF) from equations. The equation gives the time as a function of distance and transporter speed, where the distance is selected from the distance array data blocks (see Appendix D). The fixturing activity (PALFX) takes place with the splitting of batches into part sets (KITS) as shown in the activity cycle diagrams. (See Figs. 5.5 to 5.9). In the automated transport systems there are three load/unload stations to accommodate the different types of pallets. Fixturing and loading of the first set of parts is accomplished at these stations. However, with the exception of the AGV and stacker crane systems, subsequent loading and unloading of parts to and from pallets is performed at the intermediate storage pallet stations. In the AGV and stacker crane systems the above function is performed at the 3 load/unload stations after recalling the pallets from the intermediate store. Manual interruption is built in at each pallet storage station enabling pallet station status to be altered as required.

The relationship between entities and activities for the seven models is given by Figs. 5.4a and b. The flowcharts for the manual and automated systems illustrate the serial flow of logic in the programs that enable the sequence of activities to be performed. However, several activities may be initiated at different times but may occur in parallel depending on the presence of appropriate entities and their states in the required input queues. Thus the flowcharts are not intended to give the exact program structure in detail, but to illustrate the flow of parts through the system models.

Fig. 5.4a: Interrelationship of Activities and Entities in Manual Systems as Accommodated within each Computer Program for Configurations FMS A, B and C

ENTITIES / ACTIVITIES	Orders	Trolleys	Part Sets	Buffers	Machines	M/C Operators
GENRT.	ALL					
MIXUP	ALL					
ENTER	ALL	ALL				
PALEN		ALL				
INBUF		ALL		ALL		ALL
REBUF				ALL		
MCFIX				ALL		ALL
MCGEN		ALL	ALL			
MLOAD			ALL	ALL		ALL
MCRUN		ALL	ALL		ALL	
TLSET		ALL	ALL		ALL	
UNLOD				ALL	ALL	ALL
EXBUF		ALL				ALL
PALEX	ALL	ALL				

DESCRIPTION OF ACTIVITIES

GENRT - Generate orders.
MIXUP - Mix sequence of orders randomly.
ENTER - Schedule and enter order.
PALEN - Load trolleys.
INBUF - Input to store.
REBUF - Reset buffer status.
MCFIX - Fixture APC pallet station or machine.
MCGEN - Split batches into part sets.
MLOAD - Load part set at APC pallet station or machine.
MCRUN - Machining operation.
TLSET - Load toolpack.
UNLOD - Unload part set at APC pallet station or machine.
EXBUF - Output from store.
PALEX - Unload trolleys.

Fig. 5.4b: Interrelationship of Activities and Entities in Automated Systems as Accommodated within each Computer Program for Configurations FMS D, E, F and G

ENTITIES / ACTIVITIES	Orders	Pallets	Part Sets	Buffers	Machines	M/C Operators	Store Pallet Stations	Stacker Crane	Rail Shuttle	AGVs
GENRT.	ALL									
MIXUP	ALL									
ENTER	ALL	ALL	ALL							
PALFX	ALL	ALL				ALL				
PALEN		ALL	ALL			ALL				
INBUF		ALL		ALL						
MCRUN		ALL		ALL	ALL					
TLSET		ALL			ALL	ALL				
EXBUF		ALL		ALL						
PALEX	ALL	ALL	ALL			ALL				
TRANP		FMS E,F,G					FMS E,F,G	FMS E	FMS F	FMS G

DESCRIPTION OF ACTIVITIES

GENRT - Generate orders.

MIXUP - Mix sequence of orders randomly.

ENTER - Schedule and enter order.

PALFX - Fixture pallet.

PALEN - Palletise.

INBUF - Input to buffer.

MCRUN - Machining operation.

TLSET - Load tool pack.

EXBUF - Output from buffer.

PALEX - Depalletise.

TRANP - Transport of pallets.

5.4 SYSTEM MODELS OF ALTERNATIVE CONFIGURATIONS

5.4.1 COMMON FEATURES IN SIMULATION PROGRAMS

The simulation time unit (i.e. 15 secs.) is the same for all models, as well as the activities counting the number of shifts and days during the simulation. At the end of the simulation run, the activity (LSTACT) computes the performance measures and outputs them into the Print file. The compilation and execution times for each of the models are of the order of 30-40 mins, and 15-20 mins respectively on the Prime 750 mainframe computer in the Department of Manufacturing Engineering at Loughborough University of Technology. The description of all the entities and their attributes in the seven models are given in Appendix D2.

The total number of parts that represents work-in-process is recorded at 2 hour periods during the 5 day simulation run.

Common operational variables in simulation programs

a) The Random number generator to create a part sequence into the system.
b) The batch variables to change the batch sizes and vary the product mix.
c) The shift variable to allow the model to be run on one, two or three shifts per day basis.
d) Alternative machine parameter to enable parts to be allocated to a fixed machine or to different machines of the same type.
e) Scheduling rules as described in section 5.2.

f) Manpower levels as required which may also be dedicated to certain machines.

g) Fixturing rules to enable changeover within machining cycle or outside it.

h) Pallet pool capacity of machining centres.

<u>Manufacturing conditions simulated</u>

a) The manufacturing schedule for the batches of parts is based on 2 week periods of finished product demand.

b) Components are allocated to one machine type.

c) The batch sizes are fixed according to the product mix and sales level for 1987 and beyond.

d) Machine operators in the cell are not allocated to any specific machines or types of machines.

e) Work is done either on one, two or three shifts per day system.

f) Manpower is available on a continuous basis within normal shift hours except during lunch breaks.

g) Manual tasks encompassed in the model are indicated in Fig. 5.4a and b, and in FMS A, B and C manual transport between machines and intermediate store as well.

h) Hoists are available for loading and unloading of heavy parts and fixtures into machines.

i) All parts are identified with particular tool packs.

j) Washing of parts and any deburring that may be required is done outside the cell.

k) Cleaning the machine of swarf after a batch of parts is completed is done by machine operators after unloading fixtures from machine. Swarf removal from cell is performed by men outside the system.

l) The simulation study has been performed using the mixed mode scheduling rule (see section 5.2).

m) Splitting of batches into part sets is allowed.

n) Parts awaiting second machining operation are given priority in fixturing.

o) Fixturing on APC can proceed independent of the machining centre provided a pallet station is available, except in the case where the fixture is mounted on the machine table.

p) Multiple toolpacks are available as delivered to each machine by tool presetter or cell attendant.

q) Tool replacement takes place after a maximum tool life quota for a tool pack or when a range of parts has been completed. For each tool pack a quota is computed according to times supplied for each tool by the company. For tool packs it is calculated on the basis of an average tool life as given in Appendix C2. The tool pack is assumed to be renewed after the tool replacement.

r) At the start of the simulation the machine operators are located in the staging area in the manual transport systems, so that position attribute of operator is zero. In automated systems the operators are initially at the supervisory computer control centre.

5.4.2 DETERMINISTIC ACTIVITY TIMES

Estimates of the duration of various activities were obtained from the company and are as follows:-

a) Loading time of tools into tool magazine = 3 mins per tool.

b) Loading time of parts into machine fixture = 2 mins (for light-parts)
= 5 mins (for heavy-parts)

c) Unloading Time of parts from Fixture (including swarf removal). = 2 mins

d) Fixture Times for Machine Centres:-

On Machine Bed:

Machine (1) - (KTM)	= 1 hr.
Machine (2) and (3) - (V4-6)	= 30 mins (dedicated-fixture)
	= 1 hr. 30 mins. (modular fixture)
Machines (4),(5) and (6) - (V5-10)	= 30 mins (dedicated-fixture)
	= 1 hour 30 mins (modular fixture)
On APC pallet station:	20 mins (light parts), and 25 mins (heavy parts)
On Fixture stations:	12½ mins (light parts) and 15 mins (heavy parts)

e) Duration of lunch break = 30 mins.

f) AGV battery change time = 30 mins.

g) Transport times are computed differently in each configuration. This is described in Appendix D1.

h) Operator walking speed = 0.6 m/s.

i) Conveyor speed = 0.25 m/s.

j) Stacker crane speed = 0.5 m/s.

k) Rail guided shuttle speed = 1.0 m/s.

l) AGV Speed = 1.0 m/s.

5.4.3 ACTIVITY CYCLE DIAGRAMS (see Figs. 5.5 to 5.9).

Activities are represented by rectangular blocks and are in an active state when one or more entities co-operate for a period of time. During the activity the co-operating entities remain fixed and may not take part in other activities simultaneously. At the end of activity, entities are removed from an input queue to an output queue. Any queue represents a passive state in which entities remain for a period which cannot be determined until the simulation is underway. Queues are represented by circles, and the input and output queues for a particular entity may be the same. The activity cycle diagram consisting of alternating queues and activities for each entity are now used to outline the models of the alternative configurations.

5.4.3.1 Systems with manual transport

The system models of the three configurations, FMS A, B and C, are similar, and are modelled by the activity cycle diagram in

Fig. 5.5. In the models the trolley is the principal entity around which other activities occur. Trolleys are loaded with parts and fixtures and moved to the intermediate store by the activities ENTER and PALEN.

The trolleys are then moved to the machine from the store, if a buffer entity is available for fixturing in the Buffer idle queue. In the model without APC, there are 6 buffer entities although the fixture is mounted on the machine bed. In models with one and two APC for each machine the larger number of fixture mounting facilities is represented by 12 and 24 buffer entities respectively. In model without APC the fixtures are mounted on the machine bed, and in the program the bed is represented by a buffer entity.

Any trolley containing parts near the machining station is divided into part sets for loading into the fixture by the activity MCGEN. However, the process may not proceed further unless a fixtured buffer is available. The fixturing activity MCFIX performs this operation on the buffer in the Buffer busy queue. The tooling of the machining centre is performed by the activity TLSET, if operators are available.

Where a fixture may take more than one part this set of parts is loaded into the fixture by the activity MLOAD and unloaded by the activity UNLOD. The machining of the part set is completed by the activity MCRUN. The processed trolley of parts is moved to the intermediate store by the activity EXBUF and then removed from the system by the activity PALEX.

At the start of the simulation run the position attribute of the operators is zero. The distance travelled is computed from the distance arrays and variables. The time for operator movement

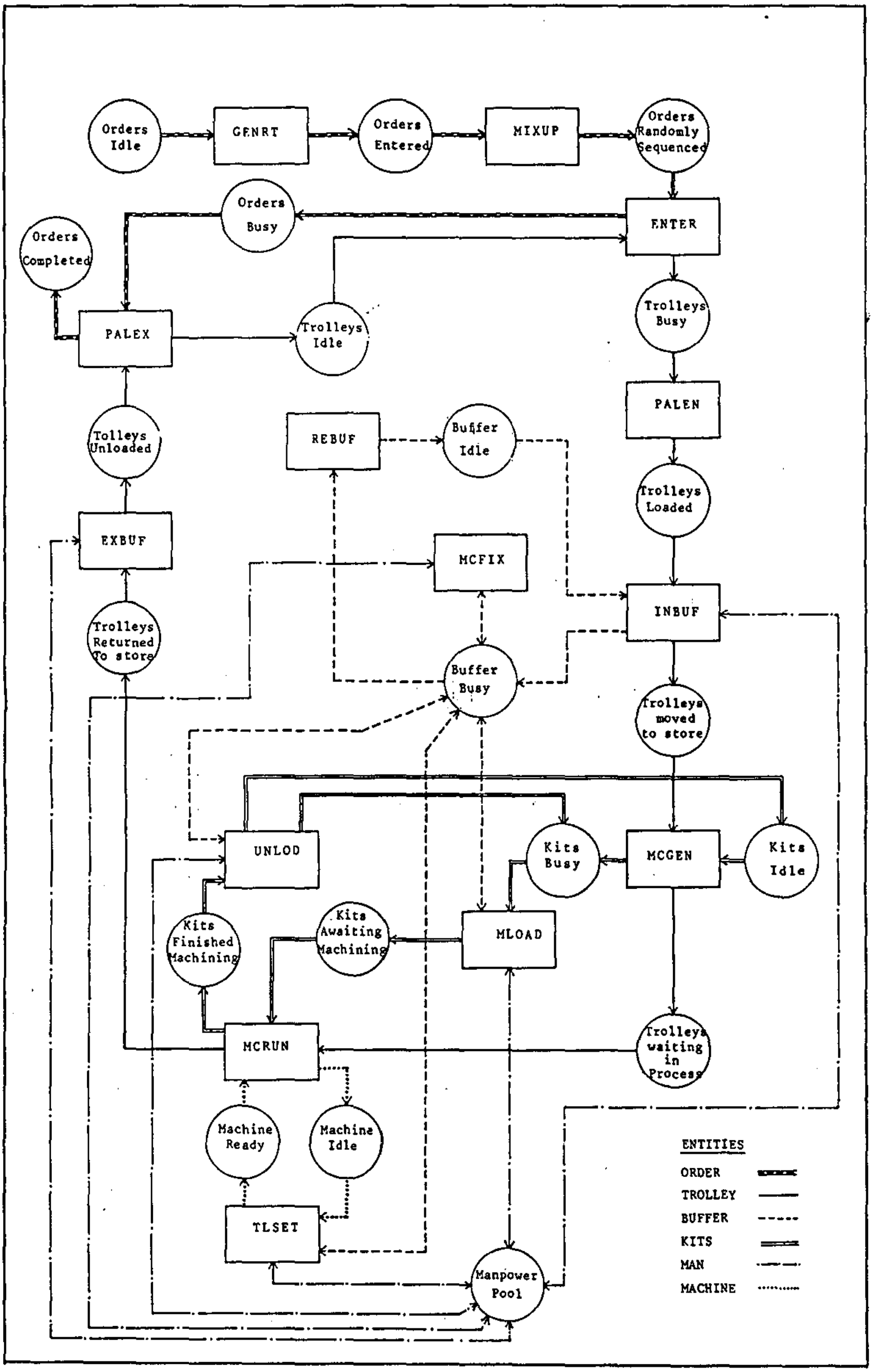


Fig. 5.5: System Activity Model for FMS A, B and C

is calculated from the distance and the average rate of operator travel. After each activity the position attribute is changed to give the current location of the operator. The movement time in the next activity is computed from the current location attribute of the operator.

5.4.3.2 Systems with automated transport

The configuration with conveyor transport is modelled by Fig. 5.6. The pallet is the principal entity controlling the movement of work through the whole cell. In the automated systems the fixture is mounted on the pallets at the fixture stations, so that the activity represented by PALFX is performed on available pallets in the Pallets idle queue. The pallets are loaded with parts by the activity PALEN and the finished parts are unloaded by the activity PALEX. The pallets are moved to the APC pallet stations by the activity INBUF and returned to the intermediate store by activity EXBUF.

In FMS D the transport activity is not modelled separately but the transport times are included in the INBUF and EXBUF activities. The transport times in FMS D are computed from the average conveyor speed and distances in the data block section of the program, and are set out in Appendix D1. However, in FMS E, F and G the transport activity, TRANP, is modelled separately. The occurrence of this activity is dependent on the availability of transporter and intermediate store entities.

Loading of parts into pallets takes place after a pallet has been fixtured. Thus the division of a batch of parts into part sets takes place in the activity ENTER. This applies to all

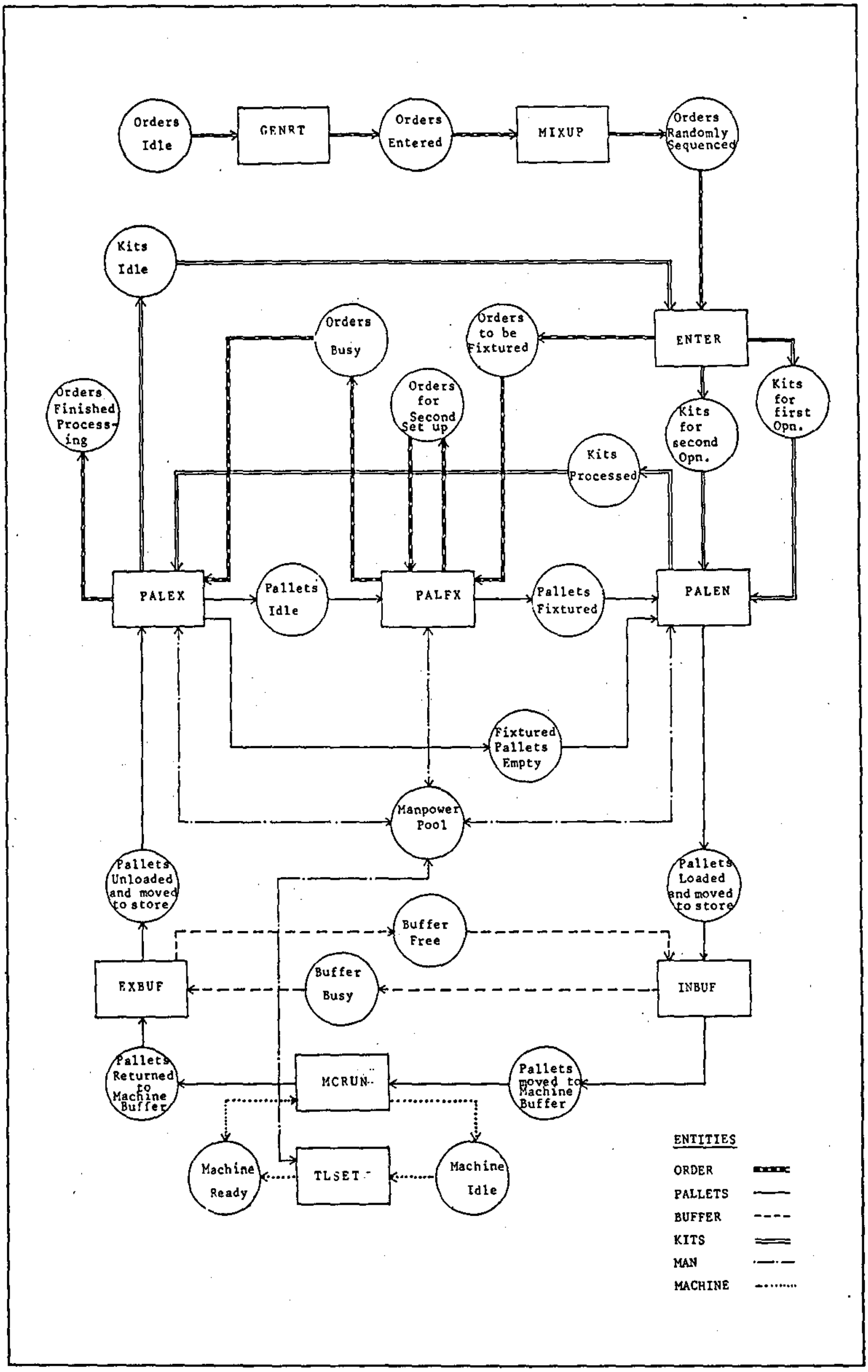


Fig. 5.6: System Activity Model for FMS D

the automated systems.

The stacker crane system, FMS E, is modelled by the activity cycle diagram in Fig. 5.7. It is similar in most respects to the conveyor model. The main difference is the modelling of the transport system by the separate activity TRANP. The stacker crane is a separate entity which has position attributes from which the distance travelled may be calculated using the distance arrays, variables and crane velocity. The average crane velocity is the resultant velocity of the components along the X, Y and Z axis. The distance travelled by the crane is considered to be from point to point. The transport times are computed as shown in Appendix D1. The stacker crane entity has attributes which represent its position co-ordinates. These attributes are altered during the transport activity to give the current location of the stacker crane.

The model of the rail guided shuttle system is given by Fig. 5.8. In this model the shuttle is an entity with location attributes which give the position of the shuttle relative to machining centres and load/unload pallet stations. The distance travelled is calculated from these attributes and the distance arrays in the data section of the programme. The time is derived by simple division from the distance and average shuttle speed as outlined in Appendix D1.

The AGV system is modelled by the activity cycle diagram in Fig. 5.9. The AGVs are a separate class of entity with attributes representing the position on a section of the AGV routes. There are three sections on the AGV route, namely, the machine section, the load/unload section and the intermediate store section. One location attribute contains this information which is updated

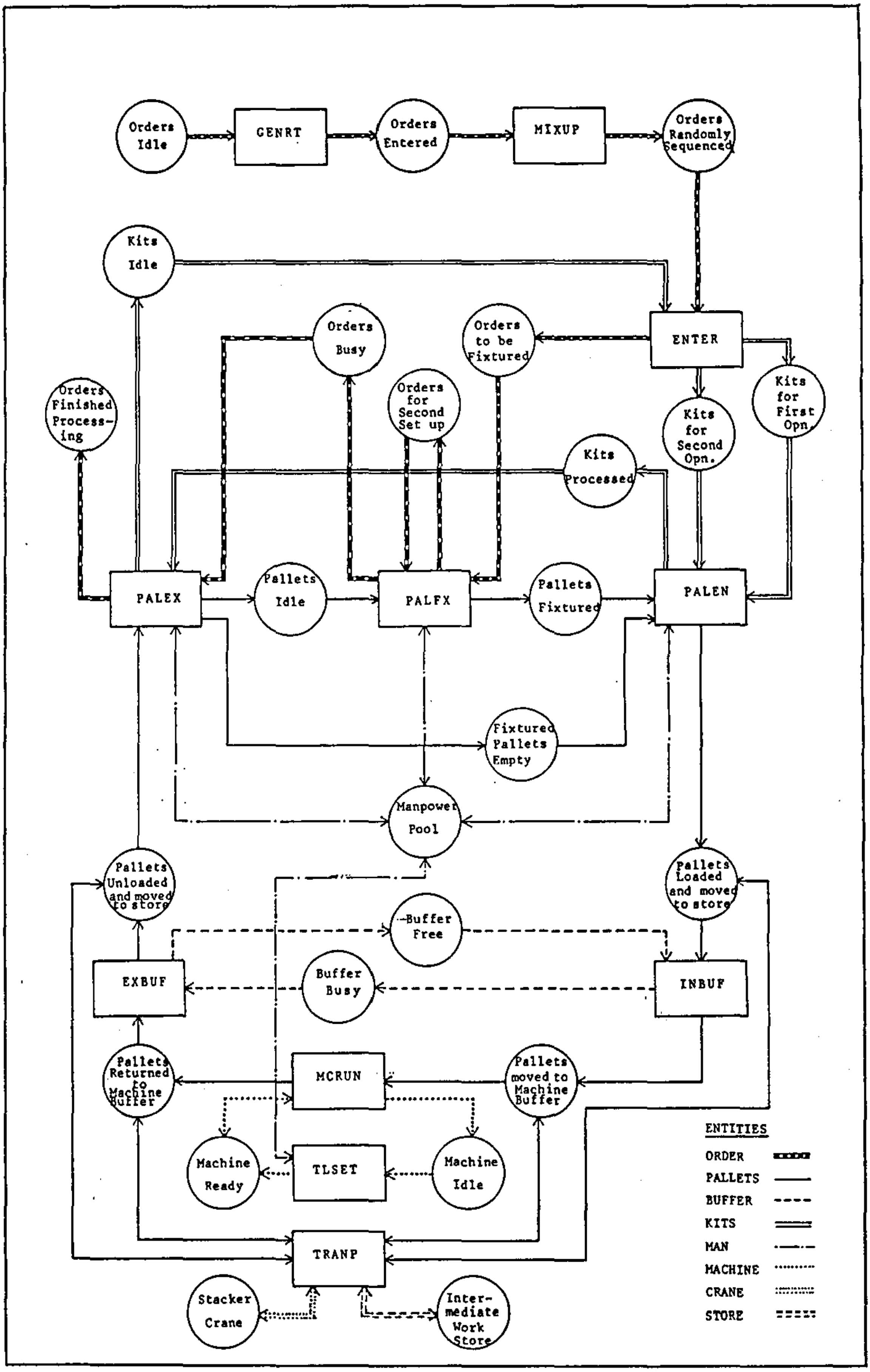


Fig. 5.7: System Activity Model for FMS E

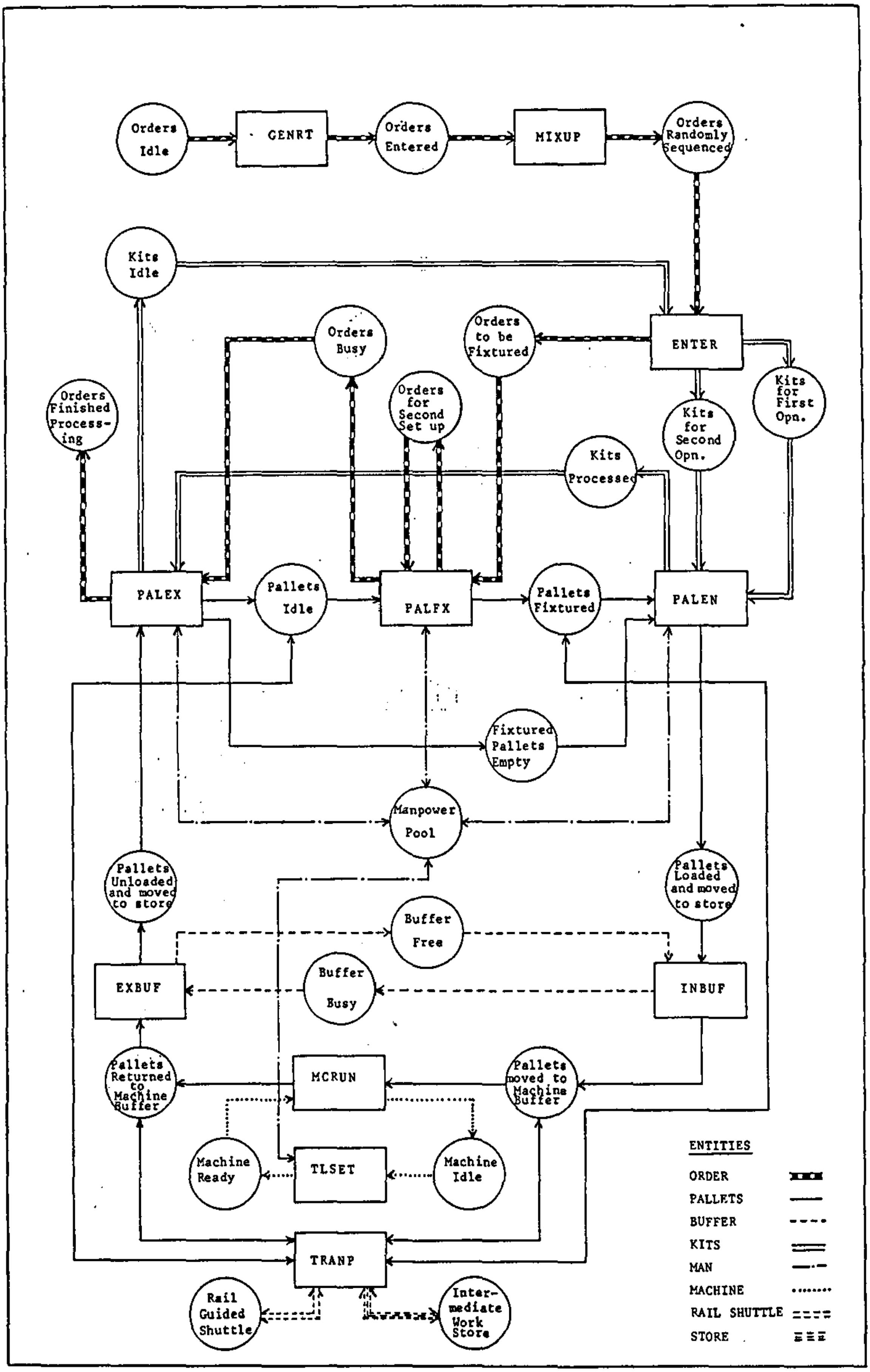


Fig. 5.8: System Activity Model for FMS F

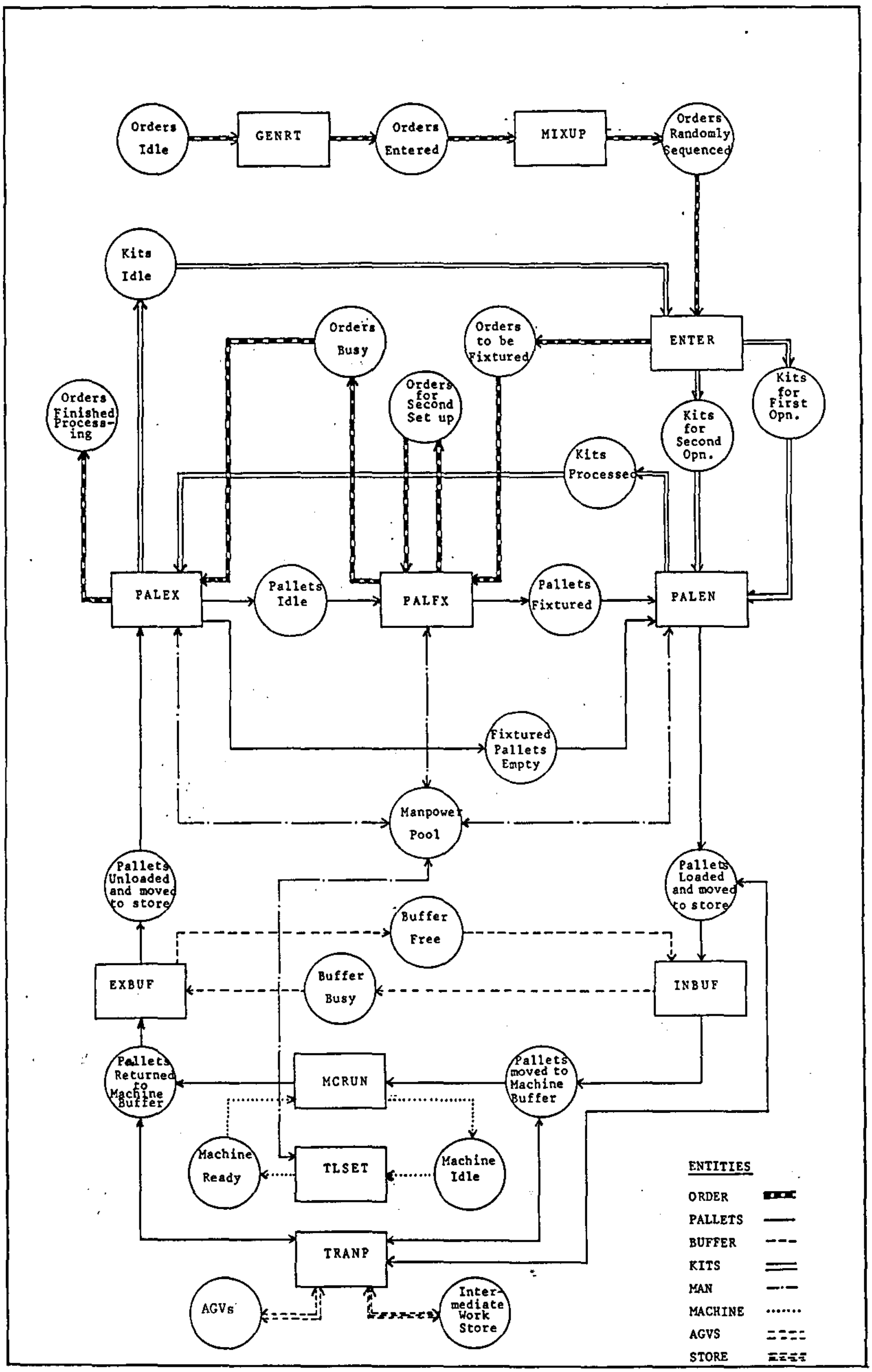


Fig. 5.9: System Activity Model for FMS G

during the simulation. Transport times are calculated as in Appendix D1, from distance travelled along the transport path and average AGV speed.

5.5 SIMULATION EXPERIMENTS

A sequence of parts, as determined for initial scheduling by using the random number generator, has been maintained for all the simulation experiments carried out.

Preliminary simulation runs for different values of variables were conducted, and the flow of every entity through the system was checked to ensure correct operation of each model. Activity times and output recorded were manually checked for any faulty execution of the programs. Results of particular runs were discussed with company executives. These were found to reflect well the comparative performance expected in the company. After ensuring correct operation of the models simulation experiments were conducted with each model for different combinations of resources. The variable resources were:-

(i) number of machine operators,
(ii) manned shift system,
(iii) number of pallets/trolleys and intermediate storage stations,
(iv) alternative system configurations.

5.5.1 PERFORMANCE MEASURES

Measures obtained were:

(a) Average machine utilisation for each machine and for the group of machines.

(b) Total work processed as a percentage of the work load (expressed as machining time).

(c) Overall average processing time.

(d) Manpower utilisation for each operator and the overall average utilisation for the group of operators.

(e) Average work-in-progress (expressed as parts) waiting for machining.

(f) Total output in terms of number of batches and parts completed.

(g) Duration of any unmanned machine operation.

5.5.2 SIMULATION TESTS CONDUCTED

A total of 264 simulation runs were performed on the seven FMS configurations for the following conditions:-

(i) CNC Stand-Alone Cell (FMS A)

Material Handling System:

Part Transport - Manually operated trolleys

Machine Load/Unload - Manual with overhead hoists.

System Conditions:

Shifts/day - 2 and 3.

No. of trolleys - 24, 30 or 36

Manpower Level - 2, 3, 4, 5 and 6.

(ii) Flexible Machining Cell (FMS B)

Material Handling System:

Part Transport - Manually operated trolleys.

Machine Load/Unload - Twin pallet shuttle.

Buffer Load/Unload - Manual with overhead hoists.

System Conditions:

Shifts/day - 1, 2 or 3.

No. of trolleys - 24, 30 and 36.

Manpower level - 2, 3, 4, 5 and 6

(iii) <u>Flexible Machining Cell (FMS C)</u>

Material Handling System:

Part transport - Manually operated trolleys.

Machine Load/Unload - 2 x twin pallet shuttle.

Buffer Load/Unload - Manual with overhead hoists.

System Conditions:

Shifts/day - 1, 2, or 3.

No. of trolleys - 24, 30 and 36.

Manpower level - 2, 3, 4, 5 and 6.

(iv) <u>Flexible Manufacturing System (FMS D)</u>

Material Handling System:

Part Transport - Powered roller conveyor.

Machine Load/Unload - Twin pallet shuttle

Pallet Load/Unload - Manual with fork lifts, and hoists.

System Conditions:

Shifts/day - 1, 2 or 3.

No. of pallets - 18, 24 or 30.

Manpower level - 2, 3, 4 or 5.

(v) <u>Flexible Manufacturing System (FMS E)</u>

Material Handling System:

Part transport - Stacker Crane.

Machine Load/Unload - Twin pallet shuttle.

Pallet Load/Unload - Manual with forklifts, and hoists.

System Conditions:

Shifts/day - 1, 2 or 3.

No. of pallets - 24, 30 or 36.

Manpower level - 2, 3, 4 or 5.

(vi) Flexible Manufacturing System (FMS F)

Material Handling System:

Part transport - Rail guided shuttle.

Machine Load/Unload - Twin pallet shuttle.

Pallet Load/Unload - Manual with forklifts, and hoists.

System Condition:

Shifts/day - 1, 2 or 3.

No. of pallets - 18, 24 or 30.

Manpower level - 2, 3, 4 or 5.

(vii) Flexible Manufacturing System (FMS G)

Material Handling System:

Part transport - Automated guided vehicle.

Machine Load/Unload - Twin pallet shuttle.

Pallet Load/Unload - Manual with forklifts, and hoists.

System Conditions:

Shifts/day - 1, 2 or 3.

No. of pallets - 18, 24 or 30.

Manpower level - 2, 3, 4 or 5.

No. of AGVs - 2, 3

CHAPTER 6

RESULTS AND DISCUSSION OF SIMULATION EXPERIMENTS

6.1 EXPERIMENTAL RESULTS

The results of the simulation tests, each for one week of system operation, are tabulated in Appendix E. Attainment in regard to selected measures of performance is illustrated graphically in Figs. 6.1 to 6.7. The performance measures are:

(i) System Output,

(ii) Average Process Time,

(iii) Manpower Utilisation,

(iv) Machine Utilisation, and

(v) Levels of Unmanned Operation.

6.2 PERFORMANCE OF ALTERNATIVE SYSTEMS

6.2.1 SYSTEM OUTPUT

The output from the manufacturing systems with predominantly manual material handling, i.e. systems FMS A, B and C improves progressively from FMS A to FMS B, reflecting an advantage from an introduction of automated pallet changing equipment. This is more apparent for the 2 shifts per day case as shown in Figs. 6.1, 6.2 and 6.3. For the case of 2 shifts the ranges of performance resulting from an increase in manpower levels for the three systems are: FMS A (32-67%), FMS B (42-86%) and FMS C (50-92%).

Fig. 6.1: Performance Curves for FMS A

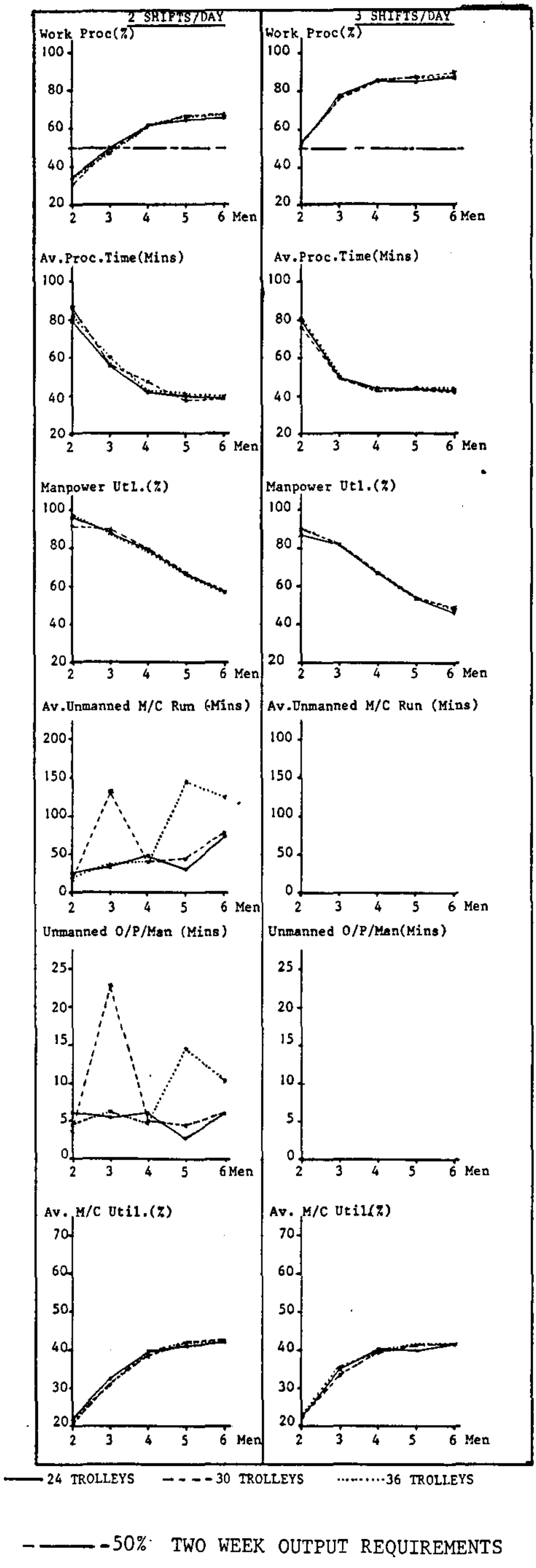


Fig. 6.2: Performance Curves for FMS B

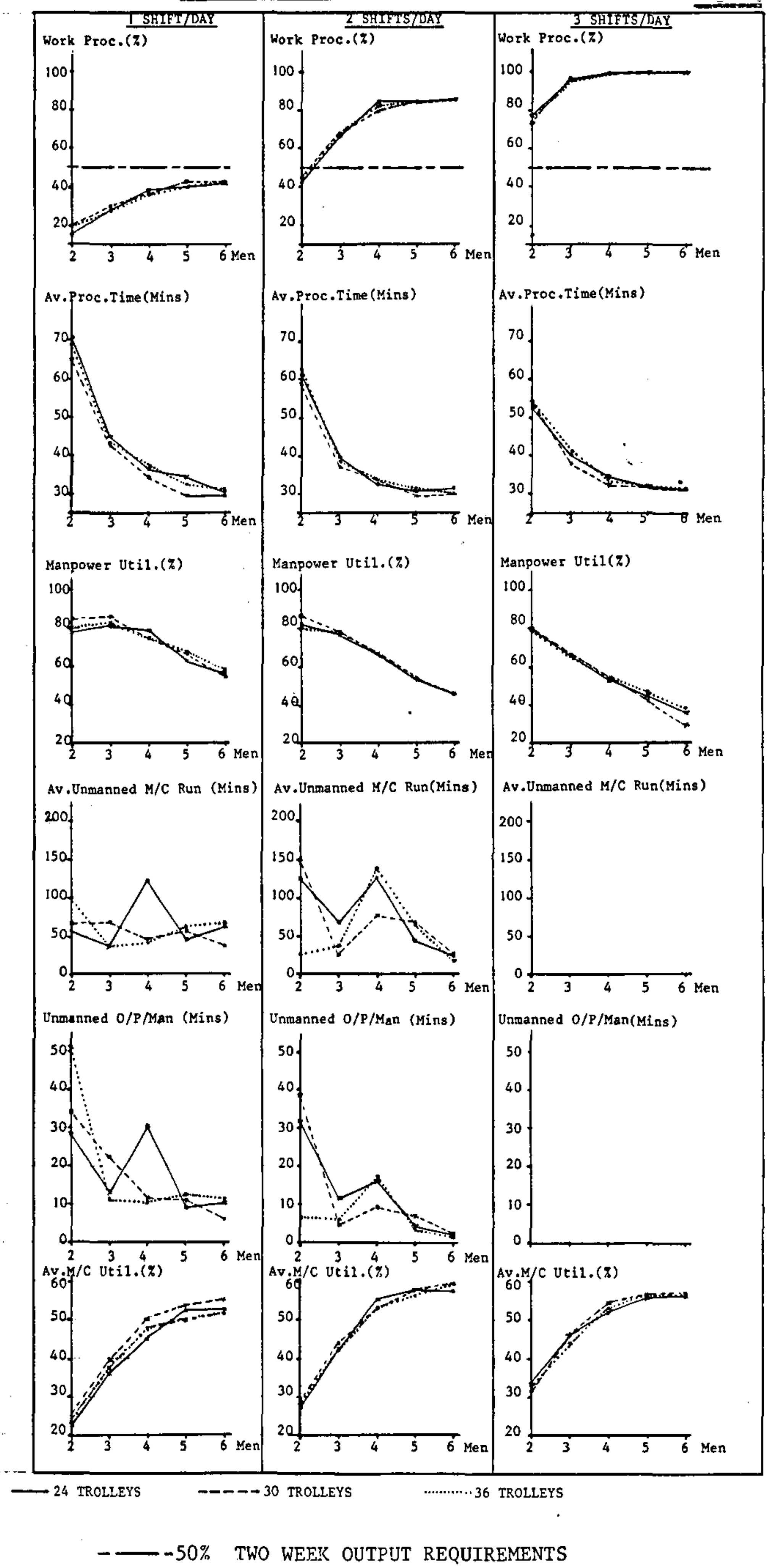


Fig. 6.3: Performance Curves for FMS C

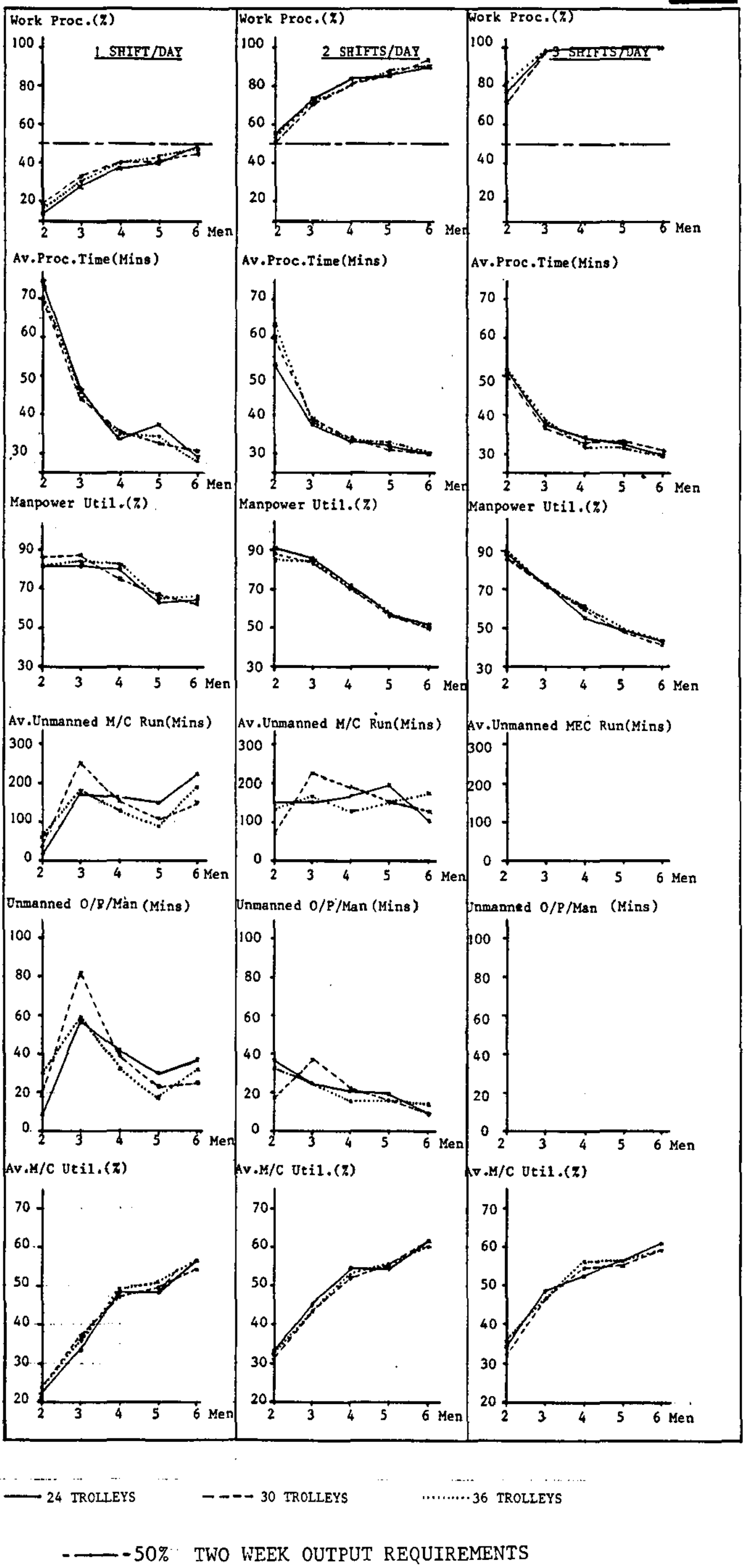
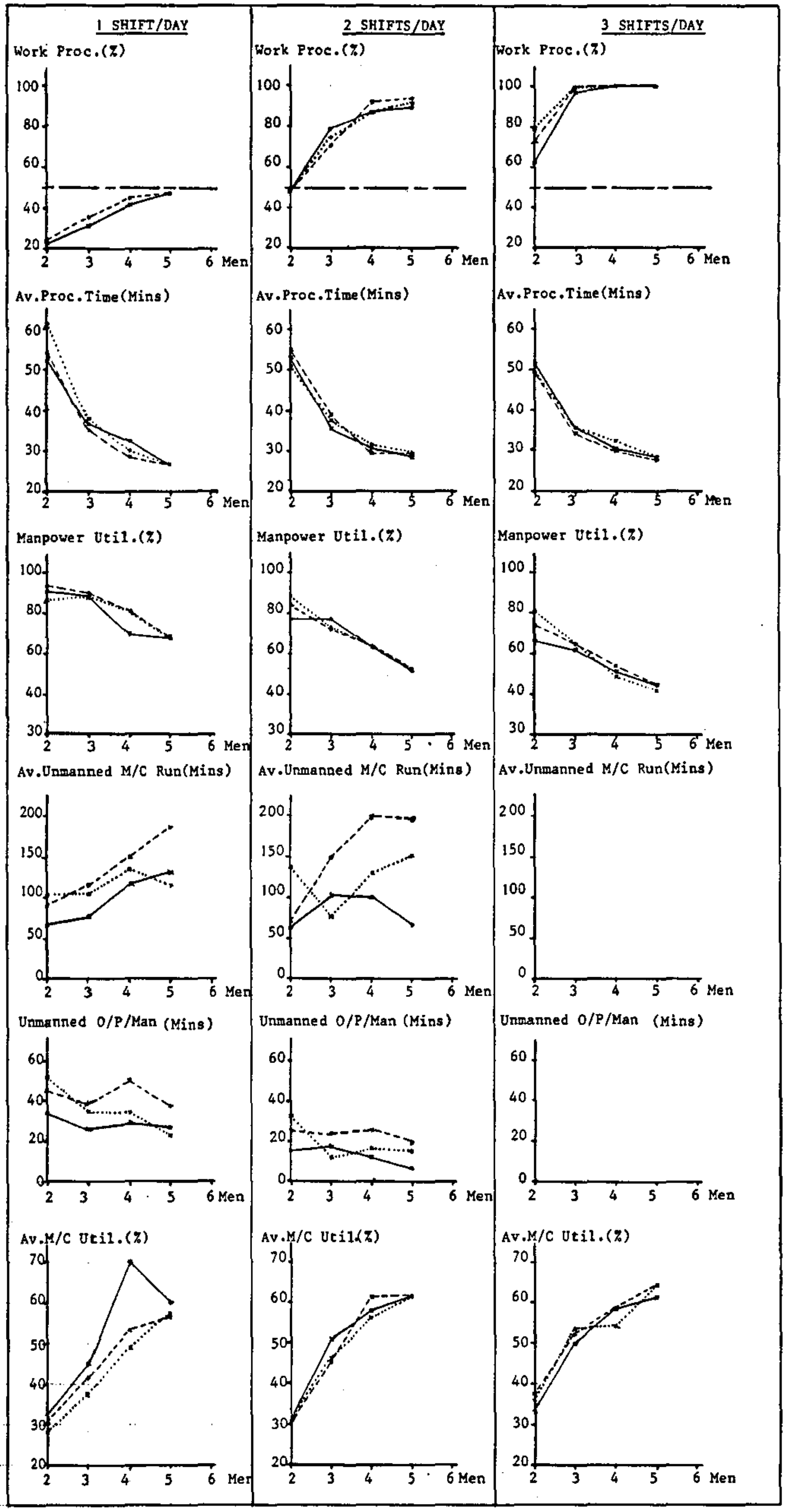


Fig. 6.4: Performance Curves for FMS D



—— 18 PALLETS
- - - - 24 PALLETS
.... 30 PALLETS

- ——— - 50% TWO WEEK OUTPUT REQUIREMENTS

Fig. 6.5: Performance Curves for FMS E

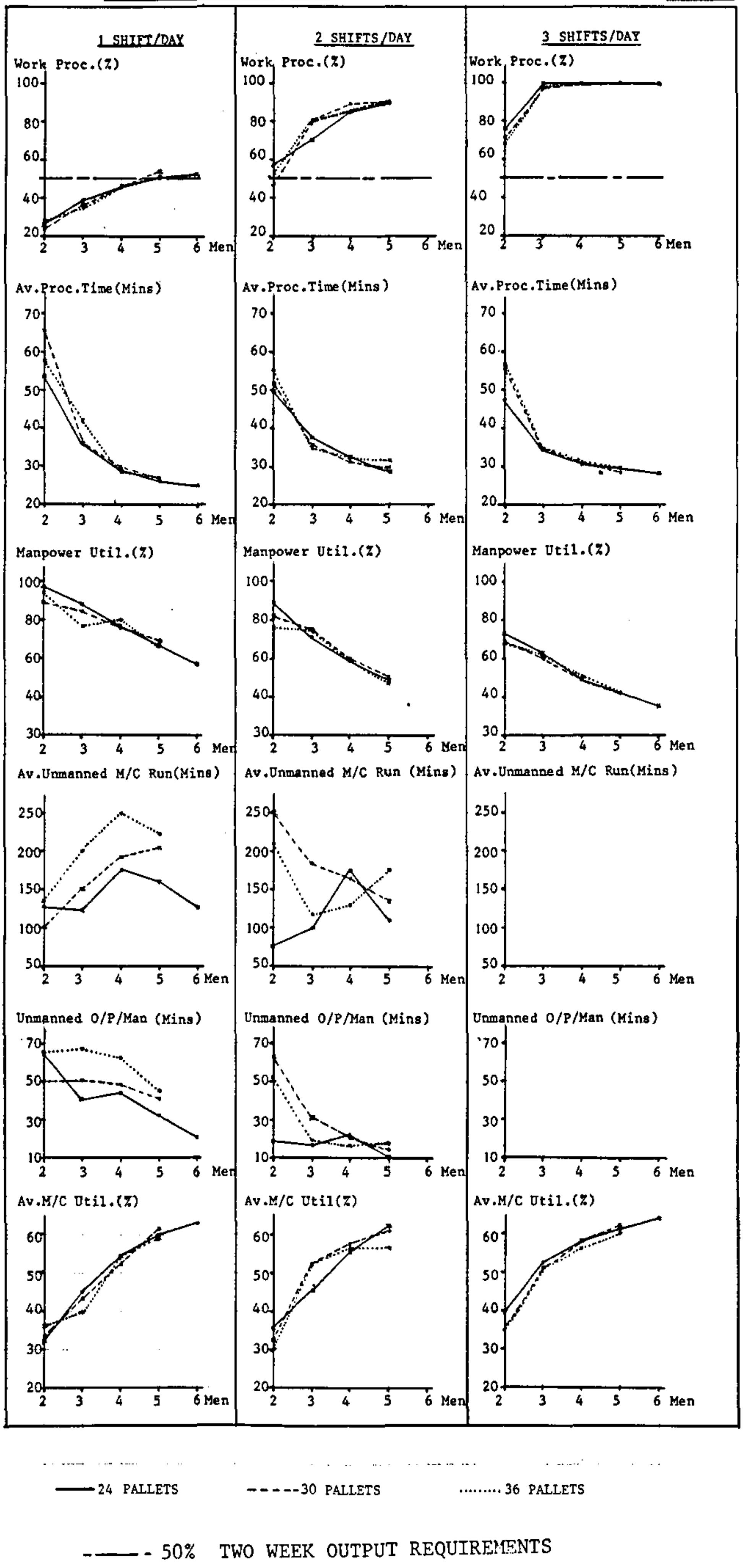


Fig. 6.6: Performance Curves for FMS F

Cherwell

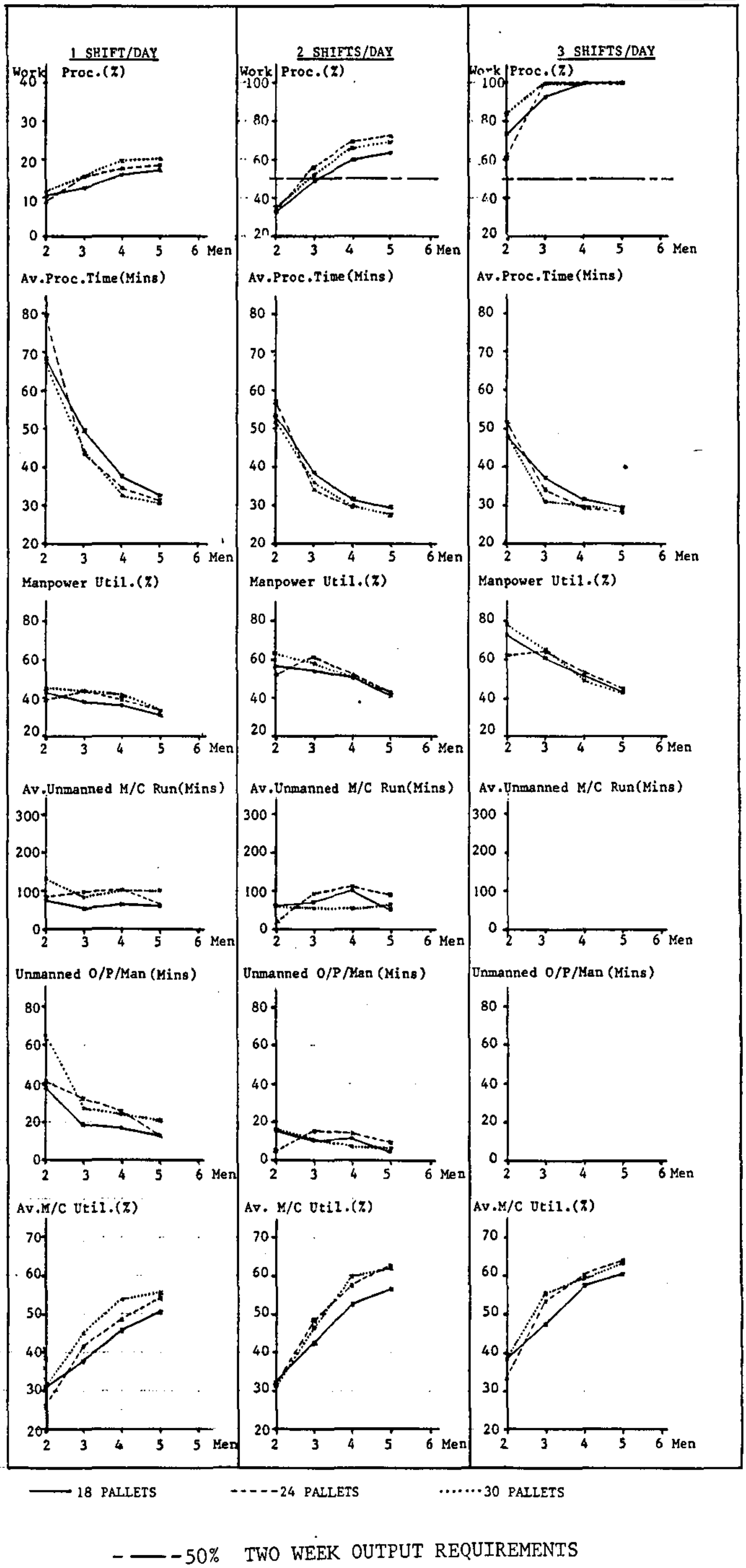
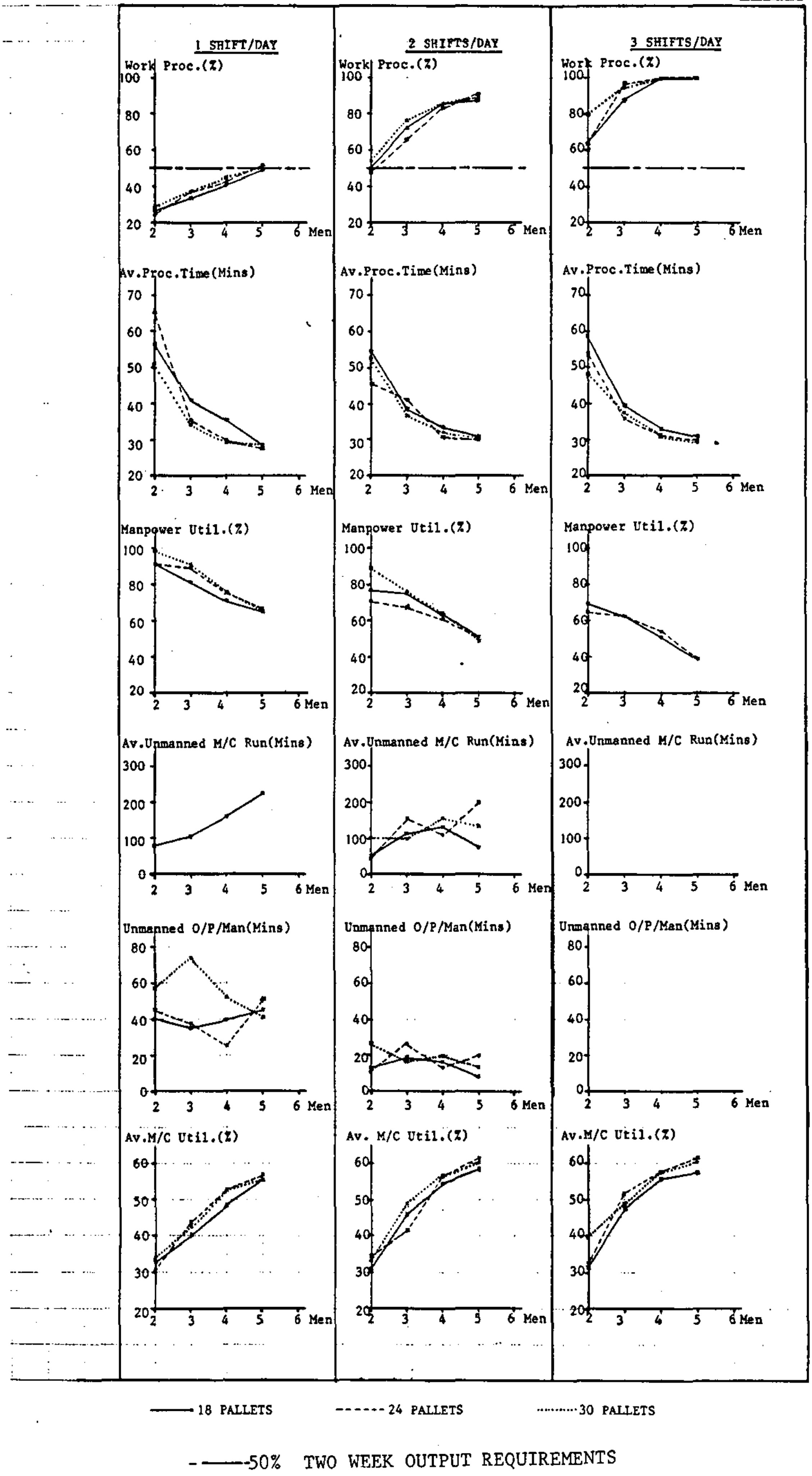


Fig. 6.7: Performance Curve for FMS G



It should be recalled that the manufacturing program is based on two week period batch control requirements. This means that some 999 parts with a total of 302.34 hours of machining time must be produced in a two week period and would represent 100% of output. Due to constraints of computer run times and a desirable compromise in determining the simulation time unit, the time span of all simulation runs has been taken as one week. Hence, the production goal may only be achieved with reasonable measure of certainty if a minimum of 50% can be processed during a simulation run. From the graphs in Figs. 6.1 , 6.2 and 6.3 it is clear that this output can be achieved by a mix of suitable combinations of the following conditions:

(i) number of shifts per day,

(ii) manpower levels, and

(iii) extra capacity at the machine buffer, i.e. additional automated material handling equipment.

In determining the mix of operational conditions which will give the best performance it is appropriate to identify the minimum resources which achieve the 50% output requirement.

For example, for systems A, B, and C the 50% output line can be achieved on a 2 shift basis using 3,2,and 2 men respectively. The production target is not achieved by one shift operation. The advantage of increasing the pallet station capacity from 2 to 4 reflects clear advantage in reducing manpower from 3 to 2 men.

If the systems are operated on a 3 shifts per day basis the minimum output goal of 50% is reached by FMS A, B and C with a manpower level of just 2 men. More specifically, FMS A, FMS B and FMS C attain approximately output performances of 52%, 76% and over 77% respectively, with a minimum number of 24 trolleys.

However, FMS C, unlike FMS A and B, appears to exhibit some sensitivity to the number of trolleys employed for a two man crew. With 36 trolleys it can reach an output goal of over 81%. But it should be remembered that these results are subject to some random effects which would be expected in such simulation experiments. This is of course evidenced in the graphical plots herein.

Of the four automated FMS models, with the exception of the rail guided shuttle (FMS F) all achieved better output performance by comparison with FMS A. This improvement is clearly shown for the double shift system at the minimum manpower level of 2 men for FMS D, E and F. FMS F (stacker crane) and FMS G (AGV) with 2 men are able to meet the 50% minimum required output, while FMS D (conveyor) and FMS F (rail guided shuttle) fails to do so by margins of under 2% for the former and 15 to 17% in the latter case. However, the improvements in output performance found for the automated systems are marginally higher using 3 men for FMS D, E, F and G compared to the improvement of performance of FMS B and C. We note that FMS F does not show such improvement although the system attains output target with 3 men.

The advantage of 3 compared to 2 AGVs has been appraised. (See Appendix D for graphical presentation of results using 3 AGVs). No advantage in output processed has been found for 3 compared to 2 AGVs. This may be expected from the low levels of use of AGVs as shown in the analysis of transporter utilisation (see Fig. 6.9). Hence the comparison of systems draws on results using 2 AGVs. The output curves for FMS types do show some sensitivity to the In-Process storage capacity and the number of pallets in the system. For FMS D (conveyor) operated on a double shift the output appears to be better with 18 pallets at lower manpower levels of 2 and 3 men, but at higher manpower levels additional pallets and In-Process storage seem to give greater output. FMS E (stacker crane) on the otherhand with 2 shifts per day produces more output with 24 pallets and storage capacity with 2 men, but at higher manpower levels more pallets are required. FMS F (rail guided shuttle) needs to be operated with at last 3 men on a 2 shift basis to achieve the minimum production goal of 50%, but appears to be more effective generally across the entire range of manpower with 24 pallets and storage capacity. This may be partly due to the loading and unloading of pallets directly at the intermediate store pallet station, instead of at the load/unload stations.

With a 3 or 2 man crew on a double shift, FMS G attains an advantage using at least 30 pallets.

Comparison of output performance from adding an extra shift, i.e. 3 shift/day, shows an interesting comparison when comparing output for the same daily manpower level, i.e. 3 men on 2 shifts or 2 men on 3 shifts. For manual systems FMS A, B and C the total output is very similar for either the 2 men/3 shifts or 3 men/2 shifts arrangement. For FMS D and G there is no real difference in output obtained between these man/shift arrangements. FMS E shows slightly higher output for 3 man/2 shifts and FMS F a positive advantage for 2 men/3 shifts. But in all these cases the output level reached is above that set for a 1 week production requirement. In FMS E, the In-Process storage is in the form of a multilevel store, so that the load/unload activity is more dependent on the stacker crane transporter. In FMS D and F the load/unload function can be performed directly from the In-Process store which is on a single level and thus directly accessible to operators on the ground.

In all the systems investigated, it is generally apparent that although an expected increase in output results from increasing the manpower the rate of improvement declines at the higher manpower levels. A maximum increase in output has resulted when manpower level is increased from 2 to 3 men. This is important in automated manufacturing systems, since one of the reasons for introducing automation is to minimise manpower levels.

The results of this study show that to achieve the stated production output goal with assurance the stand alone FMS systems A,B, and C require at least 4, 3 and 2 men respectively on a double shift operational basis. FMS E and G with twin pallet shuttle and automated material handling studied can also attain the required output with 2 men on 2 shifts per day. FMS D (conveyor) and F (rail guided shuttle) requires at least 3 men under similar conditions.

6.2.2 AVERAGE PROCESSING TIMES

In all the systems simulated the average processing time decreases with increasing manpower levels. This decrease is greater for lower manpower levels. At higher levels of manpower the average processing time remains nearly constant. This minimum value for the seven configurations is given by Table 6.1 for the two shifts per day system.

Table 6.1: Minimum Average Processing Times

SYSTEM	FMS A	FMS B	FMS C	FMS D	FMS E	FMS F	FMS G
TIME(MINS)	39.5	30.7	29.8	28.4	29.6	27.7	30.1
TROLLEYS/PALLETS	24	24	24	18	30	24	30

By way of comparison the average machining time per part for the total workload is approximately 18.2 mins. With manpower levels (as low as 2 men), a clear improvement is seen in average process time when moving from a single to a double shift system.

The average processing times for systems with manual transport using 24 trolleys and 2 men operating on a double shift is 81.4 mins for FMS A, 61.4 mins for FMS B, 53.2 mins for FMS C. This demonstrates the relative effectiveness of increasing the capacity at the machine buffer. By introducing a twin pallet shuttle an improvement in average process time by 25% is achieved while increasing the capacity to four pallet stations results in a further improvement of approximately 13%.

Thus, in FMS D, E, F and G, the twin pallet shuttle form of machine buffer was retained for testing by simulation, with additional improvement in performance expected alongside the incorporation of automated transport system. Such systems give rise to two requirements: (i) the use of pallets as the primary part carrier, and (ii) some form of In-Process store. Both items entail comparatively greater additional expense, and in this study they go together.

For FMS D (conveyor) which requires at least 3 men on a double shift to process the required workload, the best processing time of 35.5 mins is obtained with 18 pallets. Under the same conditions, the corresponding times for the stacker crane, rail guided shuttle, and AGV systems are 35.1 mins, 34.2 mins, and 36.6 mins with the pallet requirement being 30, 24 and 30 respectively. Although these performance measures are close to each other the varying number of pallets required reflect the specific nature of the four automated transport systems and the resulting In-Process storage capacity required.

In taking a general overall view we see that improved average process time is obtained by introducing automated pallet changers to the machining centres. A further improvement, but to a much lesser degree, is attained by addition of automated transport systems. Increased manpower levels also improve average processing time especially at lower levels. Addition of extra shifts per day result in better process times, and the improvement is marked in moving from a single to a double shift system.

6.2.3 MANPOWER UTILISATION

The utilisation decreases with increasing manpower levels as expected (Fig. 6.1 to 6.7). This decrement is approximately linear in most cases within the range tested. The changing levels of manpower utilisation with number of part carriers is of lesser consequence. At higher levels of manpower, increasing the number of shifts per day has the effect of decreasing manpower utilisation in all systems with the exception of the rail guided shuttle model. This is because increasing numbers of parts with longer machine times enter the system.

For a double shift mode of operation with 3 men the ranges of manpower utilisation for FMS A, B, C, D, E, F and G are 87.9-88.6%, 77.7-78.6%, 83.9-86.2%, 72.3-78.4%, 70.7-75.1%, 58.6-60.9% and 68.3-76.2% respectively. It is to be expected that FMS A, B and C with manual transport should give higher levels of manpower utilisation. On introduction of a twin pallet shuttle, manpower utilisation decreases by about 10% but when the capacity is increased to four per pallet shuttle, the utilisation levels rise by 6 to 7% presumably because of increasing manual work at the machine buffer. For FMS D, E, F and G with automated material handling the utilisation levels are lower in all cases than the manually operated twin pallet shuttle system. This decrease is greatest for the rail guided shuttle system and least for FMS D (conveyor), the fixed automation case. More flexible automated transport systems appear to give improved manpower utilisation levels.

6.2.4 MACHINE UTILISATION LEVELS

The machine utilisation measure for systems with manual transport are relatively unaffected by increase in the number of part carriers i.e. trolleys and pallets. However with the introduction of multiple shift systems they do show an improvement in machine utilisation but the rate of improvement decreases with increase in manpower levels.

The introduction of greater capacity at the machine buffer is shown to advantage by the better utilisation levels obtained.

Typically, for a 2 man crew on a double shift the figures for FMS A, B and C are approximately 21%, 27% and 32% respectively. With the addition of another man to the shift they give the largest improvement as shown by changes to 31%, 43% and 45%. With 4 men they show some natural increase as reflected by changes to 39%, 54% and 55%.

However, to achieve the set production goal with a double shift mode of operation FMS A has to be operated with at least 4 men, FMS B with 3 men and FMS C with 2 men. With the above target the comparative levels of machine utilisation are 39%, 43% and 32%. This illustrates the complex interrelationship between various factors in the type of manufacturing systems represented here such as form of automation, machine buffer capacity, manpower level, part carriers and work store, shift system and production goal when selecting alternative forms of manufacturing systems.

Machine utilisation for various numbers of pallets in systems with automated transport is shown in Table 6.2 for a 3 man crew. There appears to be some inconsistency in the results but there is a general trend. More protracted analysis would be helpful here in a closer examination of the influence of the number of pallets. The systems need to be studied for queueing patterns and identification of any bottlenecks in the machining cell. However, it may be noted that pallet costs are lower than the costs of other equipment in the cell, such as automatic pallet changers and transport systems.

Table 6.2: Machine Utilisation in Automated Transport Systems

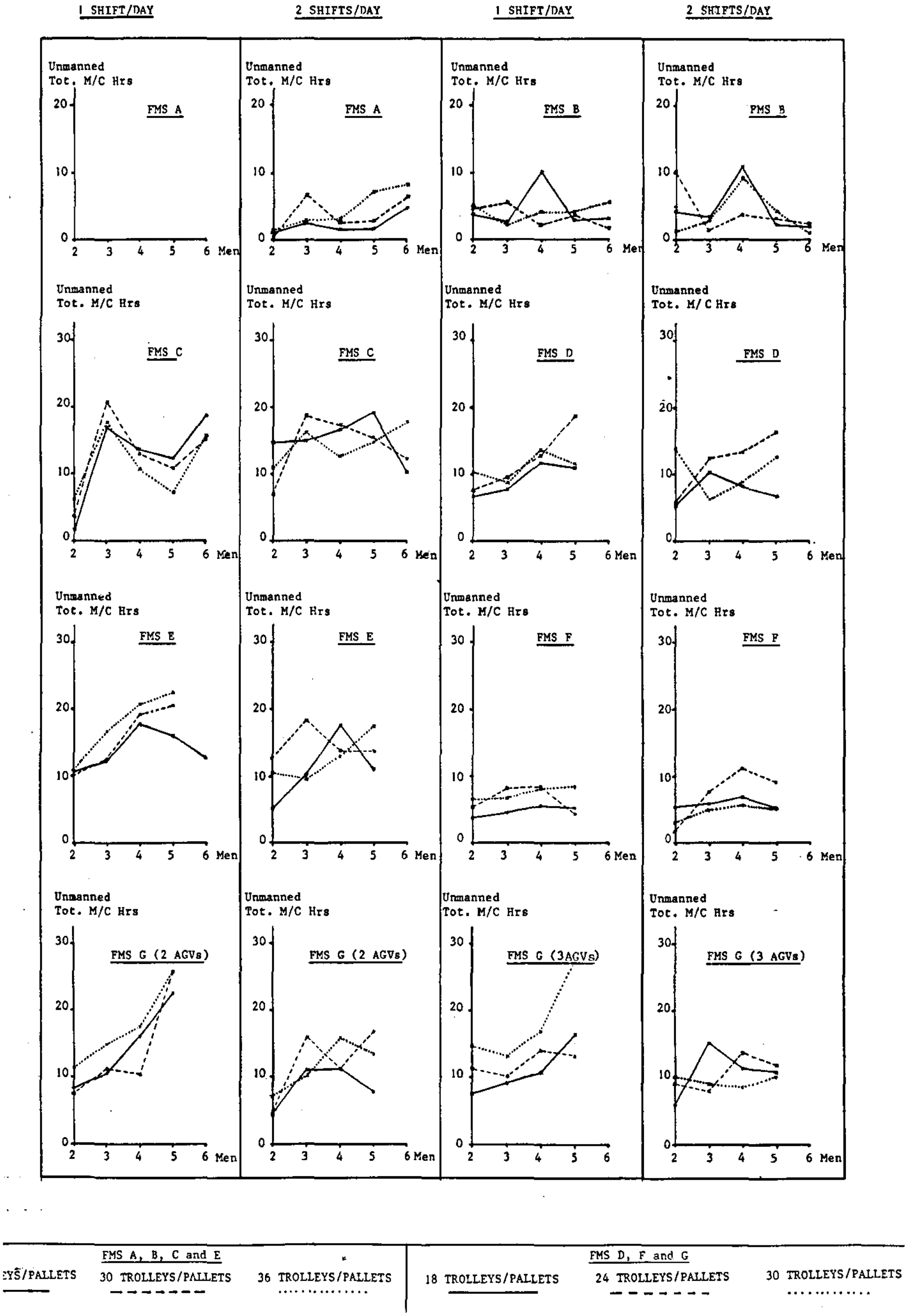
MANPOWER = 3 MEN		MACHINE UTILISATION (%)			
SYSTEMS	NO. OF PALLETS	18	24	30	36
FMS D	CONVEYOR	51.07	45.82	46.52	-
FMS E	STACKER CRANE	-	45.87	51.23	52.14
FMS F	RAIL GUIDED SHUTTLE	42.71	48.38	46.44	-
FMS G	AGV	45.97	41.62	49.03	-

6.2.5 BENEFITS OF UNMANNED OPERATION

An important advantage of introducing automation in a manufacturing system is the possibility of unmanned operation. This is of course true for the single and double shift mode of operation. The magnitude of the resulting benefit would be expected to increase with the level of automation, i.e. with increased technological resource inputs and the particular mix of resources.

In Fig. 6.8 the total unmanned run in machine-hours is plotted against manpower levels for the different manufacturing systems under various conditions. Varying the number of part carriers i.e. pallets or trolleys does not seem to show any marked

Fig. 6.8: Unmanned Machining Hours for Alternative Systems



trend. This may be due to the fact that unmanned operational performance is very closely dependent on the variability in machining times of the part spectrum and the capacity of the machine buffer. The latter possibility is apparent when the unmanned performance curves for the three systems with manual transport on a double shift are compared.

It appears that unmanned operational levels may be improved by:

(i) increasing the machine buffer capacity,

(ii) introducing more flexible transport system (e.g. AGVs),

(iii) providing a larger capacity Automatic Storage and Retrieval System (e.g. multilevel stacker crane store).

All three methods may be used in combination but obviously at greater expense. Such further combinations have not been tested in this study.

6.3 EVALUATION OF ALTERNATIVE FORMS OF FMS

6.3.1 SELECTION OF RESOURCES AND OPERATIONAL CONDITIONS

The first consideration in selecting the mix of resources and operational conditions is in achieving an established production goal at an accepted cost. The resulting machine requirement in this study was analysed in preliminary investigations as reported in Chapter 3. Having set the number of machines at six machines a broad range of system output may be attained by varying other resources and conditions. In the process of selecting the resources to be associated with the group of six machines the following additional objectives have been pursued.

(i) Minimisation of average processing time.

(ii) Maximisation of manpower utilisation.

(iii) Minimisation of manpower requirements.

(iv) Maximisation of machine utilisation.

(v) Minimisation of other resource requirements, and

(vi) Maximisation of other system benefits.

The minimisation of work-in-process levels is considered to be relatively unimportant in this investigation, since manufacturing operations are for the most part confined to a single stage.

From the experimental results obtained it is clear that a single shift system would be completely inadequate in regard to target output. Attention is therefore focused on the double shift mode of operation in preference to a continuous 3 shifts per day system. This is because 2 shift working has the additional benefit of unmanned operation.

In selecting a preferred combination of machines and associated resources the manpower level which has achieved the production target has been selected in tandem with the part carrier requirement. There is a regard for advantageous performance in respect of average process time.

For FMS A and B with manual transport it is clear that they must be operated with 4 and 3 men respectively (see Figs. 6.1 and 6.2) although this gives outputs well above the 50% output level. The minimum number of part carriers tested, i.e. 24 pallets, will suffice for these configurations.

For FMS C, this choice is of critical importance since the system may be operated with 2 men having also an additional benefit from the larger machine buffer capacity. From the results it appears that for FMS C, 24 part carriers will accomplish the manufacturing task.

FMS D requires to be manned by at least 3 men since a 2 man crew would be marginally insufficient. The outputs for the various conditions tested are well above the weekly requirement, so that the minimum of 18 pallets and 18 In-Process buffer stations have been selected. The benefits of better processing time, manpower and machine utilisations are clearly reflected by these selections.

With an automated stacker crane system (FMS E) the production goal may be achieved with 24 or 30 pallets and In-Process store. The choice preferred has been that of 30 pallets and 3 men since this results in longer unmanned operation levels.

The minimum manpower level for the rail guided shuttle system (FMS F) is 3 men with 24 pallets. Under these conditions, the best combination of performance levels are obtained.

The most flexible automated system (FMS G) operated with 2 AGVs requires at least 30 pallets to reach the weekly production level with 2 men. For the load requirements in this study it was found that for the single and double shift operation the AGV battery change may be avoided during shifts by appropriate choice of battery capacity. This is illustrated in Appendix D3, and the required rating for the battery is 85-90 Ahr.

6.3.2 COMPARISON OF SELECTED ALTERNATIVE SYSTEMS

For the individually preferred mix of resources and conditions, the performance levels are as follows for a double shift system (Table 6.3).

On a system output per man basis, it may be noted that systems FMS A and G have the lowest and highest performance respectively. By introducing a machine buffer capacity as in FMS B in the form of a twin pallet shuttle the output per man is improved. To obtain greater levels of output this capacity may be increased as in FMS C by increasing pallet shuttle capacity from 2 to 4.

However, instead of only increasing capacity at the machine buffer, increased output per man may be achieved by selecting an 'integrated automation' alternative such as FMS D, E or G. The first case tends to increase manpower utilisation at the expense of average processing times whereas it is the reverse for the latter case. This is because there is less manual work in the 'integrated automation' alternatives. In FMS F the advantages of better output and average process times are obtained by increasing manpower levels. However, a decrease in manpower utilisation follows.

Additionally, for systems with a higher manpower requirement there is a further flexibility that may be useful. For example, FMS B, D and F have a manpower level of 3 men per shift, which means the overall size of the crew is 6 men. It is, of course, possible to operate these systems on a continuous 3 shift basis at a manpower level of 2 men. This is advantageous for FMS B and F

Table 6.3: Selected Configurations and Performance Measures

SYSTEM	PALLETS & TROLLEYS	MANPOWER	OUTPUT LEVEL %	OUTPUT /Man %	AV.PROC.TIME (MINS)	AV.M/C UTIL (%)	AV.MAN UTIL (%)
FMS A	24	4	62.11	15.5	43.06	39.17	78.74
FMS B	24	3	66.87	22.3	39.59	42.61	77.70
FMS C	24	2	54.76	27.4	53.19	33.02	91.38
FMS D	18	3	79.93	26.6	35.52	51.07	77.38
FMS E	30	2	53.25	26.6	51.66	32.87	82.84
FMS F	24	3	55.83	18.6	34.22	48.38	60.86
FMS G	30	2	57.81	28.9	47.95	36.32	86.81

which yield increases in output levels of over 10% and 5% respectively. FMS D when similarly operated results in an overall decrease in total output of over 16% although the output per man is better.

In this analysis, the selection of the mix of resources and conditions is on the basis of achieving a minimum output level of 52.5% in the one week simulation period. This is because the 100% output is to be completed in a two week span. To ensure certain completion of the total workload in this period an output performance of 105% in the two weeks was established.

The breakdown of the average manpower utilisations for the related configurations into the various manual activities are shown in Table 6.4. It should be noted that in the simulation programs the nearest available man is used in the various activities such as fixturing, loading and unloading parts and tools. Time spent moving between stations and machines is thus minimal and only times greater than one simulation time unit are recorded.

The utilisation levels of automated transport systems in FMS D, E, F and G is shown in Fig. 6.9. For the purpose of comparison the utilisation curve for the 3 AGV system is also indicated. The utilisation of the conveyor system in FMS D is significantly higher since it is slower and continuously available compared to other transport systems. The stacker crane (FMS F) utilisation is generally higher than the rail guided shuttle. However, the AGVs in FMS G have a slightly better utilisation level than the stacker crane for manpower level of 2 men. At higher manpower levels, the utilisation of the AGVs is less than the rail guided shuttle in FMS F.

Table 6.4 Elements of Manpower Utilisation for Selected Configurations

SYSTEM	MEN	PALLETS	AV. MAN UTIL (%)	MAN UTIL(%) FIXTURE	MAN UTIL (%) M/C LOAD/UN	MAN UTIL (%) TOOL MAG LD.	OUTPUT LEVEL(%)
FMS A	4	24	78.74	37.81	16.08	24.84	62.11
FMS B	3	24	77.70	18.53	23.53	35.62	66.87
FMS C	2	24	91.38	23.58	25.60	42.18	54.76
FMS D	3	18	77.38	12.65	29.55	34.82	79.93
FMS E	2	30	82.84	14.99	27.44	40.33	53.25
FMS F	3	24	60.86	10.95	20.65	27.33	55.83
FMS G	2	30	86.81	16.01	31.65	39.13	57.81

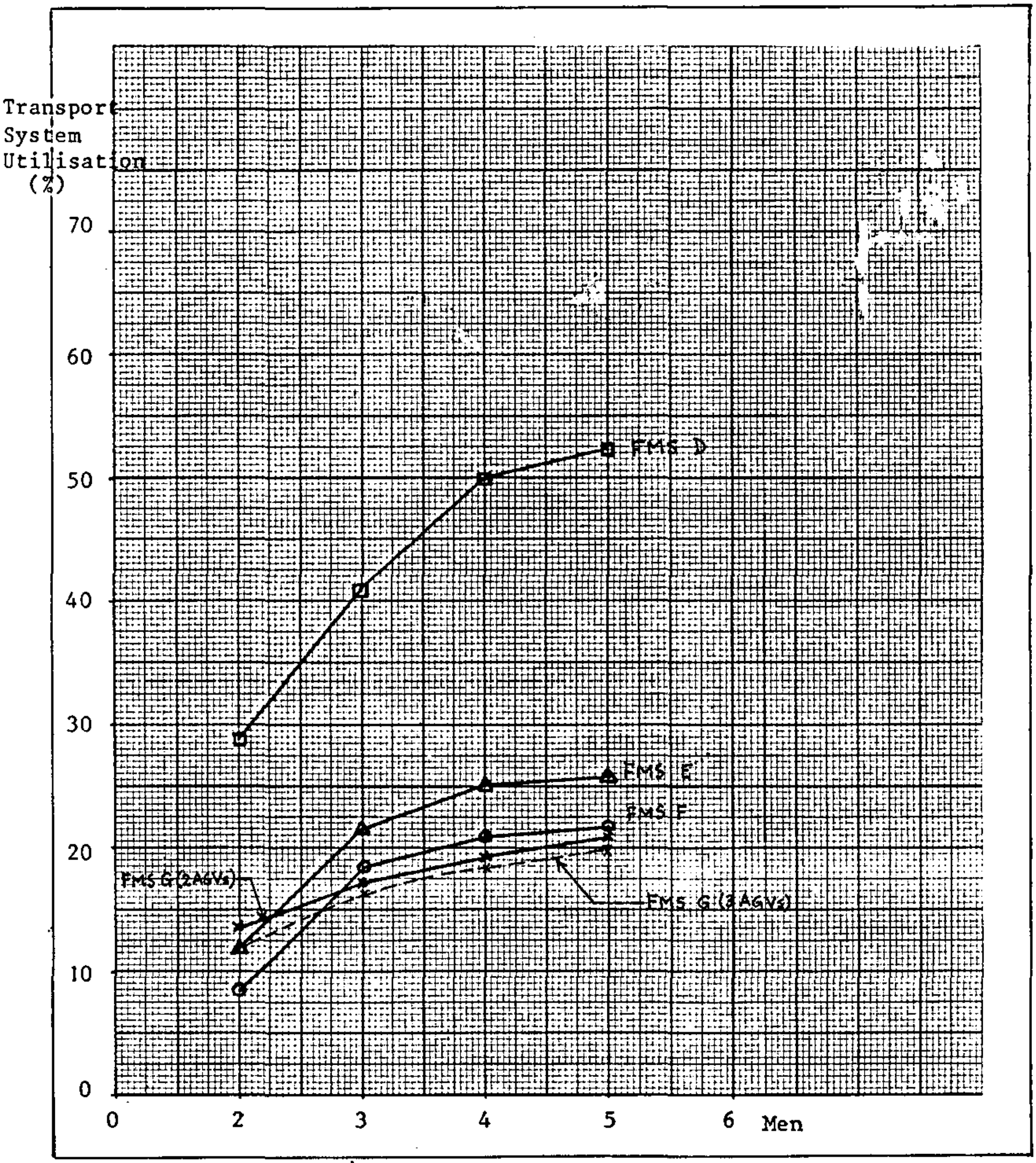


Fig. 6.9: Utilisation Levels of Automated Transport System

To illustrate the relative operational performance characteristics of the seven manufacturing systems studied, performances for various operational conditions are given in Table 6.5. The table uses the performance values of average process time, manpower and machine utilisations for the CNC machining cell (FMS A) with 2 men as the base for comparison. The corresponding values for the other systems are expressed as a fraction or multiple of the FMS A performance. Thus the average process time and manpower utilisation values will be less than unity as would be expected for increasing automation, whereas the improved machine utilisation is expressed as a multiple of the FMS A performance. However, examination of operational performance is now complemented by a cost appraisal of the FMS configurations.

TABLE 6.5: Performance Measures from Systems and their Selected Operating Conditions

SYSTEM*	MANPOWER SHIFT: APC STATIONS	PALLETS (TROLLEYS)	2: 2 SHIFTS	2: 3 SHIFTS	3: 2 SHIFTS	3: 3 SHIFTS	4: 2 SHIFTS	4: 3 SHIFTS	5: 2 SHIFTS	5: 3 SHIFTS
PROCESS TIME										
FMS A	-	24	1.00	1.00	0.68	0.63	0.53	0.55	0.50	0.55
FMS B	2	24	0.75	0.65	0.49	0.50	0.40	0.42	0.38	0.39
FMS C	4	24	0.65	0.63	0.46	0.46	0.41	0.42	0.39	0.38
FMS D	2	18	0.65	0.63	0.44	0.44	0.37	0.38	0.35	0.36
FMS E	2	30	0.63	0.68	0.44	0.43	0.38	0.37	0.36	0.35
FMS F	2	24	0.69	0.66	0.42	0.42	0.37	0.36	0.34	0.35
FMS G (2 AGVs)	2	30	0.64	0.59	0.45	0.46	0.39	0.38	0.37	0.36
FMS G (2 AGVs) NO BATT.CHANGE	2	30	0.59	-	0.42	-	0.39	-	0.37	-
MANPOWER UTILISATION										
FMS A	-	24	1.00	0.91	0.92	0.87	0.81	0.70	0.69	0.57
FMS B	2	24	0.86	0.85	0.80	0.69	0.69	0.56	0.55	0.47
FMS C	4	24	0.95	0.90	0.89	0.74	0.74	0.57	0.59	0.52
FMS D	2	18	0.80	0.69	0.80	0.65	0.65	0.53	0.54	0.46
FMS E	2	30	0.86	0.72	0.77	0.62	0.62	0.52	0.51	0.44
FMS F	2	24	0.54	0.64	0.63	0.66	0.54	0.54	0.44	0.46
FMS G (2 AGVs)	2	30	0.93	0.85	0.79	0.66	0.66	0.56	0.52	0.40
FMS G (2 AGVs) NO BATT. CHANGE	2	30	0.90	-	0.80	-	0.60	-	0.49	-
MACHINE UTILISATION										
CNC CELL	-	24	1.00	1.03	1.49	1.61	1.81	1.88	1.90	1.84
FMC	2	24	1.24	1.54	1.97	2.11	2.55	2.39	2.67	2.57
FMC	4	24	1.52	1.58	2.09	2.25	2.41	2.41	2.50	2.60
FMS-CONVEYOR	2	18	1.44	1.53	2.36	2.32	2.81	2.72	2.84	2.83
FMS-STACKER CRANE	2	30	1.52	1.61	2.37	2.40	2.69	2.69	2.85	2.89
FMS-RAIL SHUTTLE	2	24	1.47	1.52	2.23	2.48	2.66	2.80	2.90	2.96
FMS-AGV (2)	2	30	1.53	1.82	2.26	2.26	2.63	2.67	2.79	2.78
FMS-AGV (2) NO BATT. CHANGE	2	30	1.68	-	2.41	-	2.66	-	2.80	-

* = CONDITIONS ASSOCIATED WITH SELECTION GIVEN IN TABLE 6.

CHAPTER 7

COST EFFECTIVENESS OF ALTERNATIVE SYSTEMS

7.1 INTRODUCTION

The study of alternative configurations of FMS has so far been confined to technological performance measures based on the results of simulation. The analysis is now extended to determine the comparative average annual total production costs. The cost of production has two components, viz. the fixed investment cost and the operating (or running) cost. An investment appraisal of the seven alternative systems is also performed.

7.2 SELECTION OF ALTERNATIVE SYSTEMS FOR COST APPRAISAL

The manpower and operational mix selected previously in comparing performance with different technological forms was linked with resourcing that achieved a 52.5% level of required output. However, some of the preferred configuration/resource combinations achieve output well beyond this level. Hence the selections introduce a degree of bias in the cost effectiveness comparison of some alternative systems.

A review of output levels equating to 50% of load required as illustrated on graphs in Figs. 6.1 to 6.7, indicates combination of resources for each configuration. In seeking to meet the 50% level as near as possible it is necessary to select the system combinations which achieve most nearly this output level. Hence, the combinations produce output levels from +8% to -8% of the 50% load as stated in Table 7.1

7.3 COST APPRAISAL OF ALTERNATIVE FORMS

Most evaluations of flexible manufacturing systems as evidenced in the literature, e.g. Airey (1983), Primrose and Leonard (1984, 85, 86), are based on traditional approaches of investment appraisal. However, in this study consideration is also given to estimated actual costs of production using Discounted Cash Flow (DCF) techniques, and to indications attained from a NPV analysis. This takes note of investment necessary, with such expenditure related to a life of equipment of 10 years.

7.4 PRODUCTION COST ANALYSIS BASED ON DCF

7.4.1 CAPITAL INVESTMENT COST

The capital investment is divided into the following cost categories:-

(a) Machine Tool Costs

(b) Inspection Costs,

(c) Auxiliary Equipment Costs,

(d) Tooling Equipment Costs,

(e) Fixture Costs,

(f) Pallet Cost,

(g) Material Handling Cost,

(h) Computer Costs,

(i) Part Programming Cost

(j) Load/Unload Station Cost,

Table 7.1: Selected Combinations of Resources and performance increases

SYSTEM	MANPOWER	PALLETS/TROLLEYS	OUTPUT (%)	AV.PROCESS TIME (mins)
A	3	24	50.5	55.3
B	2	24	42.8	61.4
C	2	24	54.8	53.2
D	2	18	49.5	53.0
E	2	30	53.3	51.7
F	3	24	55.8	34.2
G	2	30	57.8	48.0

Table 7.2: System Investment Costs for Systems and their Selected Resource Combinations

SYSTEM	A	B	C	D	E	F	G
INVESTMENT COST (£)	408,125	514,685	603,485	837,502	714,263	630,791	824,597
AMORTISED INVESTMENT COST (£)	71,069	89,625	105,089	145,839	124,379	109,844	143,593

(k) Installation Cost,

(l) Engineering and Commissioning Cost,

(m) Grant (for FMS generally 33 1/3%, here 26% is assumed since the full grant is not always obtained). (Farrow (1984)).

The detail of estimated costs for the alternative manufacturing systems are included in Appendix F. The investment cost is amortised over the expected life of the system, and the amortised investment cost (C_{AIC}) is given by the equation:

$$C_{AIC} = \frac{(I_c - S_c)\ i\ (1+i)^N}{(1+i)^N - 1} + (iS_c)$$

where, I_c = Investment Cost,

S_c = Salvage value at year N, (assumed to be 5% of I_c),

N = Production Life, (estimated at 10 years).

i = Investment Interest rate, (estimated to be 12%).

The total and amortised investment costs are summarised in Table 7.2.

7.4.2 <u>OPERATING COST ESTIMATES</u> (C_{op})

The guideline period for asset depreciation of computer equipment that would be used in business is quoted as 6 years by Jelen & Black (1983). For depreciable assets employed in the manufacture of machinery the corresponding figure is 10 years. The operating (or running) cost is thus based on a 7 year projection taking into account inflation. This cost is discounted (at 12%) and averaged to arrive at an annual operating cost (C_{op}). The discount rate represents the marginal rate of time preference and compensates for the relative marginal values of consumption at different points in time, with respect to the first year. These estimates also take into account the tax benefit that accrues from the writing down allowance on capital equipment, and this has been accounted in the operating cost category. The breakdown of operating costs is as follows:-

(a) Heat, Light and Rates.
(b) Power Costs,
(c) Direct Labour Costs,
(d) Supervision Cost,
(e) Machine Maintenance Costs,
(f) Computer Maintenance Costs,
(g) Consumables - Tools and Inserts Costs,
(h) Consumables - Cutting Fluid Cost,
(i) Swarf and Waste Disposal Cost,
(j) Contingencies (5% of Direct Costs),
(k) Insurance (1/3% of Capital Value of Plant),
(l) Indirect Labour Cost.

Operating cost estimates of alternative systems have been each estimated for manpower levels of 2, 3 and 4 men for 2 shift working as set out in Appendix G. These costs are tabulated in Table 7.3(a). A computer program has been written to perform these estimates according to the schedule of operating cost elements described in Appendix H.

Table 7.3(a): Operating Cost Estimates of Alternative Systems

	OPERATING COST (Cop) ESTIMATES (£/YEAR)		
MANPOWER	2	3	4
FMS A	80041	97523	114919
FMS B	78520	96002	113398
FMS C	77320	94802	112198
FMS D	75587	93069	110464
FMS E	75998	93480	110876
FMS F	76968	94450	111845
FMS G	75767	93249	110645

Table 7.3(b): Average Annual Production Costs (£/year)

	AV. ANNUAL PRODUCTION COSTS, (Cprod)		
MANPOWER	2	3	4
FMS A	151110	168592	185988
FMS B	168145	185627	203023
FMS C	182409	199891	217287
FMS D	221426	238908	256303
FMS E	200377	217859	235255
FMS F	186812	204294	221689
FMS G	219360	236842	254238

7.4.3 TOTAL PRODUCTION COST (C_{prod})

The total annual production cost is given by the expression,

$$C_{prod} = C_{AIC} + \frac{1}{7} \left(\sum_{t=1}^{7} C_{op}\right)$$

The average annual production costs for different manpower levels are shown in Table 7.3(b). Business accounting would rightly justify provision for depreciation. However, in this analysis it has not been included since we refer directly to the estimated actual costs that the company would bear. Investment and average annual production costs are tabulated in Table 7.4 for the alternative systems and their selected conditions together with the performance measure of average process time against the nearest output achievements to (50% ± 8%) of the two week production period requirement.

7.5 COST-BENEFIT ANALYSIS OF ALTERNATIVE SYSTEMS

7.5.1 PROCESS TIME PERFORMANCE

The average annual production cost has been plotted against the average process time for the various alternative systems in Fig. 7.1 for constant manpower levels of 2, 3, and 4 men. There is a clear advantage in introducing APCs on machining centres as shown by the points in the graph representing FMS A and FMS B (2 station APC). For FMS B to FMS C (4 station APCs) the process time advantage is clear for a manpower level of 2 men, but

Table 7.4: Performance, Investment, Operating and Production Costs of Alternative Systems with Selected Resources for Output Range 50 ± 8% of Target for 1 week

SYSTEM	TOTAL INVESTMENT COST	AMORTISED INVESTMENT COST	AV. DISCOUNTED OPERATING COST	AV. ANNUAL PRODUCTION COST	OUTPUT	PROCESS TIME	PALLETS OR TROLLEYS	MANPOWER PER SHIFT
	(£)	(£)	(£)	(£)	%	(MINS)		
A	408125	71069	97523	168592	50.5	55.3	24	3
B	512100	89625	78520	168145	42.8	61.4	24	2
C	603490	105089	77320	182409	54.8	53.2	24	2
D	837500	145839	75587	221409	49.5	53.0	18	2
E	717200	124379	75998	200377	53.3	51.7	30	2
F	630790	109844	94450	204294	55.8	34.2	24	3
G	824600	143593	75767	219360	57.8	48.0	30	2

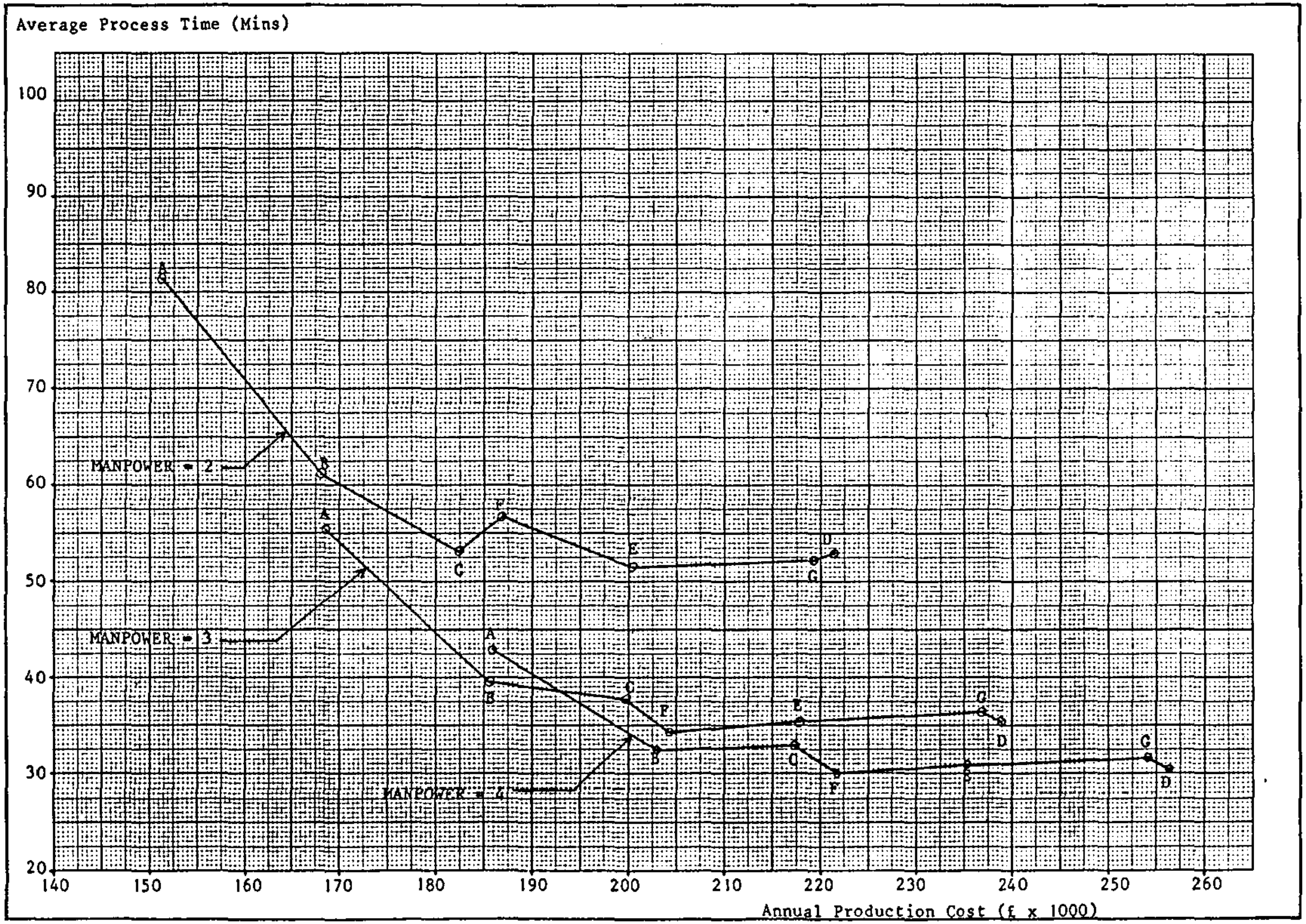


Fig. 7.1: Constant Manpower Curves of Annual Production Cost v.s. Average Process Time

decreases with the addition of another man. With 4 men, there is no difference between FMS B and FMS C.

Comparing FMS C (4 station APC) with the other systems (FMS D, E, F and G) with automated transport and 2 station APC, no marked advantage in process time is found. However, with 2 men FMS F has a slightly higher process time than FMS C, D, E and G, but for manpower levels of 3 and 4 men FMS F has the lowest process time of the five configurations. The process time can be improved as the graph indicates by increasing manpower. The advantage is distinct in moving from 2 to 3 men and less marked in changing from 3 to 4 men. For equal manpower resources, the configurations in the order of increasing average annual production cost are: FMS A, B, C, F, E, G and D. The constant manpower curves in Fig. 7.1, indicate that the cost-benefit relationships between alternative systems change significantly, when different configurations are selected with varying manpower levels. For example, FMS C with 2 men has a lower production cost and higher process time than FMS A with 4 men which would be required for a 50% assured output. However, when selected on the basis of an output level of 50% ± 8%, then FMS C requires 2 men and FMS A requires 3 men. FMS C with 2 men has a higher cost and lower process time than FMS A with 3 men. (See Appendix E for results from simulation).

The improvement in process time with incremental changes in production cost for FMS A, B and C is illustrated quantitatively in Tables 7.5 and 7.6. The percentage improvement in process time, ΔT_{AB}, in changing from FMS A to B is attained with a percentage production cost increase of ΔC_{AB}%. $\Delta T_{A_{23}}$ is the percentage improvement in processing time in increasing manpower from 2 to 3 for System A for the corresponding increase

Table 7.5: Process Times (mins)

MEN	A	ΔT_{AB}	B	ΔT_{BC}	C
2	81.5	-24.9%	61.2	-13.4%	53.0
ΔT_{23}	-32.2%		-35.5%		-28.9%
3	55.3	-28.7%	39.5	-4.6%	37.7
ΔT_{34}	-22.2%		-17.7%		-13.8%
4	43.0	-24.4%	32.5	0%	32.5

Table 7.6: Production Cost (£)

MEN	A	ΔC_{AB}	B	ΔC_{BC}	C
2	151110	+11.3%	168145	+8.5%	182409
ΔC_{23}	+11.6%		+10.4%		+9.6%
3	168592	+10.1%	185627	+7.7%	199891
ΔC_{34}	+10.3%		+9.4%		+8.7%
4	185988	+9.2%	203023	+7.0%	217287

in production cost $\Delta C_{A_{23}}$.

It is apparent that for a manpower level of 2, by moving from system A to B the increase in production cost is 11.3% resulting in an improvement in processing time by 24.9%. By increasing the machine buffer capacity further from B to C a further production cost penalty of 8.5% is borne for an extra process time improvement of 13.4%. However, for system A a greater improvement of 32.2% in process time may be obtained by increasing manpower level from 2 to 3 than by equipping for system B, but at a slightly higher production cost increase of 11.6%. Thus improving performance by increasing manpower for systems A, B and C is relatively an expensive undertaking compared to introducing twin pallet stations on machines at a lower additional production cost.

If we wish to consider the introduction of automated transport to obtain unmanned working, we note that System C with 4 pallet stations gives the most favourable results for unmanned working output. This is partly due to FMS C having a 4 station APC whereas the automated systems FMS D, E, F and G have 2 pallet station APC. Additionally, the automated transport systems have three fixturing stations, while in FMS C fixturing is performed directly on the APCs at the machining centres.

7.5.2 OUTPUT PERFORMANCE

Comparison of output levels from alternative systems with various manpower levels is shown in Fig. 7.2. With the exception of the rail guided shuttle (FMS F), the automated flexible manufacturing systems (D, E and G) give higher output than FMS A and B. At a lower manpower level, FMS C with 4 pallet stations achieves the same relative level of output.

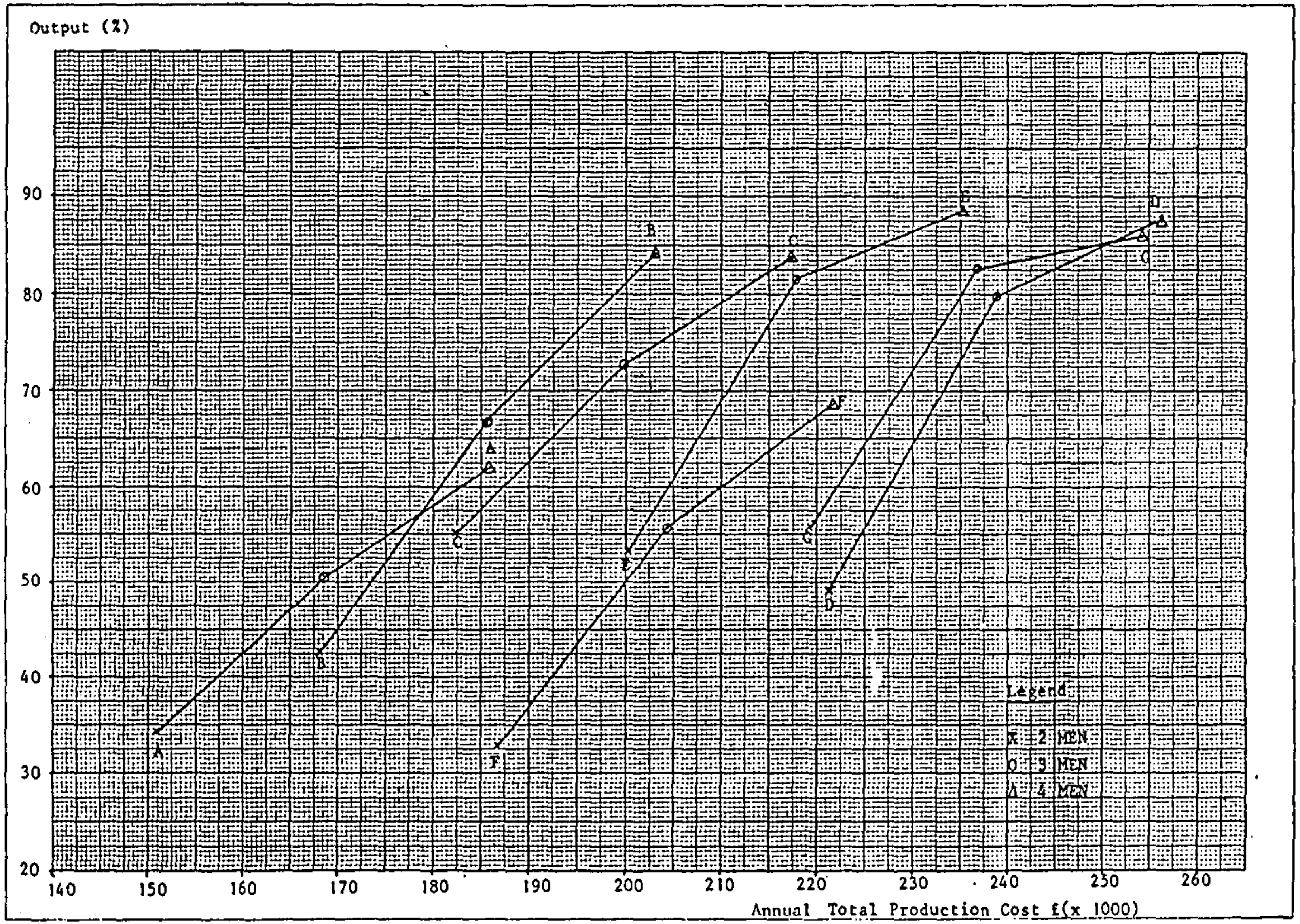


Figure 7.2: Constant Manpower Curves of Annual Production Cost V.S Output Levels

However, FMS D, E and G show a sharp fall in a rate of increase in output at higher manning levels as evidenced by the slope of the output curves. Nonetheless, at lower manpower levels they show the best improvement in output performance. All output improvements bear an associated increase in production cost.

With a 2 man crew FMS C, D, E and G yield higher levels (49.5 to 57.8%) compared to FMS A, B and F. For manpower levels of 3 and 4 men FMS D, E and G yield higher output ranges of 80 to 82.5%, and 85.8 to 88.5% respectively. However, FMS D and G have a much higher annual total production cost as shown by the output curves (Fig. 7.2).

The relative merits of FMS E, F and G have to be weighed against more long term strategic goals. Although, FMS F has a lower throughput time and processing time than the other systems, it has a higher manpower requirement than FMS E and G. One can argue that reducing the dependance on direct labour will result in more consistent quality which in turn reduces rework and scrap. FMS G has a lower relative throughput rate than FMS E, but the latter has a greater scope for unmanned production time.

7.5.3 UNMANNED MACHINING

In this particular study none of the alternative systems achieved a completely unmanned shift for each 2 shift period during a one week run. This is mainly due to the particular part spectrum in this system, the degree of commonality in fixture types for the different parts and the number of part types machined by a particular tool pack.

However, the maximum unmanned production time of 14.8 hrs is achieved by FMS C, the four pallet station system. Among the systems with integrated material handling FMS E (i.e. the stacker crane) achieved 12.8 hrs of unmanned run. The corresponding levels for FMS D, F and G are 5.3, 7.8 and 6.3 hours. The manual systems FMS A and B produced 2.8 and 4.3 hours of unmanned run time respectively. The higher unmanned working by FMS C is because fixturing is performed directly on the APCs at the machining centres. In the automated transport systems (FMS D, E, F and G), fixturing is performed at three fixturing stations. Space constraints on the available cell area at the factory concerned was responsible for this limitation.

7.6 COMPARISON OF SELECTED ALTERNATIVE SYSTEMS

Comparisons need to be related to chosen levels of assurance in meeting production output requirements. In this study the comparison has so far proceeded on the basis of FMS systems and their combination of operational factors which most nearly centre on 50% output, i.e. half the output of the two week production control period. These results are shown in Fig. 7.3. This shows somewhat unfairly in direct comparison, e.g. output for FMS B at 42.8% compared to FMS G at 57.8%. Thus, the systems are also compared on the basis of achieving at least 52.5% of the two week requirement (See Fig. 7.4). The accompanying performance characteristics for both selected groups are tabulated below the appropriate graphs.

Output achievement is a measure of machining-hours achieved against machining-hours required, whereas average processing time is the average time it takes for a part to go through the system and includes part preparation, handling, machining, tool setting and fixturing. This explains partly the difference in performance

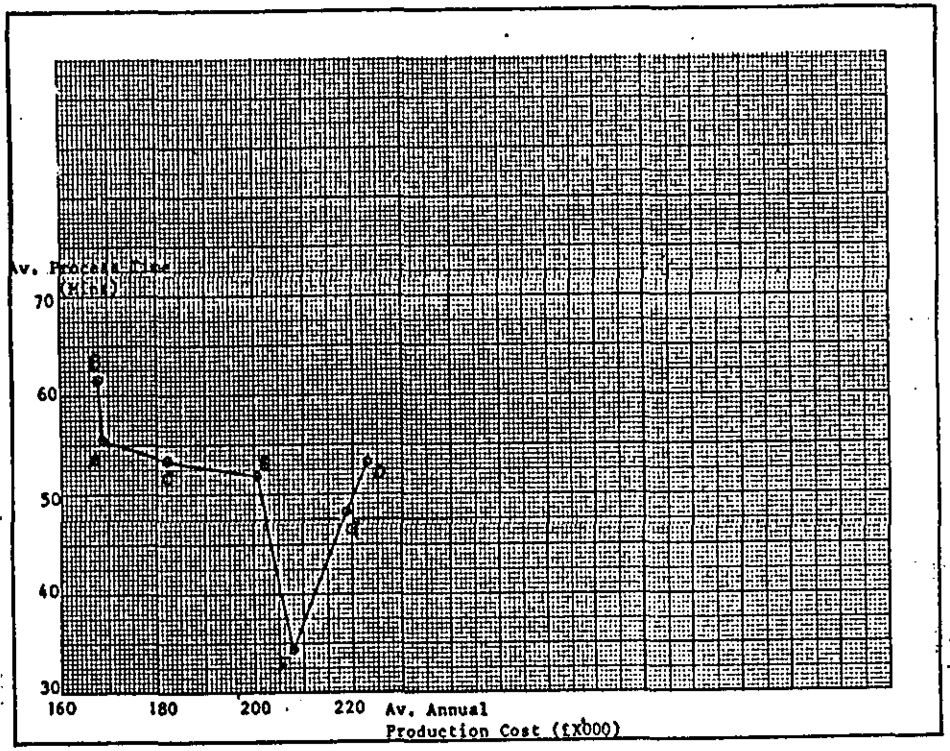


Fig. 7.3: Cost-Performance of Selected Configurations for Output Range 50±8%

SYSTEM(men)	B_2	A_3	C_2	E_2	F_3	G_2	D_2
% Output Level Achieved	42.8	50.5	54.8	53.3	55.8	57.8	49.5
Tot.Relative Throughput Time (Hrs)	83.4	80.5	88.8	87.6	61.7	83.3	83.2
Unmanned Production Time (Hrs)	4.3	2.8	14.8	12.8	7.8	6.3	5.3

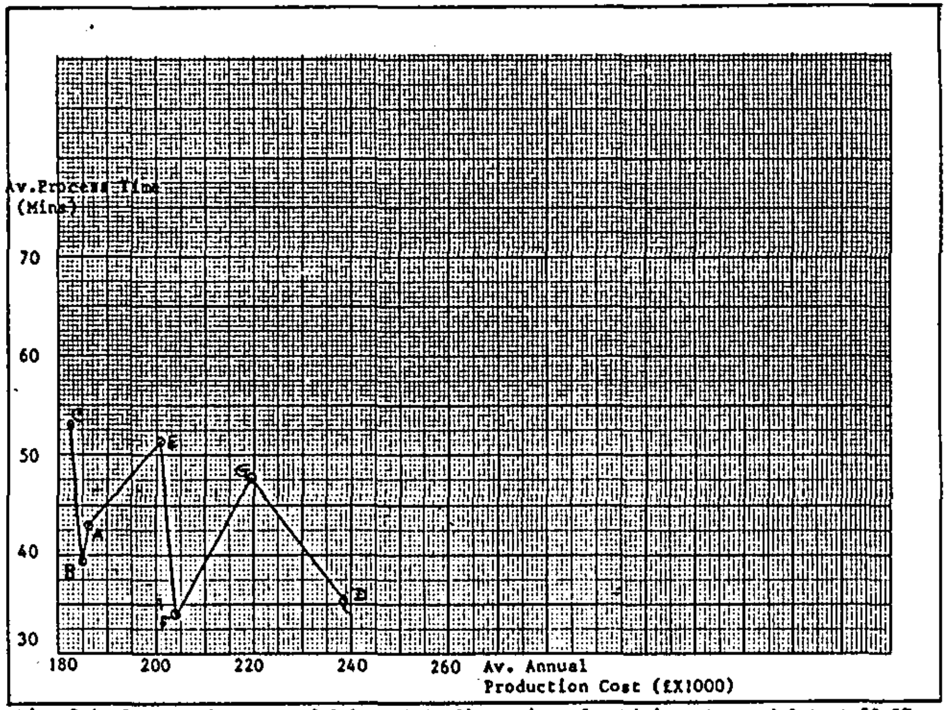


Fig. 7.4: Cost-Performance of Selected Configurations for Minimum Assured Output 52.5%

SYSTEM(men)	C_2	B_3	A_4	E_2	F_3	G_2	D_3
% Output Level Achieved	54.8	66.9	62.1	53.3	55.8	57.8	69.9
Tot.Relative Throughput Time (Hrs)	88.3	81.2	80.9	87.6	61.7	83.3	82.5
Unmanned Production Time (Hrs)	14.8	3.4	1.6	12.8	7.8	6.3	10.5

figures for output and processing time. Hence, capacity can be available for some systems beyond the immediate requirements.

7.7 ADDITIONAL FUTURE COSTS

In the planning of flexible manufacturing systems, scope for the future expansion and integration into networks may have to be built-in. These possible future costs of interfacing and networking could be in the range of 50% - 70% of cost of CIM as reported by Cadiou (1987). Thus, a choice of computer system may be dictated by possible future expansion strategies.

In this study the possibility of the unavailability of primary and/or secondary equipment due to breakdown has not been included in cost estimates (although an estimated cost of maintenance has been included). Some form of condition monitoring may have to be included into the computer information system in the future. This would increase the system costs. From recent reports in the commercial and trade literature, it appears that two thirds of breakdown occurred in hydraulic, electrical and electronic systems which are readily amenable to continuous monitoring.

7.8 INVESTMENT APPRAISAL OF FMS CONFIGURATIONS

The investment appraisal evaluates two groups of preferred selections, i.e. on the basis of an output range of 50 ± 8% and minimum assured output of 52.5%. A fixed output range is helpful for a general comparison of alternative systems. However, since this study is of a specific application the latter approach has been included in order to evaluate the selected systems in relation to a particular sales volume.

It is possible to take two views of investment analysis in examining alternative FMS systems. The previous approach used an annual production cost average over 7 years using the DCF technique. The analysis now proceeds from a conventional investment appraisal viewpoint. Thus a NPV analysis is also performed for the seven alternative systems. The after tax discount rate used is 12%. In assessing the running costs of each configuration it is necessary to include the tax advantage found annually from writing down allowance of capital equipment. The writing down allowance is a statutory 25%. The tax saving is estimated at the rate of 35% of each year's written down value of 25% of capital cost. The annual operating cost is thus decreased by this amount.

The variation in resource mix in the alternative systems and their different performance levels illustrate the difficulties in comparing alternative configurations financially against their manufacturing performance. Thus the financial appraisal of the seven FMS alternatives are now examined in three stages by comparing the NPV cash flows for each case. The calculation of these annual cash flows are included in Appendix I.

7.8.1 COMPARISON BASED ON ANNUAL PRODUCTION COST

The average annual production cost has been plotted against the average process time performance measure for the selected configurations for the output range 50 ± 8%, and minimum assured output of 52.5%. They are also shown in Figs. 7.3 and 7.4 respectively. For the output range (50 ± 8%) the order of increasing production cost of the manual systems is FMS B, A and C. To achieve the minimum assured output, the relative costs are altered for these systems due to the different manpower levels and the order is FMS C, B and A. For both output requirement, the order of increasing cost for the systems with automated transport is FMS E, F, G and D.

7.8.2 NPV ANALYSIS BASED ON EQUAL MANPOWER RESOURCES

The NPV cash flows for the seven FMS configurations have been plotted against the percentage output level in Fig. 7.5 for the 2, 3 and 4 men cases. The values fall broadly into two groups. The conveyor (FMS D), stacker crane (FMS E) and AGV (FMS G) systems requiring higher levels of financial inputs are in one group. The remaining configurations (i.e. FMS A, B, C and F) achieve similar output levels at less cost. The same result may be seen in Fig. 7.6, where NPV cash flows are plotted against average process time. However, at higher manpower levels the FMS D, E, F and G systems do give marginally lower average process times, but at a much higher cost. In particular applications requiring specific output levels, the relative advantages between the alternative systems may appear differently depending upon the manpower levels selected.

In the output range, 42-58%, the systems in order of increasing NPV cash outflow are FMS B, A, C, E, F, G and D (Fig. 7.5). However, for a minimum assured output levelof 52.5% of the forthnightly requirement the order of the first three systems is changed to FMS C, B, and A. This is due to the step changes in resourcing of the alternative systems which result in discrete changes in NPV cash outflows.

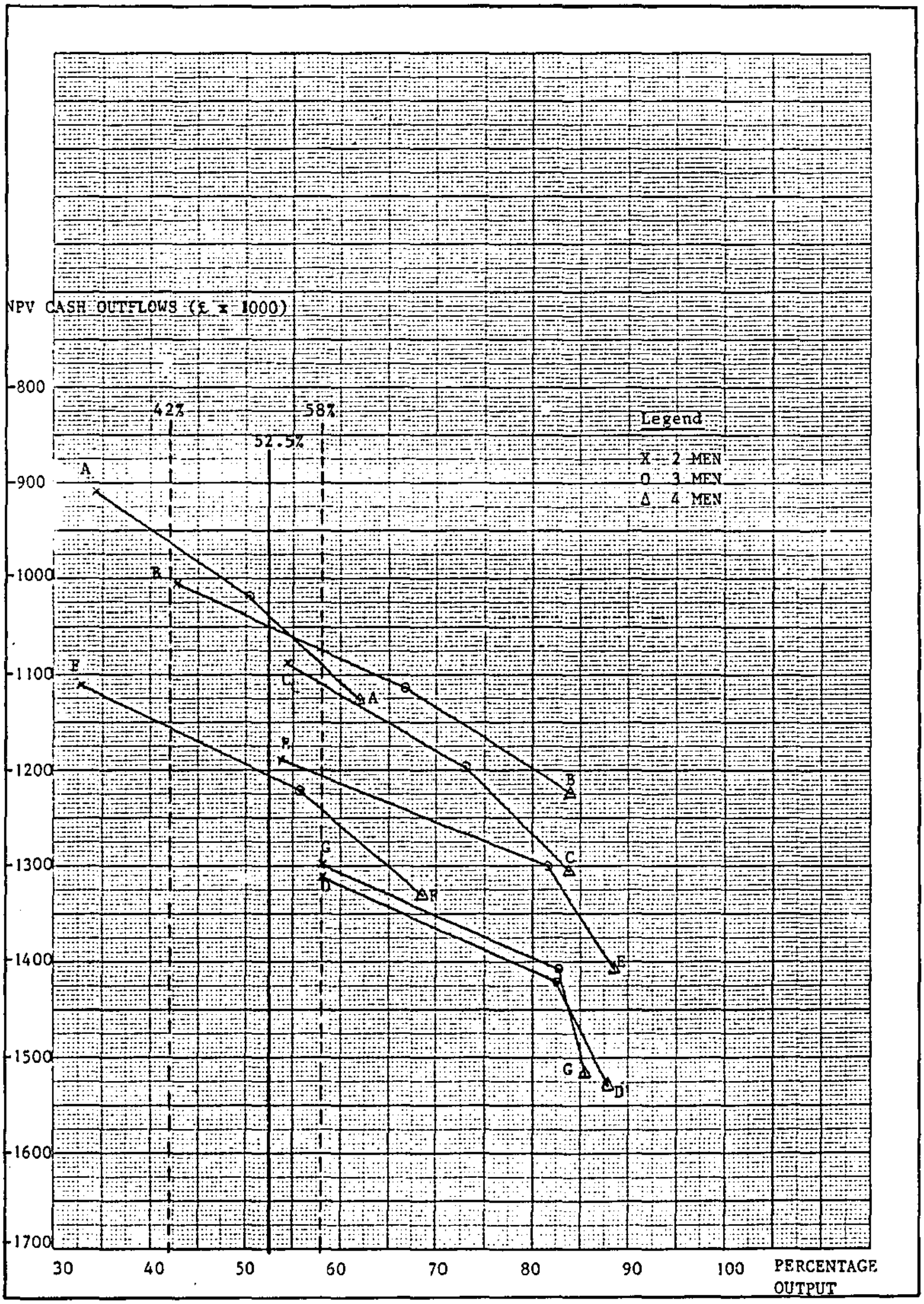


Fig. 7.5: NPV Cash Outflows v.s. Output for Manpower Resources of 2, 3 and 4 Men

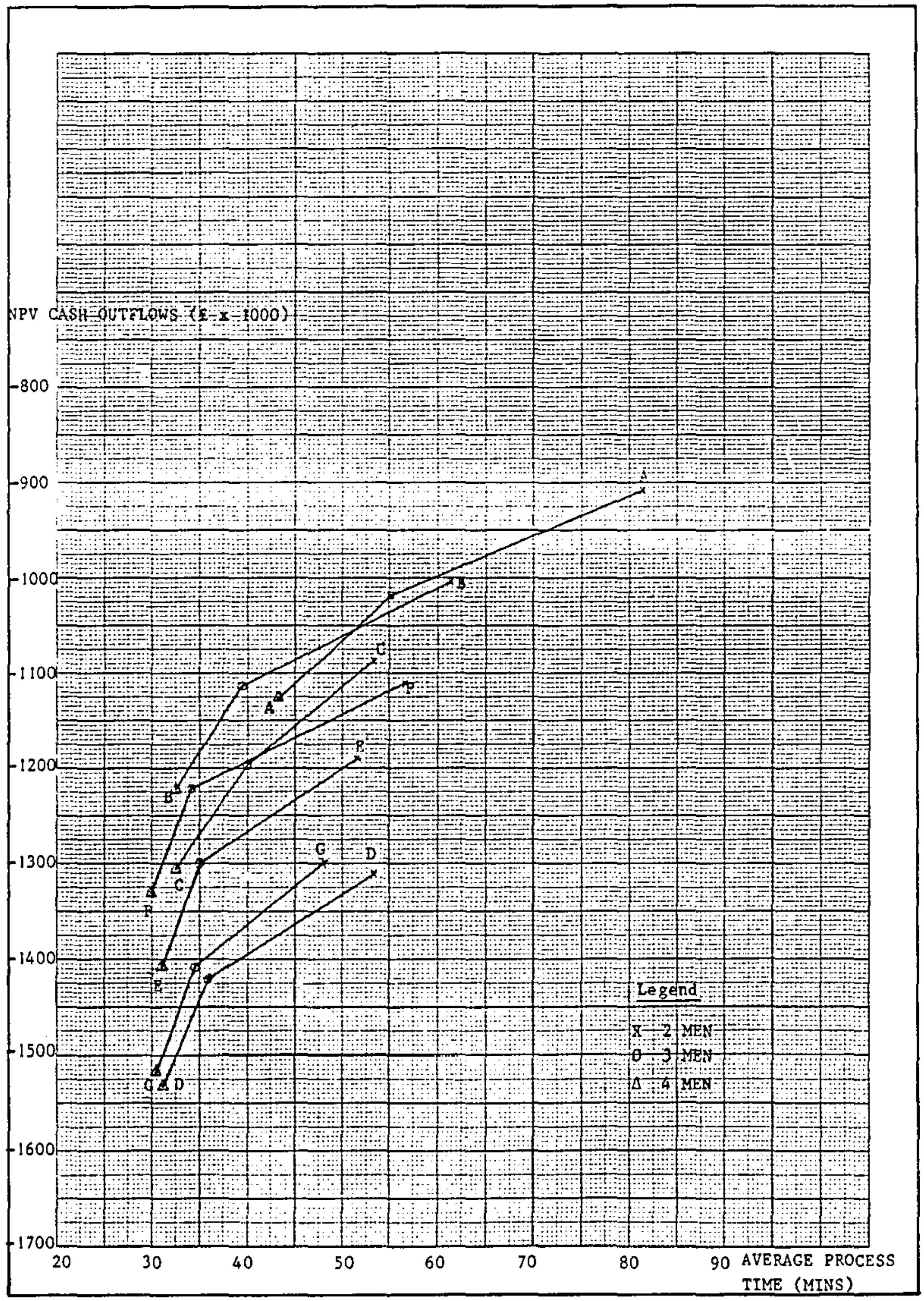


Fig. 7.6: NPVCash Outflows v.s. Average Process Time for Manpower Resources of 2,3 and 4 Men

7.8.3 NPV ANALYSIS BASED ON ASSURED MINIMUM OUTPUT (52.5%)

The graphs of NPV cash outflows against output and average process time are shown in Figs. 7.7(a) and (b) respectively. In relation to FMS A, the configurations FMS B, and C have an increasingly advantageous NPV cash flow position. Of the remaining systems (FMS D, E, F and G) only FMS D gives far better output and process time performance for a much higher NPV cash outflow level. FMS F (rail guided shuttle) has a better NPV cash flow situation than FMS G but yields less output albeit at a much lower process time.

7.8.4 NPV ANALYSIS BASED ON THE OUTPUT RANGE (42-58%)

For an unbiased financial appraisal of the different configurations, an analysis based on selected alternative systems with output level in the range 42 - 58% is examined. The graphs of output and average process time against NPV cash outflows are given in Figs. 7.8(a) and (b) respectively. From Fig. 7.8(b) it is seen that with increasing NPV cash outflow, there is a general improvement in average process time, except for the conveyor system (FMS D). On this basis, the maximum and minimum process time performance is achieved by FMS B and F respectively.

7.9 RANKING OF ORDER OF SYSTEM SUPERIORITY RELATING COST TO AVERAGE PROCESS TIME

The ranking of the seven FMS configurations with respect to production cost, and NPV cash outflows is given in Table 7.7, for the selected output criteria.

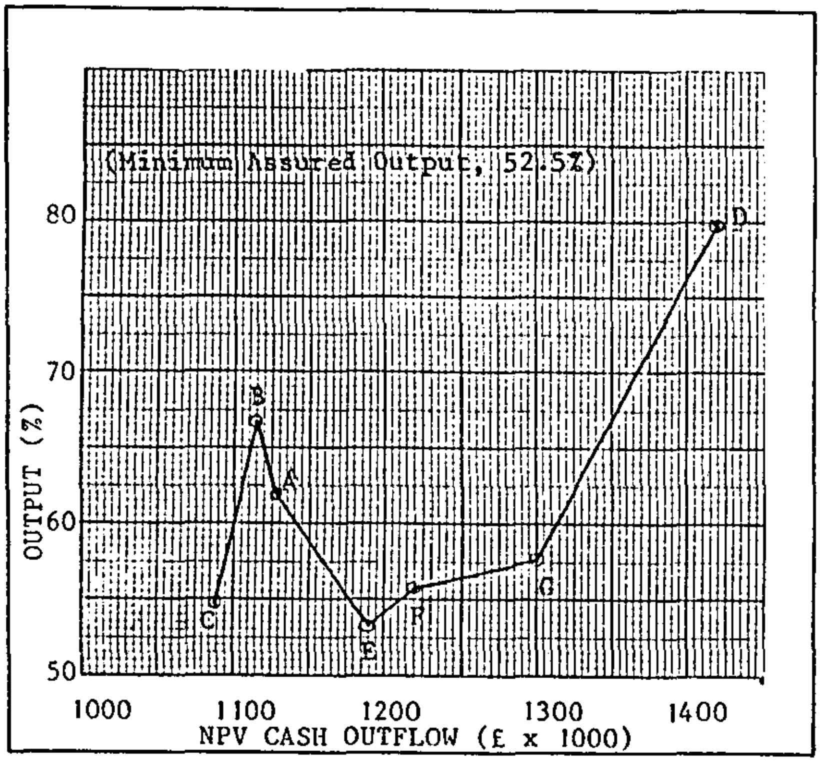


Fig. 7.7a: NPV Cash Outflow v.s. Output

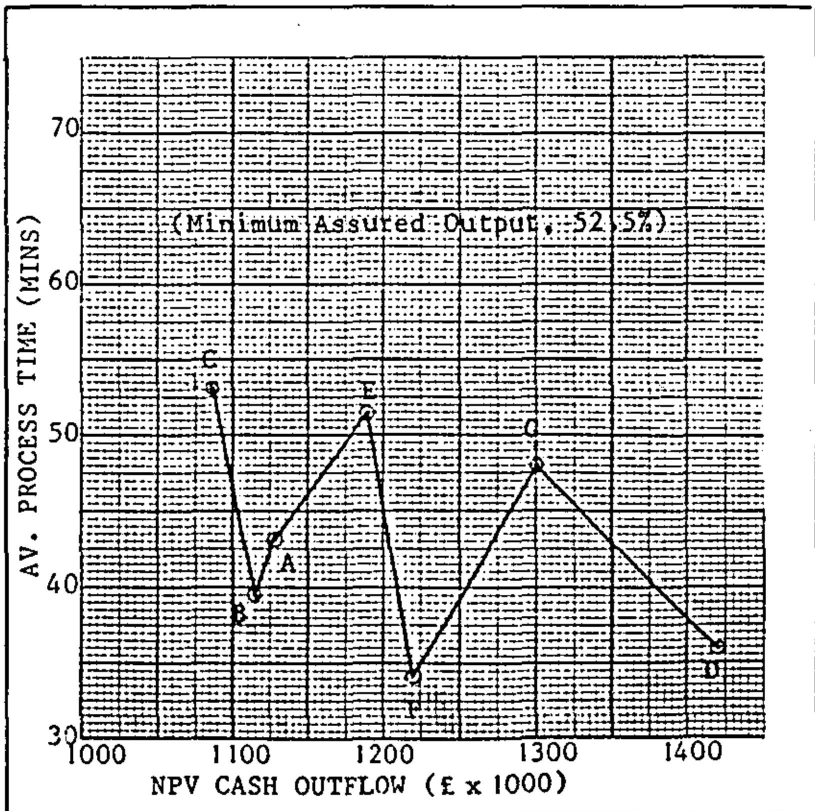


Fig. 7.7b: NPV Cash Outflow v.s. Av. Process Time

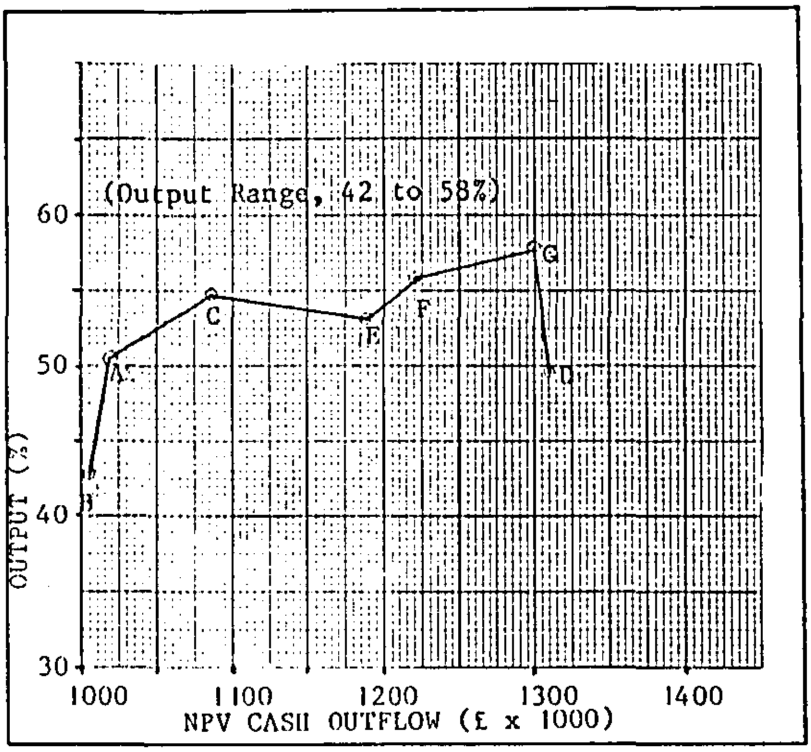


Fig. 7.8a: NPV Cash Outflow V.S Output

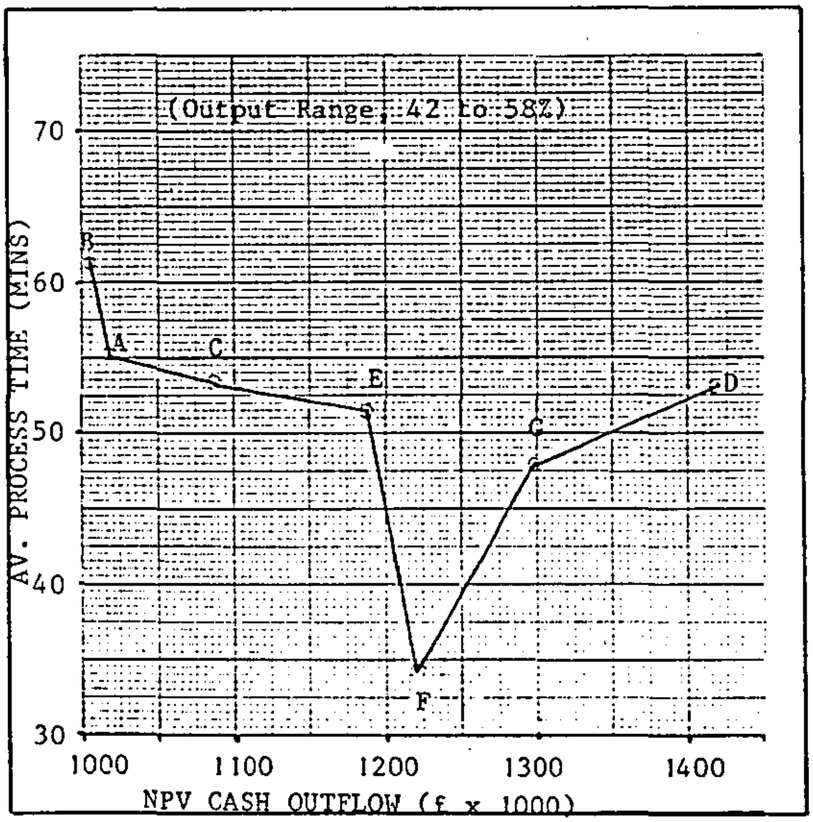


Fig. 7.8b: NPV Cash Outflow v.s. Av.

Process Time

Table 7.7: Ranking of Alternative Systems

OUTPUT	COST METHOD	FMS A	B	C	D	E	F	G
Minimum assured level of 52.5% *	Av. Annual Production Cost	3	2	1	7	4	5	6
	NPV Cash Outflow	3	2	1	7	4	5	6
	Av. Process Time (mins)	43.1	39.6	53.2	35.5	51.7	34.2	48.0
Output range 42-58% *	Av. Annual Production Cost	2	1	3	7	4	5	6
	NPV Cash Outflow	2	1	3	7	4	5	6
	Av. Process Time (mins)	55.3	61.4	53.2	53.0	51.7	34.2	48.0

* See Figs. 7.3 and 7.4 for the different output levels obtained by each system and their associated resources.

The ranking of the system configurations according to the two methods of costing (i.e. Production Cost and NPV) is the same in each of the output levels. However, there is a slight difference in the ranking across the two output categories for FMS A, B and C. The rankings of the automated systems FMS D, E, F and G are the same. The difference in the rankings for the former group is clearly due to the varying manpower resourcings for the three manual transport systems under the two output requirements. FMS F (rail guided shuttle) has a markedly lower average processing time, but this is achieved at a higher cost. Costwise, System F is ranked fifth. For the minimum assured output level of 52.5%, FMS D achieves the same order of process time performance and higher output level but at an even greater cost, and is ranked seventh.

The cost appraisal performed in this section is on the basis of direct implementation of the alternative systems. This was because the configurations were evaluated individually in terms of cost and performance measures. However, a limited investigation of any financial advantage to be gained by the acquisition of some of the more automated systems (e.g. FMS C, D, E, F and G) on an incremental basis is now performed.

CHAPTER 8

FEASIBILITY OF INCREMENTAL AUTOMATION

8.1 INTRODUCTION

FMS development is capable of incremental automation. Salomon and Biegel (1984) reported the possibility of saving up to 12% in capital recovery costs if an FMS is implemented on an incremental basis as compared to direct automation. A limited exploratory examination has therefore been conducted of the estimated costs of various sequences of incremental automation in the particular industrial application in this study. The different sequences of incremental automation selected from the alternative systems developed are compared with direct automation. The sequences are classified into two groups - single stage and two stage incremental automation. The comparison is based on the NPV approach, and the cash flows are included in Appendix J.

8.2 SELECTED ROUTES TO INCREMENTAL AUTOMATION

8.2.1 TWO STAGE INCREMENTAL AUTOMATION

If the benefits of incremental automation is to be assessed, the simplest basic system would be FMS A. This could be followed by the addition of two pallet stations APC to machining centres resulting in FMS B. Finally, there is a choice in further automation of FMS B, i.e. introduction of an automated transport system or increasing the pallet station capacity at the machines.

FMS C is an example of the latter form of automation. FMS D, E, F and G are systems with different types of automated transport. The relative NPV cash outflow positions of the above systems have been examined in Chapter 7 for the two levels of output achievement. (See Figs. 7.7 and 7.8).

The financial consequences of the five routes to two stage incremental automation over a seven year period for the output range, 42-58%, and minimum assured output of 52.5% are shown in Table 8.1. It is observed that the ranking of the automated systems on the basis of NPV cash outflow, for both output levels, is altered slightly in order of decreasing superiority to: FMS F, E, G and D. In comparing the different methods of automation, it is assumed that FMS A is installed at the beginning of the first year, FMS B in the third year, and followed by FMS C, D, E, F or G in the fifth year. The NPV cash outflows have been calculated using a discount rate of 12%. Additionally, investment costs over the seven year time span have been adjusted for an assumed inflation rate of 3% The method of spreading investment costs has been on the basis of differences between the costs of the alternative systems. No allowances were made for additional expense which may be associated with the delayed fitting. However, since the installation and engineering costs for the systems (excepting FMS C) vary, a part of this cost has thus been included in computing the differences in investment costs for FMS D, E, F and G, relative to FMS A and B.

8.2.2 SINGLE STAGE INCREMENTAL AUTOMATION

From Figs. 7.7(b) and 7.8(b) it is observed that the NPV cash outflow of FMS B is less than that of FMS A under both output

Table 8.1: Two Stage Incremental Automation

FINAL SYSTEM	NPV CASH OUTFLOWS (£)			
	DIRECT AUTOMATION		INCREMENTAL AUTOMATION	
	OUTPUT RANGE, 42-58%	MINIMUM ASSURED OUTPUT, 52.5%	OUTPUT RANGE, 42-58%	MINIMUM ASSURED OUTPUT, 52.5%
C	-1,086,727	-1,086,727	-1,087,201	-1,156,125
D	-1,309,910	-1,419,169	-1,247,953	-1,357,741
E	-1,189,286	-1,189,286	-1,161,726	-1,230,650
F	-1,221,089	-1,221,089	-1,145,665	-1,214,589
G	-1,298,430	-1,298,430	-1,239,227	-1,308,151

Table 8.2: Single Stage Incremental Automation

FINAL SYSTEM	NPV CASH OUTFLOWS (£)			
	DIRECT AUTOMATION		INCREMENTAL AUTOMATION	
	OUTPUT RANGE, 42-58%	MINIMUM ASSURED OUTPUT, 52.5%	OUTPUT RANGE, 42-58%	MINIMUM ASSURED OUTPUT, 52.5%
C	-1,086,727	-1,086,727	-1,070,465	-1,175,790
D	-1,309,910	-1,419,169	-1,246,635	-1,351,960
E	-1,189,286	-1,189,286	-1,152,011	-1,256,706
F	-1,221,089	-1,221,089	-1,089,608	-1,194,933
G	-1,298,430	-1,298,430	-1,237,215	-1,342,539

conditions. It is thus possible that incremental automation may be achieved in a single stage, i.e. starting with FMS B in the first year and automating to FMS C, D, E, F or G in the third year. The same discount and inflation rates as for two stage incremental automation have been employed. The NPV cash outflows for the two output conditions are included in Table 8.2. The ranking in decreasing order of system superiority is again FMS F, E, G and D.

8.3 INCREMENTAL V.S. DIRECT AUTOMATION

The incremental NPV cash outflow changes (ΔNPV) are given by

$$\Delta NPV = NPV_I - NPV_D$$

where, NPV_D and NPV_I are the NPV cash outflows for direct and incremental implementation respectively. The incremental NPV cash outflows (ΔNPV) are shown in Table 8.3 for single and two stage automation under both output conditions. A positive sign indicates a favourable position relative to direct implementation of a particular system, since the NPV cash outflow for incremental automation is less than that for direct automation. The notation indicates the system changes and their manpower resourcings.

In the output range, 42-58%, single stage incremental automation is preferable to direct automation for all systems. FMS F (rail guided shuttle) yields the highest cumulative benefit in terms of NPV cash outflow, i.e. £131,481 over 7 years. FMS D and G yield an incremental benefit of just over £60000, whereas FMS E achieves nearly £38000. Single stage incremental automation of FMS C results in a relatively modest NPV benefit of £16,262.

Table 8.3: Incremental NPV Cash Outflows (£)

OUTPUT RANGE, 42-58%			MINIMUM ASSURED OUTPUT, 52.5%		
SYSTEM** CHANGE*	SINGLE STAGE (ΔNPV)+	TWO STAGE (ΔNPV)	SYSTEM** CHANGE*	SINGLE STAGE (ΔNPV)	TWO STAGE (ΔNPV)
A3→(B2→C2)	+16,262	-474	A4→(B3→C2)	-89,063	-69,398
A3→(B2→D2)	+63,275	+61,957	A4→(B3→D3)	+67,209	+61,428
A3→(B2→E2)	+37,275	+27,560	A4→(B3→E2)	-67,420	-41,364
A3→(B2→F3)	+131,481	+75,424	A4→(B2→F3)	+26,159	+ 6,500
A3→(B2→G2)	+ 61,215	+59,203	A4→(B3→G2)	-44,109	- 9,721

* The number against the system identity indicates the manpower resourcing.

** The single stage incremental system changes are enclosed in brackets.

+ Positive incremental NPV changes indicates a favourable position for incremental automation.

For a minimum assured output of 52.5%, direct automation of FMS C, E and G is more advantageous. If incremental automation is to be considered at all for any reason, two stage incremental automation appears preferable in comparison with single stage automation. Single stage incremental automation of FMS D and F is superior to both direct and two stage automation. It is observed that FMS F yields the lowest average processing time performance, and for a minimum assured output of 52.5% FMS D achieves nearly the same performance.

8.4 CONDITIONS FOR INCREMENTAL AUTOMATION

It is observed that incremental automation of FMS C, E and G, involves a slightly higher cost penalty for a minimum assured output level of 52.5%. The benefit of incremental investment over the first five years is nullified by the cost of additional manpower required to operate the cell as FMS A and B in the initial years. Incremental automation of FMS F and G seems more favourable at lower output requirements (42-58%).

An examination of the system changes and their associated manpower levels appears to indicate that incremental automation is more attractive for two conditions. Firstly, if the manpower requirement over the timespan remains constant or the additional direct labour costs in earlier years is not greater than the savings created by spreading investment costs over time. Additionally, lower manpower levels seems to favour incremental automation. This form of automation would thus be more viable if increased levels of sales are forecast over the timespan. However, for higher sales levels it may be necessary to increase manpower since higher output may be obtained in this way than incremental automation with constant direct labour content.

Moreover there is the problem of manpower planning for the period of time over which the investment is to be spread. It may not be realistic to commence operation of a cell with 4 men per shift and decreasing the manpower level as more automation is introduced. However, it may be possible to do so if the excess manpower may be utilised in other departments in an organisation. A longer timespan would naturally mitigate this problem more amenably.

The appraisal of incremental automation in comparison with direct implementation would alter with a change in the discount rate. This rate is generally chosen to reflect the cost of capital. However, this varies for debt and equity capital. The rate for the former is lower than the latter (e.g. 10-14%), whereas the cost of equity capital would be at a rate over the dividend rate (e.g. 24-28%). Thus, the capital gearing in a particular company would determine the cost of capital, since it is linked with a given level of interest. The higher the debt in relation to the equity the greater the risk to the lenders and the greater, therefore, the interest they will expect on their loan.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

The flexible machining systems modelled in this study pertain to the conditions relating to a required rate and volume of output existing in a particular company. A method of performing cell formation has been modified and applied to a range of parts produced in the firm. The study has concentrated subsequently on one cell for the machining of prismatic parts.

Conclusions drawn relate to the conditions and requirements in the factory. The conditions embrace:

(i) A specific output volume,

(ii) Two week period batch production,

(iii) A range of some 147 parts for a particular product line,

(iv) Some parts are dedicated to particular types of machine,

(v) A part spectrum with varying machining times,

(vi) Single stage machining with a maximum of two fixture set ups,

(vii) A specific mixed mode basis of scheduling.

Additionally, since the length of the simulation run has had to be limited to one week's production the systems have been examined on the basis of two output criteria, namely (a) a minimum assured output level of 52.5%, and (b) an output range centering on 50% (ranging from 42 to 58%), of the two week period batch production requirements. These output conditions have resulted from preferred conditions for the different systems. The resource variables of these preferred conditions encompass manpower, shift system, in-process pallet storage stations, the number of automated pallet changing stations, and pallets or trolleys.

9.1.1 FMS CELL FORMATION

(a) A modification introduced into Rajagopalan and Batra's method is shown to advantage by application in this study. The analysis is based on minimum machine requirement analysis. The procedure enables the analysis to proceed without having to make arbitrary choices. Hence the routine illustrated manually can be fully computerised.

(b) The method enables the analysis to incorporate other operational conditions beyond those required in this study as, for example, an interlinking of cells through materials handling facilities, central storage with individual cell buffer stocks, duplication of machines to give cell independence.

9.1.2 PERFORMANCE AND EVALUATION OF ALTERNATIVE SYSTEMS

The superiority of one system in relation to another has been examined by relating cost to performance measures. Average processing time has been given principal attention due to the importance of output rate. Conclusions are drawn in regard to the two output levels noted in Section 9.1.

In assessing the costs of alternative systems, two forms of financial analysis have been used, viz. (i) average annual production cost incorporating discounting techniques, and (ii) investment analysis using conventional NPV method. Both methods show agreement in the orders of system superiority. However, in appraising the quantitative effects in cost terms of the ranking order of superiority of the alternative systems, the choice between methods of costing could well tend towards using investment analysis since appraisals for incremental change in the systems will be assisted.

Indications have been obtained from a limited exploration of the financial advantage associated with a limited choice of the various sequences and timings of incremental automation which could be implemented.

Production Costs and NPV Cash Outflows

(a) The testing by simulation has shown order of superiority and associated preferred resources in regard to production and investment cost of obtaining output in the range of 42% to 58% of required volume, as shown in the table below. The cost for FMS B has been taken as unity, thus giving a proportionate comparison cost.

ORDER	1	2	3	4	5	6	7
SYSTEM	B	A	C	E	F	G	D
PRODUCTION COST	1.000	1.003	1.085	1.192	1.215	1.305	1.317
NPV CASH OUTFLOW	1.000	1.012	1.081	1.183	1.215	1.291	1.303

(b) Looking beyond this category of output performance the relative advantage of systems in regard to average process time was as follows:

ORDER	1	2	3	4	5	6	7
SYSTEM	B	A	C	E	F	G	D
AV. PROCESS TIME	1.000	0.901	0.866	0.842	0.557	0.782	0.863

(c) In this range of output clear advantages are reflected for all systems with their selected "preferred" resources in regard to average process time. However, such advantage would be accompanied by increasing costs of the order identified in conclusion (a) and amplified in section 7.8.

(d) Marked differences arise in the relative cash outflows between the groups of systems B, A, C and E, F. G. D. However, FMS F, has reflected to greater advantage in achieving a significant lower average process time. (In viewing the average process time by comparison with percentage output levels; we keep in mind that it includes idle times, machining times, fixturing times, and is influenced by different operational procedures).

(e) Testing for an order of cost superiority related to a minimum assured output level of 52.5% gave the following result:

ORDER	1	2	3	4	5	6	7
SYSTEM	C	B	A	E	F	G	D
PRODUCTION COST	1.0000	1.018	1.020	1.099	1.120	1.203	1.310
NPV CASH OUTFLOW	1.000	1.026	1.037	1.094	1.124	1.195	1.306

The difference compared to (a) is confined to the first three places. FMS C takes first place followed by B and then by A. The cost and performance analysis has confirmed that increasing the number of pallet stations (in this study up to 4) associated with CNC machines shows to production cost advantage.

(f) The comparative figures for processing times for the minimum assured output of 52.5% are given in the Table below:

ORDER	1	2	3	4	5	6	7
SYSTEM	C	B	A	E	F	G	D
AV.PROCESS TIME	1.000	0.744	0.810	0.971	0.643	0.902	0.660

FMS D and F have similar improved processing time performance. However, considerable advantage has been found for FMS D in percentage output. This is due in FMS D to the conveyor transport being continuously available, where as FMS F is dependent on the availability of the rail guided shuttle transporter. Additionally FMS D has a higher manpower level and lower numbers of pallets and in-process pallet stations storage than FMS F.

Machine Utilisation

(g) The machine utilisation levels varied between 26.8% to 51.1%, as shown in the Table below:

SYSTEM	A	B	C	D	E	F	G
OUTPUT							
Min. 52.5%	39.2	42.6	33.0	51.1	32.9	48.4	36.3
Range, 42-58%	32.4	26.8	33.0	31.2	32.9	48.4	36.3

The results suggest that machine utilisation under the conditions and resourcing tested will tend to be higher for systems D and F, that is for the conveyorised and rail guided shuttle systems. The comparatively low levels indicate a strong potential for improvement by reducing non productive time attributable to machine loading and unloading for manually controlled systems A, B and C. In automated systems, machine utilisation may be increased by more effective prioritisation of manual activities (e.g. tool loading, part loading and unloading, and fixturing or defixturing pallets).

Manpower Utilisation

(h) The manpower requirements in the seven models to achieve the required output varied between 4 and 2 men. FMS C, E and G had the lowest manpower requirement of 2 men for the minimum assured output level required in this study.

(i) It can be expected that increased manpower levels improve average processing time and machine utilisation. This has been shown to be marked at low manpower levels as shown in the Table below. (Performance of FMS A with 2 men is used as a unit base of comparison). When increasing manpower from 2 to 3 men, the improvement is marked, but there is lesser degree of improvement when increasing manpower level from 3 to 4 men.

	SYSTEM	2 SHIFTS/DAY A	B	C	D	E	F	G
PROCESS TIME	2 men	1.00	0.75	0.65	0.65	0.63	0.69	0.59
	3 men	0.68	0.49	0.46	0.44	0.44	0.42	0.42
	4 men	0.53	0.40	0.41	0.37	0.38	0.37	0.39
MACHINE UTILISATION	2 men	1.00	1.24	1.52	1.44	1.52	1.47	1.68
	3 men	1.49	1.97	2.09	2.36	2.37	2.23	2.41
	4 men	1.81	2.55	2.41	2.81	2.69	2.66	2.66

(j) The ratio of manpower utilisation for Fixturing:Machine/Pallet Loading:Tool Loading is approximately (1:2:3) for the automated transport systems. For FMS A, B and C they are in the order of (4½:2:3), (1:1 1/3:2) and (1:1:2). Thus in automated systems tested in this study, tool loading accounted for nearly half the manpower utilisation, and machine/pallet loading absorbed nearly a third of the manpower utilisation. In manual systems, the results have shown, as we would expect, that fixturing and machine/pallet loading occupies the operators to a greater degree, although with a larger number of pallet stations at the machine, this decreases.

AGVs and Transport System Utilisation

(k) Under the conditions studied no advantage in output processed has been found when using 3 compared to 2 AGVs.

(l) In comparing the utilisation of the more automated transport systems with the higher numbers of operators, decreasing utilisation levels were obtained in the order - FMS D (conveyor), E (stacker crane), F (rail guided shuttle), G (AGV). (See Fig. 6.10 for the relative levels of utilisation).

APC and In-Process Pallet Station Capacity

(m) The advantage of increasing pallet station capacity from 0 (FMS A) to 2 (FMS B) and then to 4 (FMS C) shows clear advantage in reducing manpower from 4 to 3 and again to 2 men, in relation to the minimum assured level of output.

(n) Naturally, the output from the seven systems shows some sensitivity to the In-Process storage capacity and the number of pallets in the system. The choice of storage limit and number of pallets chosen for the testing has not revealed a marked influence.

Unmanned Operation and Shift Working

(o) Two shift working has been found to be necessary to achieve the output volume requirements. This reflects to advantage with unmanned operation. With the forms of systems examined this advantage was modest to the extent of some 2 to 15 hours per week of production, with FMS C and E giving the highest unmanned working advantage (see Section 6.2.5).

(p) Comparing output performance for the same daily manpower level of 6 men on either 3 men/2 shift or 2 men/3 shift basis, it has been found that FMS E (stacker crane) had slightly higher output on the former, and FMS F (rail guided shuttle) showed a positive advantage on the latter shift manning arrangement. Little difference has been found between the arrangements for the other systems.

Direct and Incremental Automation

(q) An exploratory appraisal for a discount rate of 12% has been conducted for the possible benefits of incremental automation. In the output range, 42 to 58%, single stage incremental automation yields higher cost benefit in NPV terms. For a minimum assured output of 52.5%, direct automation is preferable for FMS C, E and G; but single stage incremental automation of FMS D and F results in a more favourable NPV cash outflow position.

On a more general note, it appears that incremental automation is advantageous for lower manpower levels, and if manpower requirement over the timespan remains constant. The appraisal of incremental automation would depend on the capital gearing in a particular company.

Cost Benefit Appraisal

(r) It is recognised that in the cost-benefit examination of alternative FMS systems there are many variables which influence various measures of performance. The interrelated appraisal of measures of attainment will require some degree of judgement to be exercised in reaching decisions on the form of system to be selected to meet particular industrial company requirements.

9.2 RECOMMENDATIONS FOR FURTHER WORK

(a) Recommendations for further development of the method for flexible cell formation have been made in Chapter 3 for various system and operational conditions.

(b) Further simulation and analysis may be performed to investigate the sensitivity of performance indicators to different numbers of pallet stations and part carriers (i.e. pallets and trolleys).

(c) Simulation should be conducted of the other two cells to be developed in the company for the machining of disc/disc gear and shaft/shaft gear parts leading to a global simulation of the network of three cells in the company.

(d) The effect of allocation of manpower to different combination of machining centres may also be examined.

(e) The performance of different manual activities by various specific combinations of men, and the resulting influence on the performance measures may also be determined by further simulation studies.

(f) The cost effectiveness of the FMS cell studied for different sales volumes could be examined to advantage of the company.

(g) An analysis of the financial effect of incremental automation in the company as a whole, would assist investment decision making.

(h) The benefit of automated tool magazine loading may be investigated in terms of cost and performance measures.

(i) The influence of machine unavailability on system performance could be studied by further simulation tests.

(j) The effect of breakdown of the automated transport systems and subsequent intermittent operation as a manual CNC cell may also be examined.

(k) The effect of different numbers of machines and scheduling procedures on cell performance may be investigated further.

(l) The influence of different discount rates on system appraisal may also prove worthwhile for further investigation.

(m) As we advance in our knowledge of Artificial Intelligence, Expert Systems and Relational Database Structures, then it may be possible to integrate the different parts of the methodology for evaluation of alternative FMS systems. The resulting flexible and modular simulation software with interactive graphical capabilities would eliminate a substantial part of the total lead time required for system evaluation. This would naturally have an impact on costs incurred.

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APPENDIX A

PRODUCT AND PART DATA

Page

APPENDIX A

A.1: PRODUCT SPECTRUM AND DEMAND DISTRIBUTION

PRODUCT TYPE				PRODUCT CHARACTERISTICS						DEMAND
MODEL		SUB-ASSEMBLY		PROPERTY A		PROPERTY B		PROPERTY C		per yr.
ACH	9		0	¾ Ton	1					566
"	9		0	1½ "	2					304
"	9		0	3 "	3					61
BCH	8		0	¾ "	1					628
"	8		0	1 "	2					304
"	8		0	3 "	3					162
CCH	7		0	¾ "	1					264
"	7		0	1½ "	2					792
"	7		0	3 "	3					1344
DCH	6		0	1/8-1 Ton	1					255
"	6		0	2-3 "	2					255
ECH	5		0	½ Ton	1					2000
"	5		0	1 "	2					2200
"	5		0	2 "	3					3000
FECH	4		0	¼ "	1	Single Speed	1			190
"	4		0	¼ "	1	Dual Speed	2			190
"	4		0	¼ "	1	Full Speed	3			190
" "	4		0	½ "	2	Single Speed	1			179
"	4		0	½ "	2	Dual Speed	2			179
"	4		0	½ "	2	Full Speed	3			179
"	4		0	1 "	3	Single Speed	1			173
"	4		0	1 "	3	Dual Speed	2			173
"	4		0	1 "	3	Full Speed	3			173
GWRH	1	Gear Box	1	0.8 Ton	1	10/20m/min	1			143
"	1		1	0.8 "	1	32 m/min	2			18
"	1		1	1.0 "	2	10/20m/min	1			145
"	1		1	1.0 "	2	32 m/min	2			18
"	1		1	1.6 "	3	10/20m/min	1			190
"	1		1	1.6 "	3	32 m/min	2			55
"	1		1	3.2 "	4	10/20m/min	1			88
"	1		1	3.2 "	4	32 m/min	2			40
"	1		1	5.0 "	5	10/20m/min	1			46
"	1		1	5.0 "	5	32 m/min	2			28
"	1	Crab	2	3.2 "	1	Long/Short	1			29
"						Drum	2			
"	1		2	6.3 "	2	"	1			68
"						"	2			
"	1		2	12.5 "	3	"	1			58
"						"	2			
"	1		2	20 "	4	"	1			55
"						"	2			
"	1	Trolley	3	3.2 "	1	"	1			206
"						"	2			
"	1		3	6.3 "	2	"	1			155
"						"	2			
"	1		3	12.5 "	3	"	1			43
						"	2			
HECH	4		0	3 "	4	"	1			100
							2			

APPENDIX A

A1.2: PART/PRODUCT DATA FILE

PART		QTY	DEMAND	PRODUCT TYPE									SIZE* A	SIZE* B
CODE		(/ Part)	(Per Yr)	1	2	3	4	5	6	7	8	9	RANGE	RANGE
001	8	1		901									1	2
002	7	1		902	903								1	5
003	7	1		902	903	802	803	702	703				2	2
004	7	1		801	901								1	2
005	7	1		902	903	802	803						1	5
006	2	1		901									1	
007	2	1		902	903								1	
008	2	1		801									1	
009	2	1		802	803								1	
010	2	1		701									1	
011	2	1		702	703								1	
012	3	1		901	902	903	801	802	803	701	702	703	1	
013	2	1		901	902	903	801	802	803	701	702	703	3	
014	3	2		903									1	
015	3	2		703									1	
016	3	1		803									1	
017	2	1		903									1	
018	2	1		903									1	
019	2	1		803									1	
020	2	1		703									1	
021	6	1		601									2	1
022	6	1		602									2	1
023	7	1		601	602								1	1
024	7	1		601									2	2
025	7	1		602									2	2
026	2	1		601	602								1	
027	2	1		601	602								1	
028	2	1		601	602								1	
029	7	1		501									1	1
030	7	1		502									1	1
031	7	1		503									2	1
032	7	2		501									1	1
033	7	2		502									1	1
034	7	2		503									1	1
035	6	1		501									2	1
036	6	1		502									2	1
037	6	1		503									2	1
038	6	1		501									2	1
039	6	1		502									2	1
040	6	1		503									2	1
041	6	1		4011	4012	4013							1	1
042	6	1		4021	4022	4023							2	1
043	6	1		4031	4032	4033							2	1
044	7	1		4011	4012	4013							1	1

*The product size range parameters are described in Appendix A3.

APPENDIX A

A.2: PART/PRODUCT DATA FILE (CONTD)

PART		QTY	DEMAND	PRODUCT TYPE									SIZE* A	SIZE* B
CODE		(/ Part)	(Per Yr)	1	2	3	4	5	6	7	8	9	RANGE	RANGE
045	7	1		4021	4022	4023							1	2
046	7	1		4031	4032	4033							2	2
047	7	1		4011	4012	4013							1	1
048	7	1		4021	4022	4023							1	2
049	7	1		4031	4032	4033							1	2
050	7	1		4011									2	1
051	7	1		4021									2	2
052	7	1		4031									3	2
053	7	1		4012									2	1
054	7	1		4022									2	2
055	7	1		4032									3	2
056	7	1		4013									2	1
057	7	1		4023									2	2
058	7	1		4033									3	2
059	6	1		4011	4012								2	1
060	6	1		4021	4022								3	1
061	6	1		4031	4032								4	1
062	6	1		4013									2	1
063	6	1		4023									2	2
064	6	1		4033									3	2
065	2	1		4011	4012	4013							2	
066	2	1		4021	4022	4023							2	
067	2	1		4031	4032	4033							3	
068	2	1		4011	4012	4013							2	
069	2	1		4021	4022	4023							2	
070	2	1		4031	4032	4033							3	
071	2	1		404									2	
072	2	2		404									2	
073	6	1		4011	4012	4013							1	1
074	6	1		4021	4022	4023							1	1
075	6	1		4031	4032	4033							2	1
076	3	2		4011	4012	4013	4021	4022	4023				2	
077	3	2		4031	4032	4033							2	
078	3	2		4041	4042								2	
079	7	1	1	1311	1312	1321	1322						1	1
080	6	1		1311	1321								1	1
081	8	1		1311	1312	1321	1322						1	1
082	6	1		1311	1312	1321	1322						1	3
083	7	1		1311	1312	1321	1322						1	3
084	7	1		1311	1312								1	2
085	6	1		1312	1322								2	1
086	6	1		1312	1322								1	2
087	6	1		1332									3	1
088	7	1		1332									1	2
089	7	1		1331	1332								1	2
090	6	1		1331									2	1

*The product size range parameters are described in Appendix A3.

APPENDIX A

A·.2: PART/PRODUCT DATA FILE (CONTD)

PART CODE		QTY (/ Part)	DEMAND (Per Yr)	PRODUCT TYPE 1	2	3	4	5	6	7	8	9	SIZE*A RANGE	SIZE*B RANGE
091	7	1		1312	1322								1	2
092	6	1		1331	1332								3	1
093	6	1		1331	1332								1	3
094	7	1		1331									1	2
095	8	1		1211	1212	1221	1222						2	1
096	7	1		1211	1212	1221	1222						1	1
097	8	1		1231	1232								2	1
098	7	1		1231	1232								1	1
099	7	1		1111	1112	1121	1122						1	3
100	6	1		1111	1112	1121	1122						3	1
101	7	1		1111	1112	1121	1122						3	2
102	7	1		1111	1112	1121	1122						1	1
103	6	1		1111	1112								5	2
104	6	1		1111	1112	1121	1122						3	1
105	7	1		1111	1112								1	2
106	6	1		1121	1122								3	1
107	7	1		1121	1122								1	2
108	7	1		1131	1132								2	2
109	6	1		1131	1132								4	2
110	7	1		1131	1132								3	2
111	6	1		1131	1132								4	2
112	6	1		1131	1132								4	1
113	6	1		1131	1132								3	1
114	7	1		1131	1132								1	2
115	7	1		1141	1142	1151	1152						2	4
116	6	1		1141	1142	1151	1152						5	2
117	7	1		1141	1142	1151	1152						3	2
118	7	1		1141	1142	1151	1152						2	4
119	6	1		1141	1142	1151	1152						5	2
120	6	1		1141	1142	1151	1152						4	1
121	7	1		1141	1142	1151	1152						1	2
122	2	1		1311	1312								4	
123	3	1		1111	1112	1121	1122						3	
124	3	1		1131	1132								3	
125	3	1		1141	1142								4	
126	3	1		1111	1112	1121	1122						3	
127	3	1		1131	1132								3	
128	3	1		1141	1142								4	
129	3	1		1111	1112	1121	1122						2	
130	3	1		1131	1132								2	
131	3	1		1141	1142								3	
132	2	1		1111	1112	1121	1122						2	
133	2	1		1131	1132								2	
134	2	1		1141	1142								3	
135	1	1		1111									3	
136	1	1		1131									3	
137	1	1		1132									3	

*The product size range parameters are described in Appendix A3.

APPENDIX A

A·.2: PART/PRODUCT DATA FILE (CONTD)

PART CODE		QTY (/ Part)	DEMAND (Per Yr)	PRODUCT TYPE 1	2	3	4	5	6	7	8	9	SIZE*A RANGE	SIZE*B RANGE
138	1	1		1141									3	
139	1	1		1141									3	
140	1	1		1111									3	
141	1	1		1131									3	
142	1	1		1112									3	
143	1	1		1151									3	
144	1	1		1151									3	
145	1	1		1152									3	
146	1	1		1142									3	
147	1	1		1312									3	
148	1	1		1312									3	
149	1	1		1312									3	
150	1	1		1312									3	
151	1	1		1321	1322								4	
152	1	1		1321	1322								4	
153	1	1		1321	1322								4	
154	1	1		1321	1322								4	
155	1	1		1211	1212								1	
156	1	1		1211	1212								1	
157	1	1		1211	1212								1	
158	1	1		1211	1212								1	
159	1	1		1211	1222								2	
160	1	1		1221	1222								2	
161	1	1		1221	1222								2	
162	1	1		1221	1222								2	
163	1	1		1231	1232								3	
164	1	1		1231	1232								3	
165	1	1		1231	1232								3	
166	1	1		1231	1232								3	
167	1	1		1331	1332								4	
168	1	1		1331	1332								4	
169	1	1		1331	1332								4	
170	1	1		1331	1332								4	
171	3	2		1111									4	
172	3	2		1112									4	
173	3	2		1131									4	
174	3	2		1132									4	
175	3	2		1141									4	
176	3	2		1142									4	
177	3	1		1152									4	
178	3	1		1151									4	
179	1	1		1111									1	
180	1	1		1131									1	
181	1	1		1112									1	
182	1	1		1141									1	
183	1	1		1132									1	
184	1	1		1142									1	

*The product size range parameters are described in Appendix A3.

APPENDIX A

A .2: PART/PRODUCT DATA FILE (CONTD)

PART CODE		QTY (/ Part)	DEMAND (Per Yr)	PRODUCT TYPE 1	2	3	4	5	6	7	8	9	SIZE*A RANGE	SIZE*B RANGE
185	1	1		1152									1	
186	3	1		1152									1	
187	2	4		1151	1152								1	
188	2	4		1211	1212								1	
189	2	4		1321	1322								1	
190	2	4		1221	1222								1	
191	2	4		1231	1232	1331	1332						1	
192	2	4		1311	1312								1	
193	1	1		1221	1222								4	
194	1	1		1212	1211								4	
195	1	1		1212	1211								4	
196	1	1		1221	1222								4	
197	2	1		1151	1152								3	
198	2	1		1151	1152								3	
199	2	1		1151	1152								3	
200	2	1		1211	1212	1221	1222						3	
201	2	1		1231	1232								3	
202	2	1		1331	1332								3	
203	2	1		1311	1312	1321	1322						2	
204	2	1		1211	1212	1221	1222						2	
205	2	1		1231	1232	1331	1332						3	
206	2	1		1151	1152								3	
207	1	1		1151									1	

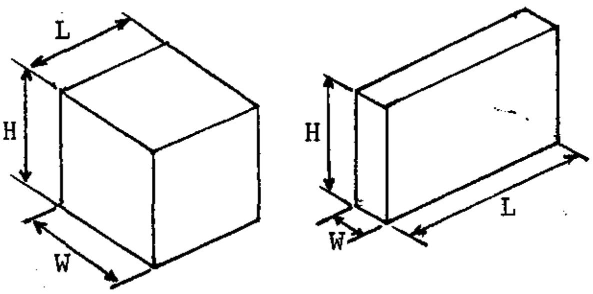
*The product size range parameters are described in Appendix A3.

A .3: CODE FOR PRODUCT SIZE CHARACTERISTICS

SHAPE	DIMENSIONS	SIZE FACTOR	NO OF RANGES
PRISMATIC: CUBE, PLATE	[L W H]	Volume($\bar{V}$)	4
ROTATIONAL: DISC	$[A_\phi\ B_\phi\ C]$	(A_ϕ)	5
		(C)	2
SHAFT	$[A_\phi\ B\ C_{1\phi}\ C_{2\phi}]$	(B)	5
		(A_ϕ)	4

PRISMATIC

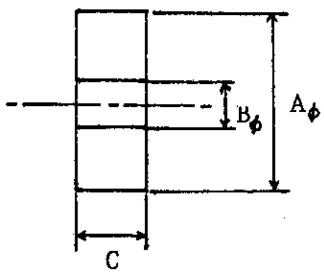
CUBE PLATE



SIZE CLASS V(mm^3)	0 -250	250-375	375-500	500-625
RANGE (CODE)	1	2	3	4

ROTATIONAL

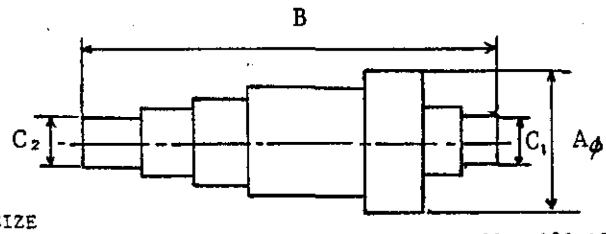
DISC



SIZE CLASS A (mm)	0-50	50-95	95-140	140-185	185-250
RANGE (CODE)	1	2	3	4	5

SIZE CLASS C(mm)	0-50	50-100
RANGE (CODE)	1	2

SHAFT



SIZE CLASS A (mm)	0-25	25-50	50-75	75-100	100-125
RANGE (CODE)	1	2	3	4	5

SIZE CLASS B(mm)	0-150	150-300	300-450	450-600
RANGE (CODE)	1	2	3	4

APPENDIX A

A .4: PART MACHINING DATA FILE

PART NO	PART CLASS	BATCH SIZE	TOT.NO OF OPS	1st OP SEQ.L	M/C1	M/C2	M/C3	M/C4	M/C TIME	M/C TIME	M/C TIME	M/C TIME	M/C TIME				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	8		2	2	1	6			4.5	28.3							
2	7		3	3	1	7	6		23.1	13.4	24.8						
3	7		3	3	1	6	8		4.1	13.9	5.6						
4	7		3	3	1	6	3		4.3	5.8	18.8						
5	7		3	3	1	7	3		20.3	11.8	23.6						
6	2		2	1	3	3			3.7	3.0							
7	2		2	1	3	3			5.7	5.1							
8	2		2	1	3	3			3.7	3.0							
9	2		2	1	3	3			5.7	5.1							
10	2		2	1	3	3			5.2	4.2							
11	2		2	1	3	3			8.1	7.2							
12	3		1	1	3				3.8								
13	2		1	1	3				6.2								
14	3		1	1	3				11.0								
15	3		1	1	3				11.0								
16	3		1	1	3				10.0								
17	2		1	1	3				10.0								
18	2		1	1	3				5.0								
19	2		1	1	3				19.0								
20	2		1	1	3				19.0								
21	6		3	3	1	5	7		5.6	1.7	11.6						
22	6		3	3	1	5	7		5.6	1.7	9.8						
23	7		3	3	1	7	8		3.2	9.2	3.8						
24	7		3	3	1	8	7		7.7	7.0	7.0						
25	7		3	3	1	8	7		7.7	7.0	7.0						
26	2		2	1	3	3			7.2	7.2							
27	2		1	1	3				7.1								
28	2		1	1	3				7.3								
29	7		3	3	1	7	8		6.2	2.6	3.5						
30	7		3	3	1	7	8		6.4	2.6	3.5						
31	7		3	3	1	7	8		6.8	2.9	3.5						
32	7		2	2	1	7			3.2	2.8							
33	7		2	2	1	7			3.3	3.2							
34	7		2	2	1	7			3.8	4.4							
35	6		2	2	1	8			12.5	4.3							
36	6		2	2	1	8			12.5	4.3							
37	6		2	2	1	8			13.5	4.6							
38	6		3	3	1	5	7		8.3	2.5	4.0						
39	6		3	3	1	5	7		10.4	2.5	6.8						
40	6		3	3	1	5	7		10.4	2.5	6.8						
41	6		3	3	1	5	7	(2)	11.3	1.9	21.8	1.8					
42	6		3	3	1	5	7	(2)	12.5	2.0	24.2	2.0					
43	6		3	3	1	5	7	(2)	14.0	2.1	32.0	3.0					
44	7		4	2	1	7	8	1	4.4	7.7	4.3	1.0					

APPENDIX A

A .4: PART MACHINING DATA FILE (CONTD)

PART NO	PART CLASS	BATCH SIZE	TOT.NO OF OPS	1st OP SEQ.L	M/C1	M/C2	M/C3	M/C4	M/C TIME	M/C TIME	M/C TIME	M/C TIME	M/C TIME				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
45	7		4	2	1	7	8	1	4.6	9.4	4.4	1.0					
46	7		4	2	1	7	8	1	5.0	10.1	4.6	1.0					
47	7		3	3	1	8	7		3.6	3.0	13.4						
48	7		3	3	1	8	7		3.9	3.1	14.3						
49	7		3	3	1	8	7		4.7	3.3	14.9						
50	7		4	3	1	8	7	8	10.7	5.9	4.4	3.1					
51	7		4	3	1	8	7	8	11.3	6.2	4.9	3.2					
52	7		4	3	1	8	7	8	12.0	6.5	5.3	3.2					
53	7		4	3	1	8	7	8	10.7	5.9	4.4	3.1					
54	7		4	3	1	8	7	8	11.3	6.2	4.9	3.2					
55	7		4	3	1	8	7	8	12.0	6.5	5.3	3.2					
56	7		4	3	1	8	7	8	10.7	5.9	4.4	3.1					
57	7		4	3	1	8	7	8	11.3	6.2	4.9	3.2					
58	7		4	3	1	8	7	8	12.0	6.5	5.3	3.7					
59	6		2	2	1	7			8.9	10.4							
60	6		2	2	1	7			10.1	11.6							
61	6		2	2	1	7			12.2	14.0							
62	6		2	2	1	7			8.9	10.3							
63	6		2	2	1	7			10.1	11.4							
64	6		2	2	1	7			12.2	13.4							
65	2		1	1	3				1.2								
66	2		1	1	3				1.4								
67	2		1	1	3				1.7								
68	2		2	1	3	3			12.2	8.2							
69	2		2	1	3	3			26.2	10.8							
70	2		2	1	3	3			18.8	12.5							
71	2		1	1	3				19.0								
72	2		1	1	3				16.0								
73	6		2	1	3	3			41.2	29.4							
74	6		2	1	3	3			51.1	41.1							
75	6		2	1	3	3			52.9	54.1							
76	3		1	1	3				4.1								
77	3		1	1	3				4.4								
78	3		1	1	3				4.4								
79	7		3	2	1	7	8		2.5	7.1	3.8						
80	6		2	2	1	6			4.3	5.4							
81	8		2	2	1	8			8.0	4.8							
82	6		2	2	1	6			5.0	6.2							
83	7		4	4	1	8	6	5	11.0	3.8	5.3	1.9					
84	7		3	3	1	5	7		4.4	1.9	5.4						
85	6		2	2	1	6			4.1	4.7							
86	6		3	3	1	5	7		4.6	1.7	6.4						
87	6		3	3	1	6	5		5.9	11.0	1.9						
88	7		3	3	1	5	7		9.3	13.0	1.9						
89	7		3	3	1	7	8		8.5	10.3	5.4						

APPENDIX A

A..4: PART MACHINING DATA FILE (CONTD)

PART NO	PART CLASS	BATCH SIZE	TOT.NO OF OPS	1st OP SEQ.L	M/C1	M/C2	M/C3	M/C4	M/C TIME	M/C TIME	M/C TIME	M/C TIME	M/C TIME				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
90	6		3	3	1	6	5		4.3	13.4	1.8						
91	7		2	2	1	8			7.7	7.0							
92	6		2	2	1	7			7.0	14.0							
93	6		4	4	1	8	5	5	21.2	4.7	9.0	1.9					
94	7		3	3	1	5	7		4.6	1.7	6.4						
95	8		2	1	1	8			7.3	5.9							
96	7		4	4	1	8	6	5	8.8	5.6	5.8	1.9					
97	8		2	1	1	8			5.0	3.2							
98	7		3	3	1	6	5		10.4	12.8	1.9						
99	7		3	3	1	8	7		18.4	12.8	16.1						
100	6		2	2	1	6			9.3	42.5							
101	7		4	2	1	8	6	7	7.8	3.8	11.1	10.3					
102	7		3	3	1	7	8		4.4	17.6	6.2						
103	6		2	2	1	7			9.2	29.5							
104	6		2	2	1	7			9.3	16.1							
105	7		3	3	1	7	8		3.9	14.2	6.1						
106	6		2	2	1	7			10.0	17.2							
107	7		3	3	1	7	8		4.2	9.5	5.8						
108	7		3	3	1	8	7		35.6	14.8	20.7						
109	6		2	2	1	7			11.4	97.7							
110	7		4	4	1	8	7	8	18.9	3.8	35.0	1.7					
111	6		3	2	1	7	8		8.5	42.7	7.4						
112	6		2	2	1	7			11.5	42.7							
113	6		2	2	1	7			11.3	36.0							
114	7		3	2	1	7	8		4.2	18.0	5.0						
115	7		3	3	1	8	6		36.4	8.8	18.8						
116	6		2	1	1	7			13.6	128.3							
117	7		4	4	1	8	7	8	26.0	3.8	38.2	14.6					
118	7		3	2	1	7	8		12.7	36.5	8.5						
119	6		2	2	7	7			13.6	73.7							
120	6		2	2	1	7			13.6	39.1							
121	7		3	2	1	7	8		5.0	14.6	6.3						
122	2		2	1	4	4			30.0	21.7							
123	3		1	1	4				28.2								
124	3		1	1	4				37.8								
125	3		1	1	4				45.5								
126	3		1	1	4				26.4								
127	3		1	1	4				40.4								
128	3		1	1	4				60.0								
129	3		1	1	4				18.8								
130	3		1	1	4				35.4								
131	3		1	1	4				47.4								
132	2		1	1	4				50.9								
133	2		1	1	4				55.7								
134	2		1	1	4				51.0								
135	1		1	1	3				5.0								

APPENDIX A

A.4: PART MACHINING DATA FILE (CONTD)

PART NO	PART CLASS	BATCH SIZE	TOT.NO OF OPS	1st OP SEQ.L	M/C1	M/C2	M/C3	M/C4	M/C TIME	M/C TIME	M/C TIME	M/C TIME	M/C TIME				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
136	1		1	1	3				5.4								
137	1		1	1	3				7.4								
138	1		1	1	3				7.2								
139	1		1	1	3				10.8								
140	1		1	1	3				17.4								
141	1		1	1	3				16.6								
142	1		1	1	3				7.0								
143	1		1	1	3				9.0								
144	1		1	1	3				9.0								
145	1		1	1	3				19.5								
146	1		1	1	3				10.8								
147	1		1	1	3				25.2								
148	1		1	1	3				18.6								
149	1		1	1	3				22.5								
150	1		1	1	3				10.8								
151	1		1	1	3				34.8								
152	1		1	1	3				23.8								
153	1		1	1	3				30.6								
154	1		1		3				16.1								
155	1		1	1	3				27.0								
156	1		1	1	3				27.0								
157	1		1	1	3				27.0								
158	1		1	1	3				27.0								
159	1		1	1	3				30.0								
160	1		1	1	3				30.0								
161	1		1	1	3				30.0								
162	1		1	1	3				30.0								
163	1		2	1	3	3			4.9	30.0							
164	1		1	1	3				30.0								
165	1		1	1	3				30.0								
166	1		1	1	3				30.0								
167	1		2	1	3	3			32.4	42.3							
168	1		2	1	3	3			57.0	32.4							
169	1		2	1	3	3			32.4	41.6							
170	1		2	1	3	3			55.2	15.5							
171	3		1	1	3				10.6								
172	3		1	1	3				11.4								
173	3		1	1	3				11.8								
174	3		1	1	3				12.8								
175	3		1	1	3				14.4								
176	3		1	1	3				14.6								
177	3		2	1	3	3			22.5	6.0							
178	3		2	1	3	3			24.0	6.0							
179	1		1	1	3				8.4								
180	1		1	1	3				5.6								
181	1		1	1	3				5.6								

APPENDIX A

A .4: PART MACHINING DATA FILE (CONTD)

PART NO	PART CLASS	BATCH SIZE	TOT.NO OF OPS	1st OP SEQ.L	M/C1	M/C2	M/C3	M/C4	M/C TIME	M/C TIME	M/C TIME	M/C TIME	M/C TIME				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
182	1		1	1	3				6.2								
183	1		1	1	3				12.1								
184	1		1	1	3				9.5								
185	1		1	1	3				10.0								
186	3		1	1	3				2.6								
187	2		1	1	3				12.0								
188	2		1	1	3				8.6								
189	2		1	1	3				9.4								
190	2		1	1	3				9.4								
191	2		1	1	3				12.0								
192	2		1	1	3				8.6								
193	1		1	1	3				51.0								
194	1		1	1	3				48.0								
195	1		1	1	3				59.0								
196	1		1	1	3				62.4								
197	2		1	1	4				75.0								
198	2		1	1	4				120.0								
199	2		1	1	3				460.5								
200	2		1	1	4				12.0								
201	2		1	1	4				21.6								
202	2		1	1	4				61.2								
203	2		1	1	3				9.1								
204	2		1	1	3				9.6								
205	2		1	1	3				6.0								
206	2		1	1	3				330.0								
207	1		1	1	3				9.5								

APPENDIX B

INFORMATION MEASURES FOR MACHINE GRAPHS

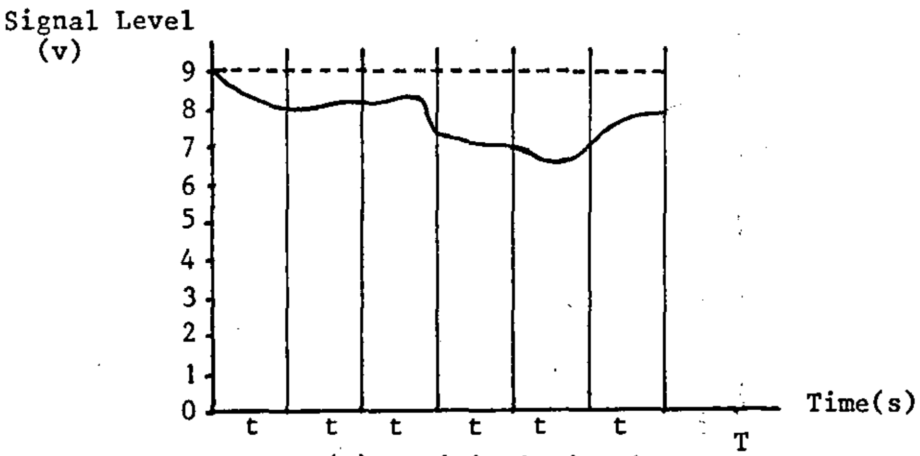
CONTENTS

B.1: INTRODUCTION

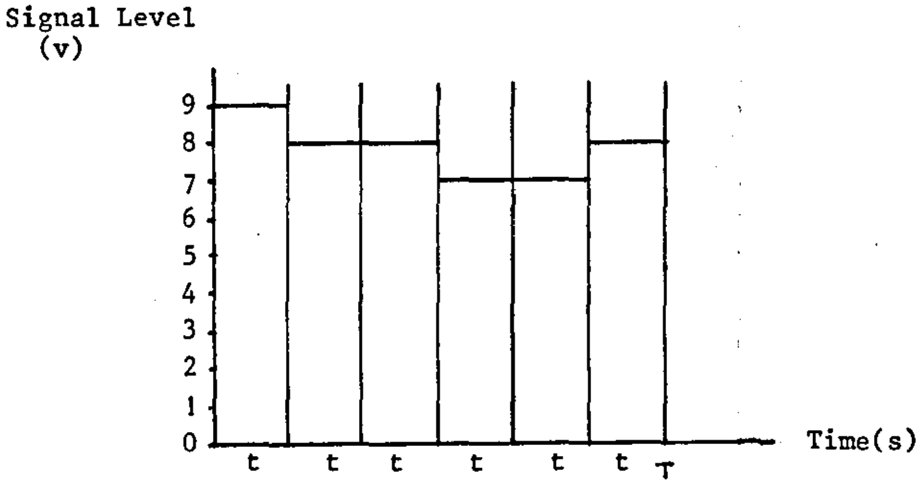
In seeking to derive an information measure for machine graphs, it is instructive to take a brief look at Information Theory as originally developed by C. E. Shannon. A more detailed treatment is given by Schwartz (1980). However, we take a brief look at the main aspects relevant to machine graphs.

B.2: INFORMATION CONTENT OF A SIGNAL

Consider a continuous signal T seconds long as shown below:



(a) Original signal



(b) Quantised Signal

The continuous signal may be quantised in t second intervals into a discrete signal as shown above. Then, from information theory, the information content of the discretised signal is defined by,

$$\text{Information} = \frac{T}{t} \log_2 n \quad \text{bits}$$

where n is the number of discrete signal levels.
For the above signal, this information content, H, is given by,

$$H = \frac{6t}{t} \log_2 10$$
$$= 19.93 \quad \text{bits}$$

From probability theory, it is known that the probability, P, of occurrence of an event is,

$$P = \frac{\text{number of times event occurs}}{\text{total number of possibilities}}$$

If n possible events are specified to be n possible signal levels at any instant, then $P = \frac{1}{n}$, for equally likely events. The information carried by the appearance of any one event in one interval is,

$$H = \log_2 n = - \log_2 P \quad \text{bits/interval.}$$

In m intervals, there is m times as much information, so that,

$$H_{TOTAL} = - m \log_2 P \text{ bits.}$$

Consider the case where the different signal levels (or events) are not equally likely. If there are just two levels to be transmitted, 0 or 1, the first with probability p_0 and the second with probability p_1, then

$$p_0 = \frac{\text{number of times 0 occurs}}{\text{total number of possibilities}}$$

$$p_1 = \frac{\text{number of times 1 occurs}}{\text{total number of possibilities}}$$

Since either 0 or 1 must always occur, $p_0 + p_1 = 1$. The information carried by a group of 0 or 1 symbols should now be the sum of the bits of information carried by each appearance of 0 or 1. If the total number of possibilities (or intervals) is m, then

$$\text{Number of times 0 occurs} = mp_0$$

$$\text{Number of times 1 occurs} = mp_1$$

Thus the information content of a signal is given by

$$H = -mp_0 \text{Log}_2 p_0 - mp_1 \text{Log}_2 p_1$$

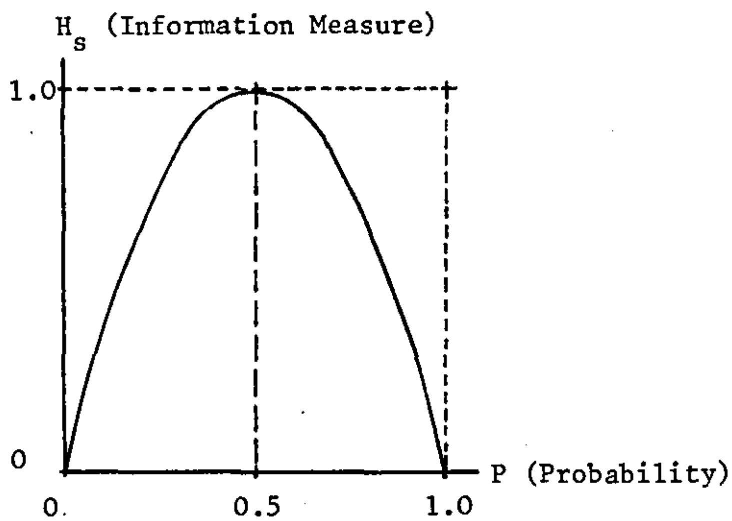
The average information content (H_S) of a signal is thus given by

$$H_S = \frac{H}{m} = - p_0 \text{Log}_2 p_0 - p_1 \text{Log}_2 p_1$$

This is the Shannon information measure of a signal. If the information measure H_S is plotted against the probability, p_0 or p_1, the curve below is obtained, since

$$H_S = - p_0 \text{Log}_2 p_0 - (1-p_0) \text{Log}_2 p_0$$

or, $$H_S = - (1-p_1) \text{Log}_2 p_1 - p_1 \text{Log}_2 p_1$$



B.3: APPLICATION OF INFORMATION MEASURE TO MACHINE GRAPHS

In a machine graph, where nodes represent machine types, and the edges represent the flow of parts using the two machine types joined by the edges. The grade of membership (signal level) of each edge is given by the similarity coefficient. The similarity coefficient associated with each machine graph edge may be quantised into a binary form, by selection of a threshold value for the similarity coefficients for the complete machine graph. Thus, for a particular threshold level the machine graph edge either exists (i.e. has a value 1) if the similarity coefficient is greater than the threshold value, or is ignored (i.e. has a 0 value). In this way a machine graph may be 'quantised' for different threshold values of the similarity coefficient, and reduced to 'binary' subgraphs.

Thus if a graph has x nodes, the total number ($Max.N_T$) of distinct graph edges possible, ignoring directionality is given by,

$$Max.N_T = \frac{1}{2}\,(x^2 - x)$$

Thus, for different threshold values, the 'binary' machine subgraphs obtained can be associated with a Shannon information measure. Thus, if the 'binary' machine subgraph has N_T edges, then

$$p_1 = \frac{\text{number of edges in the subgraph}}{\text{Total number of edges possible}}$$

$$= \frac{N_T}{Max.N_T}$$

and,

$$p_0 = \frac{\text{number of edges ignored by the subgraph}}{\text{Total number of edges possible}}$$

$$= \frac{Max.N_T - N_T}{Max.N_T}$$

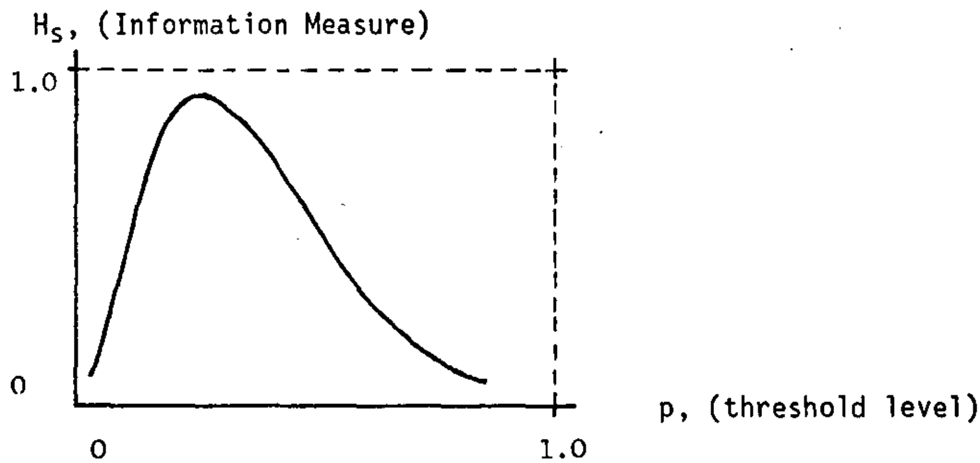
$$= 1 - \frac{N_T}{Max.N_T}$$

Thus the Shannon information measure for the 'binary' machine subgraphs is given by,

$$H_S = -p_1 Log_2 p_1 - p_0 Log_2 p_0$$

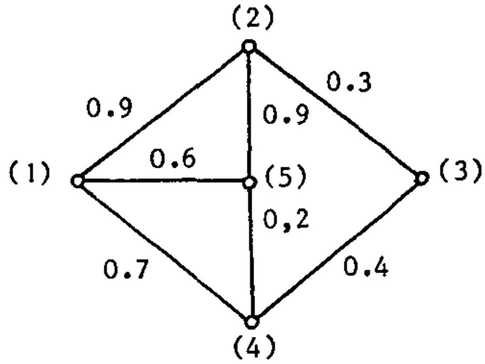
where, $p_1 = \frac{N_T}{Max.N_T}$, and $p_0 = 1 - \frac{N_T}{Max.N_T}$

It may be noted that for a particular application the actual total number of graph edges in the complete machine graph may be less than $Max.N_T$. Thus in the H_S v.s. threshold level (probability) graph, H_S=1 will never be attained. Moreover, since the mix of similarity coefficient values associated with the machine graph edges will be unique for each application, step changes in threshold level will not be accompanied by equal step changes in N_T, (the number of edges in the machine subgraph). Thus, a symmetrical curve for H_S v.s. threshold will not necessarily be obtained. It may be shown, reflecting the particular characteristic of a part spectrum. (See diagram below).

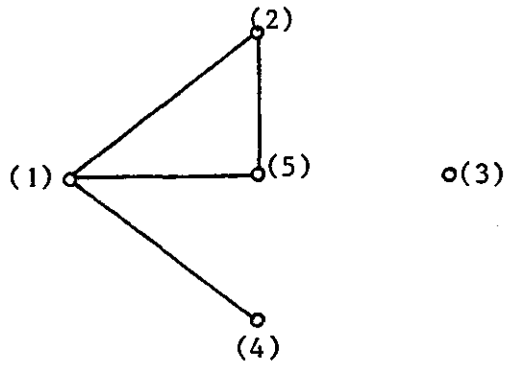


Thus for a particular application, the machine sub-graph with the highest information content may be selected.

B.4: AN EXAMPLE



(i) Complete machine graph



(ii) 'Binary machine Subgraph

Consider the above graph with 5 machine types and the machine pairs required by the parts are denoted by the edges. Ignoring directionality, the maximum number of edges possible with 5 nodes is given by $\frac{1}{2}(5^2 - 5) = 10$. In this application, machine pairs (3,5), (2,4) and (1,3) are not required, so that the complete machine graph has 7 edges as shown. The similarity coefficients of the edges are given in diagram (i). If a threshold level of 0.5 is chosen then the grade of membership is 1 for similarity coefficients greater than 0.5, and 0 for coefficients less than 0.5. The 'binary' machine subgraph obtained is shown in diagram (ii). Thus the probability of edges with a grade of membership of 1 is given by

$$p_1 = \frac{4}{10},$$

and the probability of edges with a grade of membership of 0 is

$$p_0 = \frac{10-4}{10}$$

Thus, the average Shannon information measure for graph (ii) is given by

$$H_s(p) = -\frac{4}{10}\log_2\frac{4}{10} - \frac{(10-4)}{10}\log_2\frac{(10-4)}{10}$$

$$= -0.4\log_2 0.4 - 0.6\log_2 0.6$$

$$= 0.9710$$

Similarly, the average Shannon information measure for different threshold values giving the appropriate set of machine graph edges may be computed.

APPENDIX C

INPUT DATA FOR SIMULATION MODELS

CONTENTS

C.1 PART PROCESSING FILE FOR SIMULATION OF PRISMATIC CELL

PART NO.	BATCH SIZE	FIXTURE GROUP	NO. OF OPERATIONS	NO. OF PARTS PER TROLLEY	NO. OF PARTS PER PALLET FIXTURE	DEDICATED M/C NO.	MACHINE TYPE	FIRST OPN. MACHIN-ING TIME	SECOND OPN. MACHINING TIME	TOTAL NO. OF TOOLS REQUIRED	TOOL PACK NO.	BATCH MULTIPLIER SELECTOR	FIXTURE TIME SELECTOR FOR OPS.	PART SIZE SELECTOR
1	7	1	2	12	2	3	3	30	30	20	12	0	1	1
2	9	2	2	10	2	3	3	77	61	20	12	0	1	1
3	7	3	2	12	2	4	3	30	30	20	12	0	1	1
4	9	4	2	10	2	4	3	50	40	20	12	0	1	1
5	9	5	2	12	2	3	3	73	62	20	12	0	1	1
6	5	6	2	10	2	4	3	98	92	20	12	0	1	1
7	42	7	1	48	4	3	3	50	0	3	13	0	1	1
8	42	8	1	24	4	3	3	100	0	8	13	0	1	1
9	2	9	1	48	4	3	3	110	0	5	10	0	1	1
10	98	10	1	50	4	4	3	108	0	5	10	0	1	1
11	2	11	1	50	4	4	3	50	0	7	13	0	2	1
12	2	12	1	50	4	3	3	100	0	5	10	0	2	1
13	2	12	1	50	4	4	3	100	0	5	10	0	2	1
14	2	11	1	50	4	3	3	100	0	5	13	0	2	1
15	2	11	1	50	4	3	3	100	0	5	13	0	2	1
16	21	13	1	24	1	5	2	227	0	3	13	0	1	1
17	21	14	1	24	1	5	2	248	0	5	13	0	1	1
18	3	15	1	12	1	4	3	105	0	6	13	0	2	1
19	2	15	1	12	1	4	3	120	0	6	13	0	2	1
20	10	16	2	12	2	3	3	93	82	15	14	0	1	1
21	10	17	1	12	4	4	3	94	0	10	14	0	2	1
22	10	17	1	12	4	4	3	94	0	10	14	0	2	1
23	7	18	1	20	2	3	3	120	0	20	15	0	1	1
24	5	19	1	16	2	4	3	145	0	20	15	0	1	1
25	9	20	1	12	2	4	3	180	0	20	15	0	1	1
26	15	21	2	16	2	3	3	163	132	20	15	0	1	1
27	11	22	2	12	2	4	3	272	118	20	15	0	1	1
28	5	23	2	8	2	3	3	269	181	20	15	0	1	1
29	2	24	1	10	2	4	3	156	0	7	10	0	2	1
30	2	24	1	10	2	4	3	156	0	7	10	0	2	1
31	5	25	2	10	2	2	1	300	217	25	7	0	1	1
32	2	26	2	8	2	2	1	357	255	25	7	0	1	1
33	4	27	1	10	1	2	1	282	0	25	1	0	2	1
34	4	27	1	10	1	2	1	378	0	25	1	0	2	1
35	3	27	1	8	1	2	1	455	0	25	1	0	2	2
36	4	28	1	10	1	2	1	264	0	25	1	0	2	1
37	4	28	1	10	1	2	1	404	0	25	1	0	2	1
38	3	28	1	8	1	2	1	600	0	25	1	0	2	2
39	4	29	1	10	1	2	1	188	0	25	16	0	1	1
40	3	30	1	10	1	2	1	354	0	25	16	0	1	2
41	3	31	1	8	1	2	1	474	0	25	16	2	1	2
42	4	32	1	10	1	2	1	509	0	30	16	2	1	2
43	3	33	1	10	1	2	1	557	0	30	16	2	1	2
44	3	34	1	8	1	2	1	510	0	30	16	2	1	2
45	3	35	1	16	2	6	2	50	0	5	6	2	2	2
46	3	36	1	12	2	7	3	54	0	5	6	2	2	2
47	2	36	1	12	2	7	3	74	0	6	6	2	2	2
48	3	36	1	12	2	7	3	72	0	5	6	2	2	2

C.1 PART PROCESSING DATA FOR SIMULATION OF PRISMATIC CELL

PART NO.	BATCH SIZE	FIXTURE GROUP	NO. OF OPERATIONS	NO. OF PARTS PER TROLLEY	NO. OF PARTS PER PALLET FIXTURE	DEDICATED M/C NO.	MACHINE TYPE	FIRST OPN. MACHIN-ING TIME	SECOND OPN. MACHIN ING TIME	TOTAL NO. OF TOOLS REQUIRED	TOOL PACK NO.	BATCH MULTIPLIER SELECTOR	FIXTURE TIME SELECTOR FOR OPS.	PART SIZE SELECTOR
49	3	36	1	12	2	7	3	108	0	5	6	2	2	2
50	2	35	1	16	2	6	2	174	0	5	6	2	2	2
51	2	35	1	16	2	6	2	166	0	6	6	2	2	2
52	1	36	1	16	2	7	3	70	0	5	6	2	2	2
53	2	36	1	12	1	7	3	90	0	5	6	2	2	2
54	2	36	1	12	1	7	3	90	0	5	6	2	2	2
55	2	36	1	12	1	7	3	195	0	5	6	2	2	2
56	2	36	1	12	1	7	3	108	0	5	6	2	2	2
57	2	37	1	12	2	7	3	252	0	15	5	2	2	2
58	2	37	1	12	2	7	3	186	0	18	5	2	2	2
59	2	37	1	12	2	7	3	225	0	15	5	2	2	2
60	1	37	1	12	2	7	3	108	0	15	5	2	2	2
61	1	38	1	10	2	7	3	348	0	20	5	2	2	2
62	1	38	1	10	2	7	3	238	0	20	5	2	2	2
63	1	38	1	10	2	7	3	306	0	20	5	2	2	2
64	1	38	1	10	2	7	3	161	0	20	5	2	2	2
65	2	37	1	12	2	7	3	270	0	12	5	2	2	2
66	2	37	1	12	2	7	3	270	0	12	5	2	2	2
67	2	37	1	12	2	7	3	270	0	12	5	2	2	2
68	2	37	1	12	2	7	3	270	0	12	5	2	2	2
69	1	38	1	10	2	7	3	300	0	15	6	2	2	2
70	1	38	1	10	2	7	3	300	0	15	6	2	2	2
71	1	38	1	10	2	7	3	300	0	15	6	2	2	2
72	1	38	1	10	2	7	3	300	0	15	6	2	2	2
73	1	39	1	10	2	7	3	300	0	15	3	2	2	2
74	1	39	1	10	2	7	3	300	0	15	3	2	2	2
75	1	39	1	10	2	7	3	300	0	15	3	2	2	2
76	1	39	1	10	2	7	3	300	0	15	3	2	2	2
77	1	39	1	10	2	7	3	300	0	18	3	2	2	2
78	1	39	1	10	2	7	3	300	0	18	3	2	2	1
79	1	39	1	10	2	7	3	300	0	18	3	1	2	1
80	1	39	1	10	2	7	3	300	0	18	3	1	2	1
81	7	40	1	20	4	6	2	106	0	8	3	1	2	1
82	3	40	1	20	4	6	2	114	0	8	3	1	2	2
83	1	40	1	16	4	6	2	118	0	8	3	1	2	2
84	5	40	1	16	4	6	2	128	0	8	3	1	2	2
85	1	40	1	12	2	7	3	144	0	8	3	1	2	2
86	5	40	1	12	4	7	3	146	0	8	3	1	2	1
87	1	40	1	10	2	7	3	60	0	8	3	1	2	1
88	1	40	1	10	2	7	3	50	0	8	3	1	2	1
89	2	41	1	20	4	6	2	84	0	3	9	1	2	1
90	1	41	1	20	4	6	2	56	0	3	9	1	2	1
91	2	41	1	20	4	6	2	56	0	3	9	1	2	1
92	1	41	1	20	4	6	2	62	0	3	9	1	2	1
93	3	41	1	20	4	6	2	121	0	3	9	1	2	1
94	3	41	1	20	2	6	2	95	0	3	9	1	2	1
95	1	41	1	20	2	6	2	110	0	5	9	1	2	1
96	1	41	1	20	2	6	2	95	0	5	9	1	2	1

C.1 PART PROCESSING DATA FOR SIMULATION OF PRISMATIC CELL

PART NO.	BATCH SIZE	FIXTURE GROUP	NO. OF OPERATIONS	NO. OF PARTS PER TROLLEY	NO. OF PARTS PER PALLET FIXTURE	DEDICATED M/C NO.	MACHINE TYPE	FIRST OPN. MACHIN-ING TIME	SECOND OPN. MACHIN ING TIME	TOTAL NO. OF TOOLS REQUIRED	TOOL PACK NO.	BATCH MULTIPLIER SELECTOR	FIXTURE TIME SELECTOR FOR OPS.	PART SIZE SELECTOR
97	1	41	1	20	2	6	2	80	0	5	9	1	2	2
98	1	42	1	20	2	6	2	500	0	8	7	1	2	2
99	1	42	1	20	2	6	2	150	0	8	7	1	2	2
100	2	42	1	20	2	6	2	70	0	8	7	1	2	2
101	1	43	1	16	1	7	3	26	0	6	7	1	1	1
102	1	44	1	20	2	6	2	120	0	8	8	1	2	1
103	1	44	1	20	2	6	2	86	0	8	8	1	2	1
104	2	44	1	20	2	6	2	94	0	8	8	1	2	1
105	1	44	1	20	2	6	2	94	0	8	8	1	2	1
106	3	44	1	20	2	6	2	120	0	8	8	1	2	1
107	4	44	1	20	2	6	2	86	0	8	8	1	2	1
108	4	45	1	20	2	7	3	175	0	8	1	1	2	2
109	1	45	1	20	2	7	3	390	0	8	1	1	2	2
110	1	45	1	20	2	7	3	390	0	8	1	1	2	2
111	1	46	1	20	2	6	2	43	0	8	2	1	1	2
112	1	47	1	10	1	6	2	85	0	15	1	1	2	2
113	1	47	1	10	1	6	2	645	0	15	1	1	2	2
114	1	47	1	10	1	6	2	385	0	15	1	1	2	2
115	3	48	1	10	1	7	3	195	0	15	1	1	2	1
116	2	48	1	10	1	7	3	132	0	15	1	1	2	1
117	2	49	1	10	1	6	2	36	0	10	1	1	1	1
118	10	50	1	10	1	7	3	117	0	8	2	1	2	1
119	5	51	1	20	2	7	3	59	0	8	1	1	2	1
120	2	50	1	10	1	7	3	291	0	8	2	1	2	2
121	7	50	1	10	1	7	3	231	0	8	2	1	2	2
122	2	50	1	10	1	7	3	160	0	8	2	1	2	1
123	3	51	1	20	2	7	3	93	0	8	1	1	2	1
124	1	52	1	10	1	7	3	510	0	8	2	1	2	2
125	1	52	1	10	1	7	3	480	0	8	2	1	2	2
126	1	52	1	10	1	7	3	590	0	8	2	1	2	2
127	1	52	1	10	1	7	3	624	0	8	2	1	2	2
128	1	53	1	8	1	2	1	750	0	25	15	1	1	2
129	1	54	1	8	1	7	3	1200	0	25	4	1	1	1
130	1	55	1	8	1	7	3	4600	0	30	4	1	1	2
131	1	56	1	6	1	2	1	120	0	30	15	1	1	2
132	1	57	1	6	1	2	1	216	0	30	15	1	1	2
133	1	58	1	6	1	2	1	612	0	30	15	1	1	2
134	7	59	1	20	4	6	2	91	0	10	10	1	2	1
135	10	59	1	20	4	6	2	93	0	10	10	1	2	1
136	3	59	1	16	4	6	2	60	0	10	10	1	2	1
137	1	60	1	8	1	7	3	3300	0	30	4	1	1	2
138	15	61	1	40	4	3	3	20	0	8	17	1	1	1
139	5	62	1	12	4	4	3	24	0	5	17	1	2	1
140	11	62	1	16	4	3	3	21	0	7	17	1	2	1
141	15	62	1	20	4	4	3	20	0	7	17	1	2	1
142	15	63	1	20	4	5	2	294	0	5	11	1	2	1
143	11	63	1	16	4	5	2	411	0	5	11	1	2	1
144	5	63	1	12	4	5	2	529	0	5	11	1	2	1

C.1: PART PROCESSING DATA FOR SIMULATION OF PRISMATIC CELL

PART NO.	BATCH SIZE	FIXTURE GROUP	NO. OF OPERATIONS	NO. OF PARTS PER TROLLEY	NO. OF PARTS PER PALLET FIXTURE	DEDICATED M/C NO.	MACHINE TYPE	FIRST OPN. MACHIN-ING TIME	SECOND OPN. MACHIN ING TIME	TOTAL NO. OF TOOLS REQUIRED	TOOL PACK NO.	BATCH MULTIPLIER SELECTOR	FIXTURE TIME SELECTOR FOR OPS.	PART SIZE SELECTOR
145	21	64	1	28	4	6	2	20	0	8	10	1	2	1
146	23	64	1	24	4	6	2	20	0	8	10	1	2	1
147	17	64	1	20	4	6	2	20	0	8	10	1	2	1

C.2: TOOL PACK DATA FOR SIMULATION PART SPECTRUM

TOOL TYPE	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R	S	TOOL LIFE (MINS)
	TOOL PACKS																	
	NO. OF TOOLS																	
Hertel Drill	8	7	3	4	3	3	3	7	7	6	0	8	3	6	6	4	3	15
Carb. Drill	0	0	0	0	0	0	0	0	0	1	0	1	2	2	2	0	0	60
Core Drill	0	0	0	0	2	0	0	0	0	0	0	1	1	1	1	0	0	15
L/S Drill	0	0	0	0	0	3	0	0	0	0	0	1	1	0	1	0	0	15
S/Stub Drill	7	6	4	7	4	3	3	2	2	5	0	0	2	0	0	2	1	15
Drill	0	0	0	0	0	3	1	3	0	0	0	7	3	3	3	7	4	15
Slot Drill	0	0	0	0	0	0	0	0	0	2	0	0	2	1	0	0	0	30
Chamfer Tool	4	2	3	3	4	3	2	2	6	1	0	0	0	1	0	0	0	120
End Mill	0	2	3	2	5	3	1	6	4	2	19	0	4	2	1	4	4	30
Face Mill	4	0	0	0	0	0	1	0	0	1	1	1	4	4	1	4	4	60
Pocket Mill	0	0	0	0	0	0	0	0	0	0	7	0	2	1	0	0	2	15
Climb Mill	1	1	1	1	0	0	1	0	0	0	0	0	1	1	0	0	2	60
Form Tool	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	1	120
Centre Tool	0	0	0	0	0	0	1	0	1	1	1	0	0	0	1	0	1	60
Woodruff Cutter	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	30
Trepanning Tool	0	0	0	0	0	0	2	0	0	0	0	0	0	2	3	0	0	60
Tapping Tool	3	2	4	4	5	2	1	0	1	1	0	2	0	2	2	1	0	30
Reamer	3	7	10	7	5	6	4	5	2	5	0	3	4	0	1	2	4	120
Boring Bar	0	3	2	1	2	4	9	5	7	4	0	7	0	4	8	6	4	60

APPENDIX D

ASPECTS OF SYSTEM SIMULATION MODELS

APPENDIX D

D.1: CALCULATION OF TRANSPORT TIMES IN SYSTEM MODELS

At the beginning of all simulation runs the machine operators are assumed to be in the staging area. During the simulation, the position of the operators is specified by their position attribute (or location number) and updated after each movement. In all the models the nearest available operator is called to perform the necessary activity. The simulation time unit (s.t.u.) is 15 seconds in all system models.

SYSTEMS WITH MANUAL TRANSPORT

In manual transport systems (i.e. FMS A, B and C) the machine operators are assumed to remain at the appropriate machine after performing the following activities: Tool loading and unloading, Fixturing, part loading and unloading, and transport of trolleys between central buffer and machining centre. The total distance, D metres, travelled by an operator is calculated by adding the appropriate distance elements, d_i, associated with each movement. The elements are: average inter-machine distance, average inter-buffer store distance, average machine-buffer store distance, and average distances from staging area to machines and buffer stores. The Transport time, T, is given by

$$T = \frac{D}{s} = \frac{\sum di}{s} \qquad \text{(Secs)}$$

$$= \frac{1}{9} \sum di \text{ (s.t.u.)}$$

where, s = average speed of operators (0.6 m/s

SYSTEMS WITH AUTOMATED TRANSPORT

In systems with automated transport, the location of the operators is specified by two position attributes, which are continuously updated during the simulation. The position attributes are given either in terms of the machine numbers (1 to 6), or the load/unload and fixturing stations (1 to 3). The distance elements, d_i, travelled by the operators are calculated from the average inter-machine distance, average distance between load/unload or fixture stations, average inter-buffer storage distance, and array of distances between machines and load/unload (or fixture stations). As for the manual systems the duration of operator movement is given by

$$T = \frac{1}{9} \sum di \quad (\text{s.t.u.})$$

However, the part transport time calculation is different for each type of automated system.

For the conveyor system (FMS D), the distance travelled by a pallet of parts from the fixturing station to the buffer storage stations is calculated from the location numbers and the respective average inter-station distance. If the distance from the buffer storage station to the machine is d_n metres, and the length of the conveyor loop is L metres, then

Transport time to machine $= \frac{d_n}{V_c}$ (secs), and,

Transport time back to buffer store $= \frac{L-d_n}{V_c}$ (secs.), where,

V_c is the conveyor speed, (0.25 m/s).

In the stacker crane system (FMS E) the intermediate work store locations have X_1 and Z_1 coordinates. The total distance, s, travelled from the storage location to the machine or load/unload station with X-coordinate, X_2, is given by

$$d_s = Y + \sqrt{(X_2-X_1)^2 + Z_1^2} \quad \text{(metres)}$$

where Y is the horizontal distance separating the APCs from the intermediate store or load/unload stations. The transport time for the stacker crane, T, is given by

$$T = \frac{d_s}{V_s} \quad \text{(secs.)}$$

where, V_s is the speed of the stacker crane, (0.5 m/s).

A similar approach is used for the rail guided shuttle system (FMS F) but the Z coordinate is not required in this case. Thus the distance travelled by the transporter, d (metres), is given by the

$$d_r = (X_2-X_1) + Y$$

The transport time is therefore,

$$T = \frac{d_r}{V_r} \quad \text{(secs.)}$$

where V_r is the speed of the rail guided shuttle, (1 m/s).

For the AGV system (FMS G), the position of the AGVs is given by two location attributes which are in terms of the machine number and the load/unload station value. The inter-machine distance, inter-load/unload station distance and the inter-buffer storage station distance are given. The total distance, d_a (metres), is calculated by adding the appropriate distance elements along the AGV track, so that the transport time of the AGV, T is given by

$$T = \frac{d_a}{V_a} \quad \text{(secs.)}$$

Where, V_a is the AGV speed, (1 m/s).

D.2: DESCRIPTION OF ENTITIES AND ATTRIBUTES IN SIMULATION MODELS

ENTITY: ORDER (ORDR) - batches of parts to be produced every 2 weeks (147).

Attribute:-

ODA = Part number.
ODE = Machine for which it is selected.

ENTITY: MACHINE (MACH) - machines in the system (6).

Attribute:-

MCA = Machine number.
MCB = Part number being machined.
MCC = Machine bed/buffer fixtured for first operation(= 1); second operation(= 2).
MCD = Machine tooled up for part(= 1); if not(= 0).
MCE = Maximum tool life of tool pack (computed from tool data).
MCF = Machining time accumulated by tool pack on machine.

ENTITY: BUFFER (BUFF) - machine buffer (APC) pallet stations.

Attribute:-

BFA = machine to which buffer is attached (1 to 6).
BFB = Part number of buffer.
BFC = Buffer available (= 0), unavailable (= 1).
BFD = Part loaded onto buffer (= 1), part not on buffer (= 0).
BFE = Buffer fixtured for first operation (= 1) or second operation (= 2).
BFF = Buffer address number (1 to 24).
BFG = Machining of part on buffer completed (= 1) not completed (= 0).
BFX = Fixture mounting on buffer completed (= 1), not completed (= 0).

ENTITY: TROLLEYS (TROL) - trolleys for transporting parts and fixtures.

Attribute:-

TRA = Part number on trolley.
TRB = Number of trolleys of parts to be machined in each batch.
TRC = Number of parts on trolley.
TRD = Number of times trolley used for transporting a batch of parts.
TRF = Trolley has fixture for part batch (= 0), if not (= 1).
TRH = Dedicated machine allocation for part batch on this trolley.
TRJ = Machine to which trolley sent for machining.
TRN = Trolley address number.
OPNUM = No. of set-ups required for batch of parts on trolley.

ENTITY: PART SETS (KITS) - Set of parts fixtured on a particular pallet.

Attribute:-

KTA = Part number of part set.
KTB = No. of parts in part set.
KTC = TRC (no. of parts on trolleys).
KTE = No. of part sets for batch.
KTD = Address of kits in batch of parts.
KTF = Machine on which kits are processed.

ENTITY: MACHINE OPERATORS (YAHU)

Attribute:-

YHA = Location of operator (w.r.t. machine).
YHB = Location of operator (w.r.t. load/unload station).
YHN = No. of operators and their identity.
YHZ = Operators gone to lunch (=2), operators available (= 0), unavailable (= 1).

ENTITY: PALLETS (PALT)

Attribute:-

PLA = Part No.
PLB = Pallet loaded onto machine buffer (APC).
PLC = No. of parts on this pallet.
PLD = Pallet address number.
PLE = First operation (=1) or second operation (=2) fixture on pallet.
PLJ = Machine on which pallet processed (1→6).
OPNUM = No. of operations for part on pallet.
PLG = Used fixture on pallet not required (= 0), if required (= 1).

ENTITY: STACKER CRANE (GANT)

Attribute:-

GNA = Position of stacker crane.

ENTITY: RAIL GUIDED SHUTTLE (RAIL)

Attribute:-

RLA = Position of rail guided shuttle.

ENTITY: AGVs (AGVS)

Attribute;-

AGA and,
AGB = Position coordinates of AGV.
AGC = No. of times AGV's charged.
AGN = AGV address Number.
AGX = AGV's require charge (= 1); if not (= 0).

ENTITY: INTERMEDIATE STORE PALLET STATIONS (STOR)

Attribute:-

STB = No. of storage locations (= no. of pallets in system).
STC = Machine to which pallet station allocated.
STD = Does pallet at this location require transport (= 1), if not (= 0).
STE = Part no. on pallet using this store location.

APPENDIX D

D.3: SELECTION OF AGV BATTERY CAPACITY

It should be recalled that the AGV model (FMS G) employed a battery recharge policy, whereby each AGV received a battery charge in the second of the double shift system. From the simulation results, a more judicious choice of battery capacity could be made from a range of values thus rendering a battery charge during the shift unnecessary.

Power for traction motor accounts for the current consumption; the lift motor being activated only occasionally for intermittent periods of approximately 7 seconds. Thus, the average power of the traction motor recommended by Muller (1983) is 0.5 kW with an assumed electric motor efficiency of 50%. Thus the average power consumed by the electric motor, $P_{consumed}$, is given by,

$$P_{consumed} = \frac{P_{output}}{\eta} = \frac{0.5}{0.5} = \underline{1kW}$$

where, η is the efficiency of the electric motor,

and P_{output} is the average power output of the electric motor.

The battery capacity required, B_R is given by:

$$B_R = t \times P_{consumed} \text{ (kWhrs)}.$$

where, t is the travel time during the operating time without recharging batteries in hours. The battery capacity required in terms of the ratings of the battery is given by,

$$B_R = \frac{Bat_V \times Bat_{Ah} \times \alpha}{100}$$

where, Bat_V is the battery voltage,

Bat_{Ah} is the number of Ampere hours of the battery, and, α is a factor accounting for the permissible charging of a battery without damaging the battery. Thus, the ampere-hour rating of the battery is given by, Bat_{Ah},

$$BAT_{Ah} = \frac{t \times P_{consumed} \times 1000}{\alpha \times Bat_V}$$

Typically, Bat_V = 24 volts, and α = 80%;

Therefore, $Bat_{Ah} = \frac{t \times 1 \times 1000}{0.8 \times 24}$

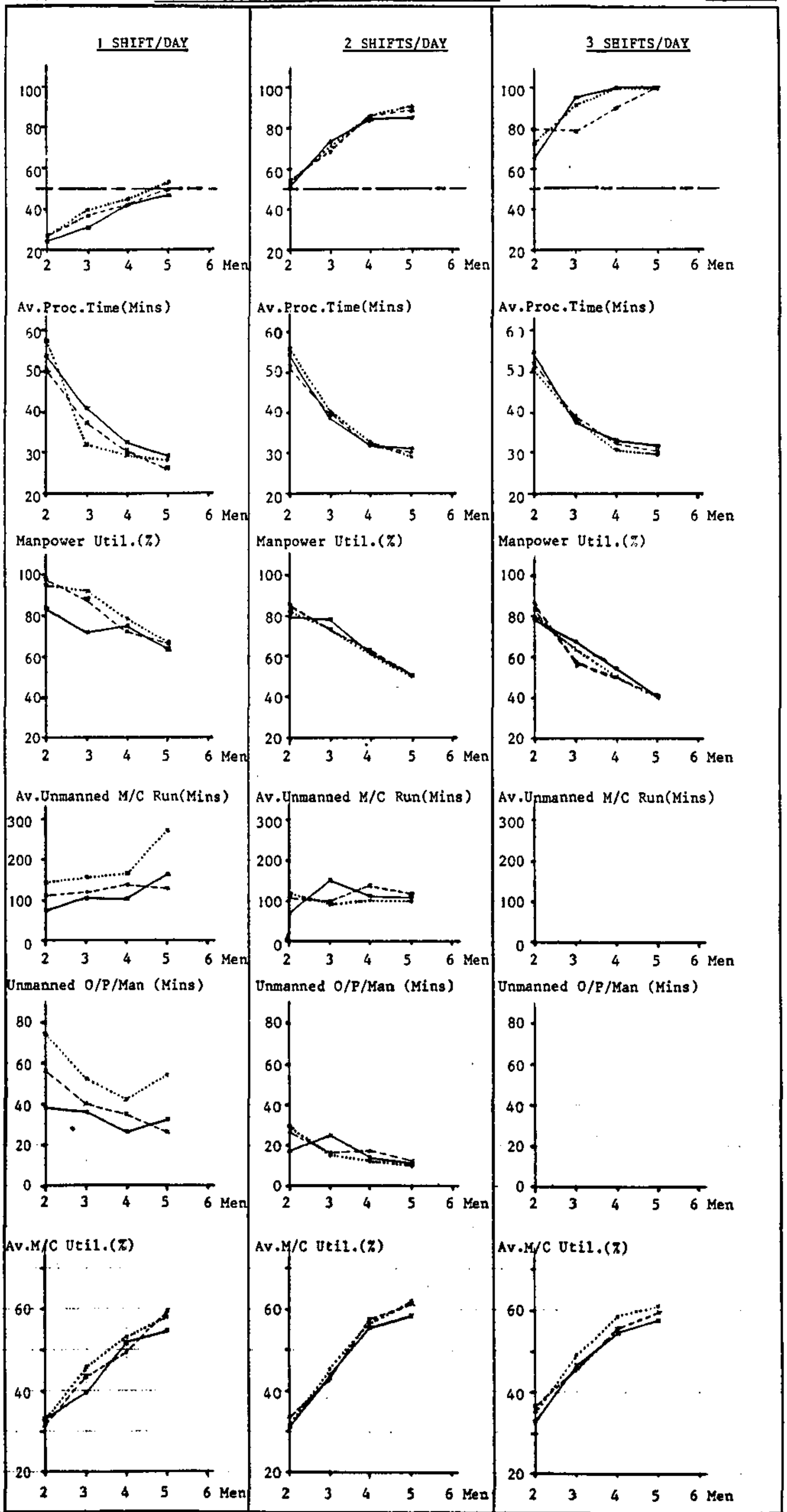
From the AGV utilisation levels the average runtime for AGV for the week may be computed, so that a range of ampere-hours rating for the AGV battery may be tabulated below, for the double shift system.

MANPOWER	UTIL. PER AGV		AV. WEEKLY RUNTIME PER AGV		REQUIRED AV. DAILY RUNTIME PER AGV		REQUIRED BAT. RATING, Bat_{Ah}	
	With charge	No charge	With charge	No charge	With charge	No charge	With charge	No charge
2	6.6%	6.9%	5.28hr	5.52hr	0.53hr	1.10	27.5Ah	57.5Ah
3	8.7%	9.3%	6.96	7.44	0.70	1.49	36.3	77.5
4	9.7%	9.7%	7.76	7.76	0.78	1.56	40.7	81.4

It is clear that with a minimum battery rating of 85 to 90 Ampere-hours, the AGV system can be run without recharging or battery change during the daily double shift. The AGV's can incorporate an automated charging system on board, and be recharged during the third shift. Slightly better processing times, machine utilisation levels and output levels are obtained as illustrated below, for a manpower level of 2 men.

SYSTEM G	IS THERE BATTERY CHANGE DURING RUN?	SYSTEM OUTPUT (%)	Av.PROCESSING TIME (mins)	Av.MACHINE UTIL. (%)	Av.MAN. UTIL
2 AGV's	Yes	54.23	52.25	33.33	89.64
2 AGV's	No	57.81	47.95	36.32	86.81

Appendix 9.4: Performance Curves for FMS G with 3 AGVs



18 PALLETS ------ 24 PALLETS .... 30 PALLETS

- ——— - 50% TWO WEEK OUTPUT REQUIREMENS

APPENDIX E

RESULTS OF SIMULATION TESTS

CONTENTS

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E.1: FMS A SIMULATION RESULTS

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS A	PROGRAM: GMAN. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS: NIL		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=1
SHIFTS/DAY: (2)	TROLLEYS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	352	515	670	704	721
PARTS FINISHED	323	493	633	686	717
BATCHES FINISHED	66	87	100	106	110
BATCHES IN SYSTEM	19	20	19	16	14
BATCHES WAITING OUT	62	40	28	25	23
UNMANNED TOTAL MACHINE HOURS	1.20	2.83	1.63	1.98	4.98
RUNTIME FOR M/C 1 (S.T.U.)	18929	18996	19043	19056	19099
RUNTIME FOR M/C 2 (S.T.U.)	19309	19179	19384	19168	18920
RUNTIME FOR M/C 3 (S.T.U.)	19082	18801	19190	19114	18707
RUNTIME FOR M/C 4 (S.T.U.)	19054	18486	19173	19155	19367
RUNTIME FOR M/C 5 (S.T.U.)	19074	19217	19409	18985	18650
RUNTIME FOR M/C 6 (S.T.U.)	19229	19316	19194	19287	19209
TOT. WORK PROCESSED (%)	34.16	50.49	62.11	65.00	66.47
AV. PROCESS TIME (MINS)	81.44	55.34	43.06	40.75	39.51
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	21.67	32.39	39.17	41.11	42.26
UTIL. FOR M/C 1 (%)	31.26	46.74	58.43	61.78	63.97
UTIL. FOR M/C 2 (%)	10.79	14.10	18.58	19.58	19.96
UTIL. FOR M/C 3 (%)	39.56	57.49	68.59	69.99	71.51
UTIL. FOR M/C 4 (%)	36.93	51.24	58.23	60.23	61.58
UTIL. FOR M/C 5 (%)	6.13	10.77	12.77	15.46	15.74
UTIL. FOR M/C 6 (%)	5.37	14.00	18.44	19.63	20.80
AV. MAN POWER UTIL. (%)	96.56	88.69	78.74	66.83	56.86
AV. WAITING W.I.P. (FOR MACHINING PARTS)	206	204	193	188	185

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS A			PROGRAM: GMAN. OBJ		
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0		M/C PALLET STATIONS NIL		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471	FIXTURING FIX←TYP=1
SHIFTS/DAY: (2)	TROLLEYS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	327	521	671	720	727
PARTS FINISHED	313	504	641	708	717
BATCHES FINISHED	63	88	101	108	110
BATCHES IN SYSTEM	26	26	21	18	16
BATCHES WAITING OUT	58	33	25	21	21
UNMANNED TOTAL MACHINE HOURS	0.53	6.93	2.87	3.0	6.55
RUNTIME FOR M/C 1 (S.T.U.)	18958	19007	19083	19177	19084
RUNTIME FOR M/C 2 (S.T.U.)	18678	19140	19432	18983	19267
RUNTIME FOR M/C 3 (S.T.U.)	18986	20520	18549	19176	19632
RUNTIME FOR M/C 4 (S.T.U.)	18994	19437	19053	19059	19364
RUNTIME FOR M/C 5 (S.T.U.)	19036	19306	19380	19410	18613
RUNTIME FOR M/C 6 (S.T.U.)	19011	19161	19343	18922	19096
TOT. WORK PROCESSED (%)	32.17	50.28	60.60	66.50	67.28
AV. PROCESS TIME (MINS)	86.90	55.94	47.96	39.84	39.56
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	20.52	31.04	38.58	42.05	42.18
UTIL. FOR M/C 1 (%)	30.21	43.58	57.24	63.71	64.02
UTIL. FOR M/C 2 (%)	8.53	17.28	20.43	19.47	21.82
UTIL. FOR M/C 3 (%)	38.12	52.68	64.10	69.76	69.24
UTIL. FOR M/C 4 (%)	35.15	49.45	58.60	60.53	61.59
UTIL. FOR M/C 5 (%)	4.68	10.56	13.00	15.87	15.77
UTIL. FOR M/C 6 (%)	6.41	12.69	18.13	22.96	20.63
AV. MAN POWER UTIL. (%)	92.22	88.64	78.22	66.94	56.82
AV. WAITING W.I.P. (FOR MACHINING PARTS)	248	253	237	228	223

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS A		PROGRAM: GMAN. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	M/C PALLET STATIONS NIL		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=1
SHIFTS/DAY: (2)	TROLLEYS: (36)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (6)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	337	477	686	705	718
PARTS FINISHED	319	459	654	679	699
BATCHES FINISHED	66	87	102	107	109
BATCHES IN SYSTEM	31	30	24	22	21
BATCHES WAITING OUT	50	30	21	18	17
UNMANNED TOTAL MACHINE HOURS	1.5	3.13	3.33	7.33	8.42
RUNTIME FOR M/C 1 (S.T.U.)	19275	19265	19184	19037	19020
RUNTIME FOR M/C 2 (S.T.U.)	18398	19073	19111	19160	19048
RUNTIME FOR M/C 3 (S.T.U.)	19117	19074	18306	20202	19027
RUNTIME FOR M/C 4 (S.T.U.)	18995	19338	19467	19163	20302
RUNTIME FOR M/C 5 (S.T.U.)	18509	19227	19394	18993	17977
RUNTIME FOR M/C 6 (S.T.U.)	18709	18994	19193	19243	19954
TOT. WORK PROCESSED (%)	33.49	48.41	61.98	66.28	66.95
AV. PROCESS TIME (MINS)	83.83	60.26	41.78	41.06	40.16
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	21.30	30.50	39.44	41.27	41.85
UTIL. FOR M/C 1 (%)	29.33	43.50	56.31	59.94	61.06
UTIL. FOR M/C 2 (%)	10.73	14.09	19.22	22.33	22.92
UTIL. FOR M/C 3 (%)	38.94	50.72	68.36	70.65	71.61
UTIL. FOR M/C 4 (%)	37.52	49.70	58.22	60.20	60.02
UTIL. FOR M/C 5 (%)	4.81	10.43	13.81	15.46	14.90
UTIL. FOR M/C 6 (%)	6.49	14.58	20.70	19.01	20.61
AV. MAN POWER UTIL. (%)	97.65	87.85	79.51	66.45	56.43
AV. WAITING W.I.P. (FOR MACHINING PARTS)	249	263	253	251	242

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS A	PROGRAM: GMAN. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	M/C PALLET STATIONS NIL		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=1
SHIFTS/DAY: (3)	TROLLEYS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	521	798	857	868	891
PARTS FINISHED	503	796	843	840	843
BATCHES FINISHED	87	122	132	131	132
BATCHES IN SYSTEM	20	13	11	11	11
BATCHES WAITING OUT	40	12	4	5	4
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	-
RUNTIME FOR M/C 1 (S.T.U.)	28678	28231	27644	28160	27212
RUNTIME FOR M/C 2 (S.T.U.)	28456	28319	28367	28238	28616
RUNTIME FOR M/C 3 (S.T.U.)	27609	28712	28768	28714	28759
RUNTIME FOR M/C 4 (S.T.U.)	28381	24609	20795	21636	20258
RUNTIME FOR M/C 5 (S.T.U.)	28634	23860	19790	20496	19632
RUNTIME FOR M/C 6 (S.T.U.)	28740	28627	28724	28350	28685
TOT. WORK PROCESSED (%)	52.23	78.95	87.73	87.03	89.08
AV. PROCESS TIME (MINS)	81.81	50.99	44.95	44.81	42.97
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	22.34	34.97	40.77	39.92	41.74
UTIL. FOR M/C 1 (%)	35.26	54.59	61.24	60.12	62.21
UTIL. FOR M/C 2 (%)	11.66	21.57	26.76	24.43	26.37
UTIL. FOR M/C 3 (%)	39.15	52.72	59.46	60.68	61.42
UTIL. FOR M/C 4 (%)	33.38	47.30	57.36	55.13	58.88
UTIL. FOR M/C 5 (%)	7.01	13.51	14.84	14.32	14.96
UTIL. FOR M/C 6 (%)	7.60	20.16	24.97	24.82	26.61
AV. MAN POWER UTIL. (%)	88.07	83.55	67.78	54.77	45.82
AV. WAITING W.I.P. (FOR MACHINING PARTS)	203	172	163	160	161

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS A			PROGRAM: GMAN. OBJ		
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS NIL		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=1
SHIFTS/DAY: (3)	TROLLEYS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	540	793	849	893	897
PARTS FINISHED	510	787	839	889	855
BATCHES FINISHED	89	122	131	134	133
BATCHES IN SYSTEM	26	15	13	11	12
BATCHES WAITING OUT	32	10	3	2	2
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	-
RUNTIME FOR M/C 1 (S.T.U.)	28762	28522	26794	26597	25832
RUNTIME FOR M/C 2 (S.T.U.)	28774	28631	28720	28192	27591
RUNTIME FOR M/C 3 (S.T.U.)	27606	28607	28731	28748	28771
RUNTIME FOR M/C 4 (S.T.U.)	28454	25691	21510	20813	19986
RUNTIME FOR M/C 5 (S.T.U.)	28724	24281	20515	19624	19307
RUNTIME FOR M/C 6 (S.T.U.)	28721	28284	28350	28690	28675
TOT. WORK PROCESSED (%)	53.04	76.89	86.95	89.13	88.93
AV. PROCESS TIME (MINS)	79.19	51.71	45.53	42.74	41.85
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	22.63	33.67	40.37	41.82	42.57
UTIL. FOR M/C 1 (%)	34.45	50.77	63.18	63.65	65.54
UTIL. FOR M/C 2 (%)	12.80	22.43	26.07	27.05	27.77
UTIL. FOR M/C 3 (%)	39.15	51.30	59.28	61.59	61.54
UTIL. FOR M/C 4 (%)	34.75	45.30	55.45	57.31	59.68
UTIL. FOR M/C 5 (%)	7.10	13.28	14.31	14.96	15.21
UTIL. FOR M/C 6 (%)	7.53	18.93	23.95	26.33	25.71
AV. MAN POWER UTIL. (%)	90.46	82.07	67.11	55.12	46.00
AV. WAITING W.I.P. (FOR MACHINING PARTS)	246	218	196	195	190

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS A		PROGRAM: GMAN. OBJ			
SALES/ WORKLOAD	MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS NIL	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=1
SHIFTS/DAY: (3)	TROLLEYS: (36)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (6)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	516	786	872	884	886
PARTS FINISHED	481	770	844	844	876
BATCHES FINISHED	90	120	132	132	132
BATCHES IN SYSTEM	29	18	14	14	13
BATCHES WAITING OUT	28	9	1	1	2
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	-
RUNTIME FOR M/C 1 (S.T.U.)	28794	28580	26795	26931	26721
RUNTIME FOR M/C 2 (S.T.U.)	28378	28795	28289	28224	28630
RUNTIME FOR M/C 3 (S.T.U.)	28410	28687	28762	28761	28147
RUNTIME FOR M/C 4 (S.T.U.)	28740	24729	21268	20761	21116
RUNTIME FOR M/C 5 (S.T.U.)	27854	24131	19903	19722	19101
RUNTIME FOR M/C 6 (S.T.U.)	27614	28718	28050	28530	28694
TOT. WORK PROCESSED (%)	52.35	77.79	87.85	88.02	88.59
AV. PROCESS TIME (MINS)	82.26	52.05	43.88	43.25	43.00
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	22.21	34.25	41.03	41.24	41.59
UTIL. FOR M/C 1 (%)	36.10	52.10	63.18	62.86	63.35
UTIL. FOR M/C 2 (%)	10.94	20.61	25.67	25.97	26.50
UTIL. FOR M/C 3 (%)	36.87	52.77	60.58	61.42	62.90
UTIL. FOR M/C 4 (%)	33.44	47.07	56.08	57.45	57.71
UTIL. FOR M/C 5 (%)	7.20	13.36	14.75	14.89	14.02
UTIL. FOR M/C 6 (%)	8.69	19.57	25.91	24.83	25.08
AV. MAN POWER UTIL. (%)	90.28	82.96	67.85	53.82	45.81
AV. WAITING W.I.P. (FOR MACHINING PARTS)	267	238	219	219	215

E.2: FMS B SIMULATION RESULTS

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS B		PROGRAM: HMAN. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	M/C PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	TROLLEYS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	198	313	408	400	477
PARTS FINISHED	113	299	384	388	447
BATCHES FINISHED	40	65	78	80	85
BATCHES IN SYSTEM	23	20	19	19	19
BATCHES WAITING OUT	84	62	50	48	43
UNMANNED TOTAL MACHINE HOURS	3.82	2.63	10.25	3.07	3.22
RUNTIME FOR M/C 1 (S.T.U.)	9221	9408	9864	9776	9438
RUNTIME FOR M/C 2 (S.T.U.)	9555	9702	9716	9814	9869
RUNTIME FOR M/C 3 (S.T.U.)	9425	9393	11387	6691	9876
RUNTIME FOR M/C 4 (S.T.U.)	9903	9348	9588	9556	9533
RUNTIME FOR M/C 5 (S.T.U.)	9571	9421	9553	9534	9791
RUNTIME FOR M/C 6 (S.T.U.)	9262	9581	9614	9802	9375
TOT. WORK PROCESSED (%)	17.58	28.20	37.81	39.37	41.90
AV. PROCESS TIME (MINS)	71.89	45.41	36.59	34.48	30.34
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	22.23	36.18	45.32	52.29	52.61
UTIL. FOR M/C 1 (%)	29.24	46.34	61.90	72.13	76.86
UTIL. FOR M/C 2 (%)	10.73	17.90	28.74	31.48	32.98
UTIL. FOR M/C 3 (%)	35.59	64.45	64.47	90.68	74.33
UTIL. FOR M/C 4 (%)	48.79	59.10	76.21	75.52	81.37
UTIL. FOR M/C 5 (%)	4.69	10.89	17.13	21.04	22.61
UTIL. FOR M/C 6 (%)	4.33	18.38	23.46	22.87	27.52
AV. MAN POWER UTIL. (%)	78.60	81.64	78.57	64.00	57.40
AV. WAITING W.I.P. (FOR MACHINING PARTS)	215	212	215	215	222

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS B	PROGRAM: HMAN. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	TROLLEYS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	221	335	401	488	466
PARTS FINISHED	120	315	378	438	423
BATCHES FINISHED	44	69	77	86	83
BATCHES IN SYSTEM	28	24	25	25	24
BATCHES WAITING OUT	75	54	45	36	40
UNMANNED TOTAL MACHINE HOURS	4.57	5.62	2.38	3.75	1.83
RUNTIME FOR M/C 1 (S.T.U.)	9518	9474	9598	9326	9589
RUNTIME FOR M/C 2 (S.T.U.)	9832	9998	9756	9857	9713
RUNTIME FOR M/C 3 (S.T.U.)	9614	8657	7109	9541	7080
RUNTIME FOR M/C 4 (S.T.U.)	10218	9885	9600	9586	9550
RUNTIME FOR M/C 5 (S.T.U.)	9150	9878	9692	9712	9830
RUNTIME FOR M/C 6 (S.T.U.)	9503	9352	9802	9738	9654
TOT. WORK PROCESSED (%)	20.18	30.65	36.46	42.55	40.35
AV. PROCESS TIME (MINS)	65.42	42.72	34.64	29.59	29.73
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	24.91	39.38	49.99	53.79	55.04
UTIL. FOR M/C 1 (%)	35.09	49.00	61.65	78.18	71.56
UTIL. FOR M/C 2 (%)	13.10	26.39	27.21	38.72	35.35
UTIL. FOR M/C 3 (%)	40.25	69.93	97.96	76.94	98.36
UTIL. FOR M/C 4 (%)	51.16	60.90	73.30	80.92	78.40
UTIL. FOR M/C 5 (%)	5.56	14.86	17.58	22.63	22.52
UTIL. FOR M/C 6 (%)	4.31	15.18	22.22	25.36	24.04
AV. MAN POWER UTIL. (%)	84.81	86.60	74.50	67.62	54.98
AV. WAITING W.I.P. (FOR MACHINING PARTS)	271	265	265	276	276

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS B		PROGRAM: HMAN. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	TROLLEYS: (36)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (6)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	211	327	380	451	472
PARTS FINISHED	113	296	345	412	434
BATCHES FINISHED	40	64	75	84	87
BATCHES IN SYSTEM	33	33	31	31	30
BATCHES WAITING OUT	74	50	41	32	30
UNMANNED TOTAL MACHINE HOURS	5.1	2.35	4.27	4.20	5.53
RUNTIME FOR M/C 1 (S.T.U.)	9575	9555	9840	9730	9781
RUNTIME FOR M/C 2 (S.T.U.)	9500	9768	9798	9808	9960
RUNTIME FOR M/C 3 (S.T.U.)	9911	9132	7527	9551	9508
RUNTIME FOR M/C 4 (S.T.U.)	10330	9579	9690	9585	9630
RUNTIME FOR M/C 5 (S.T.U.)	9528	9707	9766	9787	9738
RUNTIME FOR M/C 6 (S.T.U.)	9724	9659	9708	9972	10046
TOT. WORK PROCESSED (%)	19.32	29.60	35.70	40.25	41.81
AV. PROCESS TIME (MINS)	69.39	43.88	37.06	32.39	31.07
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	23.57	37.79	47.79	50.26	52.02
UTIL. FOR M/C 1 (%)	35.62	45.79	54.25	63.31	66.35
UTIL. FOR M/C 2 (%)	10.76	23.24	26.15	31.24	37.69
UTIL. FOR M/C 3 (%)	37.31	66.29	92.52	76.86	77.21
UTIL. FOR M/C 4 (%)	46.78	64.91	72.62	78.11	78.68
UTIL. FOR M/C 5 (%)	4.71	11.56	16.01	20.82	21.26
UTIL. FOR M/C 6 (%)	6.23	14.93	25.16	31.22	30.96
AV. MAN POWER UTIL. (%)	80.22	83.61	74.97	66.84	58.12
AV. WAITING W.I.P. (FOR MACHINING PARTS)	265	272	279	283	288

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS B	PROGRAM: HMAN. OBJ				
SALES/ WORKLOAD — MULTIA =1.25, MULTIB =4.0, BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	TROLLEYS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	470	723	837	853	851
PARTS FINISHED	442	708	817	828	820
BATCHES FINISHED	84	110	129	130	129
BATCHES IN SYSTEM	19	16	14	13	13
BATCHES WAITING OUT	44	21	4	4	5
UNMANNED TOTAL MACHINE HOURS	4.23	3.4	10.75	2.2	2.07
RUNTIME FOR M/C 1 (S.T.U.)	19053	19180	19025	19026	19213
RUNTIME FOR M/C 2 (S.T.U.)	19045	19255	19295	19048	19101
RUNTIME FOR M/C 3 (S.T.U.)	20006	18151	20499	19279	19298
RUNTIME FOR M/C 4 (S.T.U.)	18981	19165	15833	14596	14958
RUNTIME FOR M/C 5 (S.T.U.)	19311	19250	14635	13386	14295
RUNTIME FOR M/C 6 (S.T.U.)	19062	19479	19284	19297	19236
TOT. WORK PROCESSED (%)	42.76	66.87	84.08	84.64	84.78
AV. PROCESS TIME (MINS)	61.41	39.59	32.43	30.67	31.17
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	26.81	42.61	55.21	57.85	57.20
UTIL. FOR M/C 1 (%)	39.14	61.80	76.71	78.86	80.21
UTIL. FOR M/C 2 (%)	18.34	32.92	45.44	48.35	47.78
UTIL. FOR M/C 3 (%)	39.83	59.55	74.90	73.87	72.68
UTIL. FOR M/C 4 (%)	43.24	60.20	71.58	77.64	75.77
UTIL. FOR M/C 5 (%)	11.05	15.25	24.12	26.37	24.69
UTIL. FOR M/C 6 (%)	9.29	25.92	38.52	41.99	42.08
AV. MAN POWER UTIL. (%)	83.30	77.70	66.85	53.32	44.94
AV. WAITING W.I.P. (FOR MACHINING PARTS)	211	201	178	177	179

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS B		PROGRAM: HMAN. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	TROLLEYS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	499	751	813	858	871
PARTS FINISHED	436	732	800	832	845
BATCHES FINISHED	85	114	126	130	132
BATCHES IN SYSTEM	25	17	17	15	14
BATCHES WAITING OUT	37	16	4	2	1
UNMANNED TOTAL MACHINE HOURS	10.25	1.4	3.93	3.33	2.35
RUNTIME FOR M/C 1 (S.T.U.)	18964	19113	19096	19130	19263
RUNTIME FOR M/C 2 (S.T.U.)	19454	19194	19492	19735	19220
RUNTIME FOR M/C 3 (S.T.U.)	21008	19336	19016	19124	19348
RUNTIME FOR M/C 4 (S.T.U.)	19128	18361	15878	14552	13882
RUNTIME FOR M/C 5 (S.T.U.)	19232	16524	15742	13047	13049
RUNTIME FOR M/C 6 (S.T.U.)	18489	19142	19161	19368	19228
TOT. WORK PROCESSED (%)	45.52	68.63	79.63	85.25	86.36
AV. PROCESS TIME (MINS)	58.25	37.17	33.33	30.58	29.85
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	28.14	44.20	52.97	58.15	59.48
UTIL. FOR M/C 1 (%)	42.53	64.34	73.22	80.56	79.00
UTIL. FOR M/C 2 (%)	19.72	32.80	44.07	46.47	51.59
UTIL. FOR M/C 3 (%)	42.50	58.14	70.35	72.21	73.61
UTIL. FOR M/C 4 (%)	42.44	59.89	69.26	75.57	79.22
UTIL. FOR M/C 5 (%)	10.60	23.40	24.56	29.63	29.63
UTIL. FOR M/C 6 (%)	11.04	26.66	36.34	44.44	43.83
AV. MAN POWER UTIL. (%)	86.33	78.20	63.73	53.04	45.60
AV. WAITING W.I.P. (FOR MACHINING PARTS)	266	236	226	217	218

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS B	PROGRAM: HMAN. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	TROLLEYS: (36)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (6)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	445	732	820	850	864
PARTS FINISHED	412	712	808	834	846
BATCHES FINISHED	82	112	129	132	133
BATCHES IN SYSTEM	30	19	17	14	13
BATCHES WAITING OUT	35	16	1	1	1
UNMANNED TOTAL MACHINE HOURS	1.38	3.18	9.23	4.37	1.07
RUNTIME FOR M/C 1 (S.T.U.)	19152	19048	19112	19129	19040
RUNTIME FOR M/C 2 (S.T.U.)	19292	19428	19804	19583	19289
RUNTIME FOR M/C 3 (S.T.U.)	18928	19314	20498	20675	19182
RUNTIME FOR M/C 4 (S.T.U.)	19090	19241	16234	14960	14154
RUNTIME FOR M/C 5 (S.T.U.)	19264	17432	15208	13399	12712
RUNTIME FOR M/C 6 (S.T.U.)	19171	18448	18508	19278	19258
TOT. WORK PROCESSED (%)	42.15	66.82	81.48	84.89	86.71
AV. PROCESS TIME (MINS)	64.55	38.56	33.34	31.48	29.99
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	26.69	42.47	53.09	56.49	59.42
UTIL. FOR M/C 1 (%)	40.79	56.71	71.12	74.54	77.13
UTIL. FOR M/C 2 (%)	17.49	32.24	46.04	47.80	49.82
UTIL. FOR M/C 3 (%)	42.40	64.79	74.90	74.26	80.04
UTIL. FOR M/C 4 (%)	39.22	58.03	69.81	75.76	78.08
UTIL. FOR M/C 5 (%)	9.38	20.25	23.21	26.35	27.77
UTIL. FOR M/C 6 (%)	10.85	22.83	33.47	40.26	43.68
AV. MAN POWER UTIL. (%)	81.64	78.64	67.59	55.31	46.46
AV. WAITING W.I.P. (FOR MACHINING PARTS)	269	260	242	237	235

COMPUTER SIMULATION RESULTS			T.K.D.		
FMS TYPE: FMS B		PROGRAM: HMAN. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	TROLLEYS: (24)		SCHEDULE: (4)	MAX.QUEUE AT LD.STNS. (4)Per M/C	
MANPOWER	2	3	4	5	6
PARTS MACHINED	786	928	999	999	999
PARTS FINISHED	769	924	999	999	999
BATCHES FINISHED	119	142	147	147	147
BATCHES IN SYSTEM	14	5	0	0	0
BATCHES WAITING OUT	14	0	0	0	0
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	-
RUNTIME FOR M/C 1 (S.T.U.)	28640	26021	23441	22517	21613
RUNTIME FOR M/C 2 (S.T.U.)	28565	28683	27422	25462	24914
RUNTIME FOR M/C 3 (S.T.U.)	28327	28381	26911	25366	25594
RUNTIME FOR M/C 4 (S.T.U.)	26283	19594	17359	15126	15132
RUNTIME FOR M/C 5 (S.T.U.)	25110	19940	16611	13805	14499
RUNTIME FOR M/C 6 (S.T.U.)	28730	27486	25235	25805	27328
TOT. WORK PROCESSED (%)	76.58	96.03	100.00	100.0	100.0
AV. PROCESS TIME (MINS)	52.69	40.44	34.28	32.05	32.30
CLOCK AT FINISH (S.T.U.)	28800	28800	27446	25829	27352
AV. M/C UTIL. (%)	33.30	45.79	51.80	55.76	55.67
UTIL. FOR M/C 1 (%)	51.67	65.06	72.22	75.18	78.33
UTIL. FOR M/C 2 (%)	26.40	41.22	45.56	49.75	45.84
UTIL. FOR M/C 3 (%)	47.34	59.42	65.23	65.80	65.21
UTIL. FOR M/C 4 (%)	43.12	59.40	67.05	72.70	72.67
UTIL. FOR M/C 5 (%)	14.06	16.17	19.41	28.00	26.66
UTIL. FOR M/C 6 (%)	17.24	33.48	41.36	43.11	45.28
AV. MAN POWER UTIL. (%)	81.65	66.25	53.71	45.29	36.08
AV. WAITING W.I.P. (FOR MACHINING PARTS)	182	163	148	137	138

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS B	PROGRAM: HMAN. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	TROLLEYS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	770	969	999	999	999
PARTS FINISHED	758	929	999	999	999
BATCHES FINISHED	117	143	147	147	147
BATCHES IN SYSTEM	16	4	0	0	0
BATCHES WAITING OUT	14	0	0	0	0
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	-
RUNTIME FOR M/C 1 (S.T.U.)	28563	26623	23253	22277	22279
RUNTIME FOR M/C 2 (S.T.U.)	28633	28789	24640	26612	25004
RUNTIME FOR M/C 3 (S.T.U.)	28703	28341	24821	24366	25767
RUNTIME FOR M/C 4 (S.T.U.)	26719	19947	16189	14897	15324
RUNTIME FOR M/C 5 (S.T.U.)	25751	17774	14612	13620	13962
RUNTIME FOR M/C 6 (S.T.U.)	28620	28475	26960	24517	24923
TOT. WORK PROCESSED (%)	73.44	97.37	100.00	100.0	100.0
AV. PROCESS TIME (MINS)	54.22	38.69	32.65	31.60	31.85
CLOCK AT FINISH (S.T.U.)	28800	28800	27024	26676	25831
AV. M/C UTIL. (%)	31.73	46.10	54.43	56.58	55.90
UTIL. FOR M/C 1 (%)	48.99	63.59	72.80	76.00	75.99
UTIL. FOR M/C 2 (%)	23.89	41.19	46.92	49.87	47.52
UTIL. FOR M/C 3 (%)	45.79	59.77	67.95	69.22	68.13
UTIL. FOR M/C 4 (%)	42.42	56.82	70.00	73.82	71.76
UTIL. FOR M/C 5 (%)	13.71	19.86	24.16	28.38	27.69
UTIL. FOR M/C 6 (%)	15.56	35.36	44.73	42.20	44.32
AV. MAN POWER UTIL. (%)	81.60	67.23	53.44	43.31	30.05
AV. WAITING W.I.P. (FOR MACHINING PARTS)	232	201	171	164	166

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS B		PROGRAM: HMAN. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	TROLLEYS: (36)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (6)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	763	934	999	999	999
PARTS FINISHED	758	916	999	999	999
BATCHES FINISHED	119	141	147	147	147
BATCHES IN SYSTEM	17	6	0	0	0
BATCHES WAITING OUT	11	0	0	0	0
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	-
RUNTIME FOR M/C 1 (S.T.U.)	28769	27449	23177	22463	22193
RUNTIME FOR M/C 2 (S.T.U.)	28631	28663	26653	24942	24955
RUNTIME FOR M/C 3 (S.T.U.)	26400	28769	26205	25285	26677
RUNTIME FOR M/C 4 (S.T.U.)	27244	21075	16550	15579	15516
RUNTIME FOR M/C 5 (S.T.U.)	26485	19119	15035	13250	13649
RUNTIME FOR M/C 6 (S.T.U.)	28610	28513	26088	24607	24791
TOT. WORK PROCESSED (%)	75.39	95.58	100.00	100.0	100.0
AV. PROCESS TIME (MINS)	54.41	41.11	33.46	31.56	31.98
CLOCK AT FINISH (S.T.U.)	28800	28800	26677	25349	25701
AV. M/C UTIL. (%)	32.95	44.20	53.14	56.12	55.54
UTIL. FOR M/C 1 (%)	51.04	61.67	73.04	75.36	76.28
UTIL. FOR M/C 2 (%)	24.12	41.68	48.09	48.26	50.16
UTIL. FOR M/C 3 (%)	49.43	57.87	66.99	69.43	64.39
UTIL. FOR M/C 4 (%)	41.60	53.77	68.48	72.75	73.04
UTIL. FOR M/C 5 (%)	13.33	18.46	23.48	26.64	25.86
UTIL. FOR M/C 6 (%)	18.18	31.72	38.76	44.27	43.52
AV. MAN POWER UTIL. (%)	81.63	65.74	55.49	46.15	38.71
AV. WAITING W.I.P. (FOR MACHINING PARTS)	245	229	189	178	179

E.3: FMS C SIMULATION RESULTS

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS C		PROGRAM: JMAN. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 4		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	TROLLEYS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	190	328	435	400	534
PARTS FINISHED	92	184	371	352	367
BATCHES FINISHED	41	60	77	75	88
BATCHES IN SYSTEM	23	21	19	19	19
BATCHES WAITING OUT	83	66	51	53	40
UNMANNED TOTAL MACHINE HOURS	1.67	17.07	13.72	12.57	18.60
RUNTIME FOR M/C 1 (S.T.U.)	9448	10333	10035	10614	10754
RUNTIME FOR M/C 2 (S.T.U.)	9506	9613	10122	9982	9938
RUNTIME FOR M/C 3 (S.T.U.)	9450	11292	8290	9372	9430
RUNTIME FOR M/C 4 (S.T.U.)	9357	10823	11321	10655	11553
RUNTIME FOR M/C 5 (S.T.U.)	9325	9823	9747	9885	9914
RUNTIME FOR M/C 6 (S.T.U.)	9519	9437	9407	9491	10097
TOT. WORK PROCESSED (%)	17.19	29.62	39.00	40.10	48.68
AV. PROCESS TIME (MINS)	74.48	46.74	33.86	37.50	28.88
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	22.09	33.89	47.74	47.89	56.41
UTIL. FOR M/C 1 (%)	27.42	43.74	65.55	65.81	77.55
UTIL. FOR M/C 2 (%)	11.95	18.27	29.27	25.92	38.40
UTIL. FOR M/C 3 (%)	30.03	50.57	73.03	73.47	80.99
UTIL. FOR M/C 4 (%)	53.95	64.41	77.48	84.95	88.18
UTIL. FOR M/C 5 (%)	6.06	12.50	20.17	14.85	21.85
UTIL. FOR M/C 6 (%)	3.13	13.88	20.94	22.32	31.48
AV. MAN POWER UTIL. (%)	81.71	82.46	80.11	63.66	65.07
AV. WAITING W.I.P. (FOR MACHINING PARTS)	221	258	222	246	257

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS C	PROGRAM: JMAN. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 4		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	TROLLEYS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	204	349	392	462	495
PARTS FINISHED	94	298	345	364	360
BATCHES FINISHED	41	64	75	79	88
BATCHES IN SYSTEM	28	26	24	25	24
BATCHES WAITING OUT	78	57	48	43	35
UNMANNED TOTAL MACHINE HOURS	3.73	20.98	13.08	11.07	15.32
RUNTIME FOR M/C 1 (S.T.U.)	9888	10669	9552	10117	9117
RUNTIME FOR M/C 2 (S.T.U.)	9724	9888	9872	9776	10036
RUNTIME FOR M/C 3 (S.T.U.)	9550	11239	8046	9671	9629
RUNTIME FOR M/C 4 (S.T.U.)	9566	11030	11255	10491	11143
RUNTIME FOR M/C 5 (S.T.U.)	8983	9468	8765	9869	9892
RUNTIME FOR M/C 6 (S.T.U.)	9445	9236	9843	9780	9831
TOT. WORK PROCESSED (%)	18.25	32.76	37.42	40.82	44.72
AV. PROCESS TIME (MINS)	70.04	44.08	36.56	32.31	30.13
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	22.98	36.97	47.01	49.25	54.23
UTIL. FOR M/C 1 (%)	26.20	47.67	62.44	54.89	74.28
UTIL. FOR M/C 2 (%)	11.10	18.27	24.31	32.57	36.96
UTIL. FOR M/C 3 (%)	31.52	57.10	75.24	76.04	79.31
UTIL. FOR M/C 4 (%)	57.76	72.97	77.93	85.42	81.14
UTIL. FOR M/C 5 (%)	6.29	12.45	16.75	16.82	20.93
UTIL. FOR M/C 6 (%)	4.99	13.33	25.37	29.76	32.79
AV. MAN POWER UTIL. (%)	86.0	87.25	77.51	67.91	63.52
AV. WAITING W.I.P. (FOR MACHINING PARTS)	273	271	268	277	300

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS C	PROGRAM: JMAN. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 4		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	TROLLEYS: (36)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (6)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	200	325	424	429	541
PARTS FINISHED	96	179	358	363	412
BATCHES FINISHED	39	60	74	74	92
BATCHES IN SYSTEM	33	31	31	32	27
BATCHES WAITING OUT	75	56	42	41	28
UNMANNED TOTAL MACHINE HOURS	6.12	17.75	10.83	7.3	15.9
RUNTIME FOR M/C 1 (S.T.U.)	9543	9913	9981	9633	10049
RUNTIME FOR M/C 2 (S.T.U.)	9676	9500	9855	9782	9936
RUNTIME FOR M/C 3 (S.T.U.)	9772	11612	7972	9414	9544
RUNTIME FOR M/C 4 (S.T.U.)	10026	10913	11291	10655	11242
RUNTIME FOR M/C 5 (S.T.U.)	9510	9596	9852	9598	9802
RUNTIME FOR M/C 6 (S.T.U.)	7978	9335	9543	9844	10134
TOT. WORK PROCESSED (%)	18.86	31.21	38.18	41.44	47.40
AV. PROCESS TIME (MINS)	70.63	46.82	34.49	34.34	28.05
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	23.49	35.90	47.41	50.63	56.15
UTIL. FOR M/C 1 (%)	39.04	54.65	64.55	66.06	70.37
UTIL. FOR M/C 2 (%)	7.96	19.74	25.92	34.51	40.18
UTIL. FOR M/C 3 (%)	30.80	50.65	75.94	77.25	80.02
UTIL. FOR M/C 4 (%)	52.23	63.88	76.23	84.95	86.67
UTIL. FOR M/C 5 (%)	4.72	11.80	18.92	11.79	27.34
UTIL. FOR M/C 6 (%)	6.19	14.67	22.91	29.24	32.31
AV. MAN POWER UTIL. (%)	80.64	84.44	81.58	64.72	66.89
AV. WAITING W.I.P. (FOR MACHINING PARTS)	265	308	271	297	328

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS C	PROGRAM: JMAN. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 4		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	TROLLEYS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	547	767	839	864	893
PARTS FINISHED	446	744	786	796	844
BATCHES FINISHED	84	177	126	127	133
BATCHES IN SYSTEM	19	13	13	14	11
BATCHES WAITING OUT	44	17	8	6	3
UNMANNED TOTAL MACHINE HOURS	14.75	15.13	16.83	19.28	10.3
RUNTIME FOR M/C 1 (S.T.U.)	21309	20290	20178	20919	19230
RUNTIME FOR M/C 2 (S.T.U.)	19342	18934	19881	20064	19621
RUNTIME FOR M/C 3 (S.T.U.)	19410	19686	19546	19546	19416
RUNTIME FOR M/C 4 (S.T.U.)	20125	19092	15653	16506	14667
RUNTIME FOR M/C 5 (S.T.U.)	19330	17836	14735	14394	13618
RUNTIME FOR M/C 6 (S.T.U.)	16862	19451	19926	20109	19738
TOT. WORK PROCESSED (%)	54.76	72.95	83.77	85.15	91.15
AV. PROCESS TIME (MINS)	53.19	37.58	32.75	32.27	29.76
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	33.02	45.29	54.56	54.22	61.13
UTIL. FOR M/C 1 (%)	54.85	72.20	75.72	68.81	84.85
UTIL. FOR M/C 2 (%)	22.34	34.19	43.68	46.15	48.07
UTIL. FOR M/C 3 (%)	48.89	59.15	71.76	71.76	83.52
UTIL. FOR M/C 4 (%)	57.33	62.47	72.40	72.76	77.27
UTIL. FOR M/C 5 (%)	8.82	16.46	23.96	20.40	25.92
UTIL. FOR M/C 6 (%)	5.89	27.25	39.81	45.95	47.17
AV. MAN POWER UTIL. (%)	91.38	86.19	71.69	57.00	51.00
AV. WAITING W.I.P. (FOR MACHINING PARTS)	224	220	186	207	201

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS C		PROGRAM: JMAN. OBJ			
SALES/ WORKLOAD: MULTIA =1.25, MULTIB =4.0, BT←SIZE =1.0		APC PALLET STATIONS 4	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	TROLLEYS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	481	758	830	865	900
PARTS FINISHED	412	739	753	797	868
BATCHES FINISHED	80	115	123	127	136
BATCHES IN SYSTEM	25	16	18	16	11
BATCHES WAITING OUT	42	16	6	4	0
UNMANNED TOTAL MACHINE HOURS	7.12	18.77	17.37	15.40	12.27
RUNTIME FOR M/C 1 (S.T.U.)	19990	19990	21057	20311	20032
RUNTIME FOR M/C 2 (S.T.U.)	19236	19455	19622	19459	19400
RUNTIME FOR M/C 3 (S.T.U.)	19320	17890	19201	19358	19588
RUNTIME FOR M/C 4 (S.T.U.)	19703	19921	16518	16078	14734
RUNTIME FOR M/C 5 (S.T.U.)	19138	18089	14244	14038	12917
RUNTIME FOR M/C 6 (S.T.U.)	18485	19808	19167	20006	19544
TOT. WORK PROCESSED (%)	50.22	70.03	80.42	84.93	92.29
AV. PROCESS TIME (MINS)	60.22	37.98	33.08	31.58	29.50
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	31.04	43.89	52.12	55.24	61.44
UTIL. FOR M/C 1 (%)	49.35	65.69	59.47	69.78	84.51
UTIL. FOR M/C 2 (%)	20.98	33.65	43.49	47.79	49.55
UTIL. FOR M/C 3 (%)	48.91	60.42	72.80	72.21	80.59
UTIL. FOR M/C 4 (%)	52.89	61.17	72.21	74.18	78.99
UTIL. FOR M/C 5 (%)	8.90	14.80	20.61	20.91	24.96
UTIL. FOR M/C 6 (%)	5.23	27.61	44.13	46.57	54.05
AV. MAN POWER UTIL. (%)	88.39	83.86	69.77	57.85	50.46
AV. WAITING W.I.P. (FOR MACHINING PARTS)	268	253	234	240	231

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS C	PROGRAM: JMAN. OBJ				
SALES/ WORKLOAD — MULTIA =1.25, MULTIB =4.0, BT←SIZE =1.0	APC PALLET STATIONS 4		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	TROLLEYS: (36)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (6)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	458	749	816	854	891
PARTS FINISHED	383	671	754	802	829
BATCHES FINISHED	78	113	123	129	133
BATCHES IN SYSTEM	30	20	20	16	14
BATCHES WAITING OUT	39	14	4	2	0
UNMANNED TOTAL MACHINE HOURS	11.02	16.42	12.68	14.90	17.73
RUNTIME FOR M/C 1 (S.T.U.)	20034	20586	19962	20423	20854
RUNTIME FOR M/C 2 (S.T.U.)	19050	19528	19703	19880	19944
RUNTIME FOR M/C 3 (S.T.U.)	19002	19360	19451	19762	19576
RUNTIME FOR M/C 4 (S.T.U.)	20497	18919	15743	16410	14394
RUNTIME FOR M/C 5 (S.T.U.)	19294	17066	13728	14378	11725
RUNTIME FOR M/C 6 (S.T.U.)	19363	19760	19279	19427	19570
TOT. WORK PROCESSED (%)	51.30	70.46	79.58	86.09	90.31
AV. PROCESS TIME (MINS)	64.00	38.46	33.05	32.28	29.76
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	31.41	43.81	52.63	55.31	60.31
UTIL. FOR M/C 1 (%)	57.74	60.26	70.26	76.83	74.27
UTIL. FOR M/C 2 (%)	18.93	38.05	42.14	47.72	50.96
UTIL. FOR M/C 3 (%)	45.68	55.75	68.57	71.13	79.53
UTIL. FOR M/C 4 (%)	50.17	63.04	73.93	72.68	78.73
UTIL. FOR M/C 5 (%)	6.61	17.20	23.48	20.42	30.11
UTIL. FOR M/C 6 (%)	9.34	28.53	37.42	43.10	48.26
AV. MAN POWER UTIL. (%)	85.84	84.20	69.18	58.21	50.51
AV. WAITING W.I.P. (FOR MACHINING PARTS)	297	284	241	267	264

COMPUTER SIMULATION RESULTS				T.K.D.	
FMS TYPE: FMS C	PROGRAM: JMAN. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 4		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	TROLLEYS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	792	976	999	999	999
PARTS FINISHED	747	948	999	999	999
BATCHES FINISHED	118	145	147	147	147
BATCHES IN SYSTEM	14	2	0	0	0
BATCHES WAITING OUT	15	0	0	0	0
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	-
RUNTIME FOR M/C 1 (S.T.U.)	28666	23496	21774	25122	19844
RUNTIME FOR M/C 2 (S.T.U.)	28753	28478	28334	24474	23918
RUNTIME FOR M/C 3 (S.T.U.)	28134	27869	24816	22494	22949
RUNTIME FOR M/C 4 (S.T.U.)	23764	18424	18850	15107	14581
RUNTIME FOR M/C 5 (S.T.U.)	25440	18605	17305	15035	13402
RUNTIME FOR M/C 6 (S.T.U.)	28032	28749	24696	23514	22697
TOT. WORK PROCESSED (%)	77.11	98.55	100.0	100.0	100.0
AV. PROCESS TIME (MINS)	51.39	37.30	33.98	31.47	29.38
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	34.36	48.84	52.42	56.50	60.68
UTIL. FOR M/C 1 (%)	50.92	72.05	77.75	67.39	85.31
UTIL. FOR M/C 2 (%)	29.15	41.92	44.93	52.28	53.11
UTIL. FOR M/C 3 (%)	50.61	62.99	67.26	70.36	71.08
UTIL. FOR M/C 4 (%)	48.98	61.51	68.21	75.02	77.72
UTIL. FOR M/C 5 (%)	12.67	18.97	11.59	23.48	26.34
UTIL. FOR M/C 6 (%)	13.82	35.57	44.80	50.45	50.52
AV. MAN POWER UTIL. (%)	87.06	71.89	54.95	49.41	42.71
AV. WAITING W.I.P. (FOR MACHINING PARTS)	205	184	150	153	153

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS C		PROGRAM: JMAN. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0		APC PALLET STATIONS 4		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471	FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)		TROLLEYS: (30)		SCHEDULE: (4)	MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	774	991	999	999	999
PARTS FINISHED	727	981	999	999	999
BATCHES FINISHED	118	145	147	147	147
BATCHES IN SYSTEM	17	2	0	0	0
BATCHES WAITING OUT	15	0	0	0	0
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	-
RUNTIME FOR M/C 1 (S.T.U.)	28621	26330	22075	24953	19824
RUNTIME FOR M/C 2 (S.T.U.)	28620	28561	25308	25777	25010
RUNTIME FOR M/C 3 (S.T.U.)	28674	28629	26596	23644	22935
RUNTIME FOR M/C 4 (S.T.U.)	24040	17902	16096	15395	14659
RUNTIME FOR M/C 5 (S.T.U.)	24047	18535	14756	14548	13769
RUNTIME FOR M/C 6 (S.T.U.)	28630	28701	26422	24876	23735
TOT. WORK PROCESSED (%)	72.11	98.95	100.0	100.0	100.0
AV. PROCESS TIME (MINS)	52.53	37.50	32.85	32.33	30.01
CLOCK AT FINISH (S.T.U.)	28800	28800	26600	26400	25034
AV. M/C UTIL. (%)	32.10	47.74	54.30	55.04	59.78
UTIL. FOR M/C 1 (%)	38.70	64.30	76.69	67.84	85.40
UTIL. FOR M/C 2 (%)	28.87	42.53	47.11	49.27	49.85
UTIL. FOR M/C 3 (%)	48.92	61.84	66.01	71.33	72.78
UTIL. FOR M/C 4 (%)	49.61	65.02	70.41	73.61	77.31
UTIL. FOR M/C 5 (%)	12.21	17.39	23.92	24.26	25.64
UTIL. FOR M/C 6 (%)	14.31	35.38	41.66	43.89	47.72
AV. MAN POWER UTIL. (%)	87.03	72.43	58.90	47.58	41.66
AV. WAITING W.I.P. (FOR MACHINING PARTS)	239	211	182	184	172

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS C			PROGRAM: JMAN. OBJ		
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 4		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	TROLLEYS: (36)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (6)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	788	980	999	999	999
PARTS FINISHED	776	976	999	999	999
BATCHES FINISHED	122	144	147	147	147
BATCHES IN SYSTEM	18	3	0	0	0
BATCHES WAITING OUT	7	0	0	0	0
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	-
RUNTIME FOR M/C 1 (S.T.U.)	27959	25724	21568	22743	23434
RUNTIME FOR M/C 2 (S.T.U.)	28603	28797	25389	24717	22958
RUNTIME FOR M/C 3 (S.T.U.)	28712	28103	24852	23243	23144
RUNTIME FOR M/C 4 (S.T.U.)	27347	18928	15716	16205	14517
RUNTIME FOR M/C 5 (S.T.U.)	24200	17642	14615	15455	12226
RUNTIME FOR M/C 6 (S.T.U.)	28712	28527	23856	24530	23025
TOT. WORK PROCESSED (%)	81.36	98.05	100.0	100.0	100.0
AV. PROCESS TIME (MINS)	52.52	37.68	31.53	31.76	29.86
CLOCK AT FINISH (S.T.U.)	28800	28800	25413	24741	23637
AV. M/C UTIL. (%)	35.16	47.34	56.43	55.91	59.13
UTIL. FOR M/C 1 (%)	60.55	65.81	78.49	74.44	72.24
UTIL. FOR M/C 2 (%)	29.61	41.41	45.08	52.63	50.63
UTIL. FOR M/C 3 (%)	47.45	62.47	70.64	71.81	72.12
UTIL. FOR M/C 4 (%)	46.25	61.49	72.11	73.60	78.07
UTIL. FOR M/C 5 (%)	9.51	18.27	24.15	19.00	28.87
UTIL. FOR M/C 6 (%)	17.95	34.62	48.13	43.97	52.85
AV. MAN POWER UTIL. (%)	89.37	69.88	60.14	50.00	43.78
AV. WAITING W.I.P. (FOR MACHINING PARTS)	268	246	192	200	204

E.4: FMS D SIMULATION RESULTS

<table>
<tr><td colspan="5">COMPUTER SIMULATION RESULTS</td><td>T.K.D.</td></tr>
<tr><td colspan="2">FMS TYPE: FMS D</td><td colspan="4">PROGRAM: DCON. OBJ</td></tr>
<tr><td>SALES/
WORKLOAD</td><td>MULTIA =1.25
MULTIB =4.0
BT←SIZE =1.0</td><td>APC PALLET STATIONS
2</td><td colspan="2">RANDOMISED SEQUENCE
RANDST=1
RNSEED=29471</td><td>FIXTURING
FIX←TYP=2</td></tr>
<tr><td colspan="2">SHIFTS/DAY: (1)</td><td>PALLETS: (18)</td><td colspan="2">SCHEDULE: (4)</td><td>MAX.QUEUE AT LD.STNS. (3)Per M/C</td></tr>
</table>

MANPOWER	2	3	4	5	
PARTS MACHINED	260	402	460	561	
PARTS FINISHED	244	389	439	542	
BATCHES FINISHED	50	72	74	89	
BATCHES IN SYSTEM	17	17	18	18	
BATCHES WAITING OUT	80	58	55	40	
UNMANNED TOTAL MACHINE HOURS	6.68	7.83	11.87	11.10	
RUNTIME FOR M/C 1 (S.T.U.)	9751	10331	10605	10723	
RUNTIME FOR M/C 2 (S.T.U.)	9970	9655	9775	10091	
RUNTIME FOR M/C 3 (S.T.U.)	10242	10056	10142	9872	
RUNTIME FOR M/C 4 (S.T.U.)	8312	9475	9654	9490	
RUNTIME FOR M/C 5 (S.T.U.)	8400	9377	9928	9643	
RUNTIME FOR M/C 6 (S.T.U.)	8188	9763	9836	9741	
TOT. WORK PROCESSED (%)	25.11	36.84	39.80	49.74	
AV. PROCESS TIME (MINS)	52.75	36.48	32.58	26.54	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	31.50	45.02	70.76	60.12	
UTIL. FOR M/C 1 (%)	62.62	62.76	85.01	89.80	
UTIL. FOR M/C 2 (%)	20.16	20.82	25.39	25.79	
UTIL. FOR M/C 3 (%)	62.76	74.21	89.38	91.83	
UTIL. FOR M/C 4 (%)	28.97	63.89	40.98	81.07	
UTIL. FOR M/C 5 (%)	11.20	22.01	21.74	37.22	
UTIL. FOR M/C 6 (%)	3.29	26.40	21.53	35.03	
AV. MAN POWER UTIL. (%)	91.86	89.24	70.76	68.0	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	142	155	159	157	
UTIL. OF TRANSPORT SYSTEM(%)	28.99	43.93	48.50	62.31	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS D		PROGRAM: DCON. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0		APC PALLET STATIONS 2	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	247	420	526	582	
PARTS FINISHED	226	404	513	565	
BATCHES FINISHED	48	74	84	91	
BATCHES IN SYSTEM	22	20	22	21	
BATCHES WAITING OUT	77	53	41	35	
UNMANNED TOTAL MACHINE HOURS	7.58	9.65	12.70	18.87	
RUNTIME FOR M/C 1 (S.T.U.)	10021	10424	10499	9857	
RUNTIME FOR M/C 2 (S.T.U.)	9753	9814	9736	9732	
RUNTIME FOR M/C 3 (S.T.U.)	10635	10114	11006	10174	
RUNTIME FOR M/C 4 (S.T.U.)	7535	9560	8925	11892	
RUNTIME FOR M/C 5 (S.T.U.)	7678	9789	9915	9945	
RUNTIME FOR M/C 6 (S.T.U.)	7680	9979	9724	10045	
TOT. WORK PROCESSED (%)	24.76	34.87	44.68	48.53	
AV. PROCESS TIME (MINS)	53.95	35.52	28.42	26.48	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	30.50	41.82	53.34	56.46	
UTIL. FOR M/C 1 (%)	62.91	77.65	84.25	76.68	
UTIL. FOR M/C 2 (%)	19.15	23.58	29.70	30.13	
UTIL. FOR M/C 3 (%)	68.40	68.18	80.65	88.22	
UTIL. FOR M/C 4 (%)	20.54	41.38	67.83	68.48	
UTIL. FOR M/C 5 (%)	8.49	21.55	32.74	37.25	
UTIL. FOR M/C 6 (%)	3.53	18.60	24.87	37.98	
AV. MAN POWER UTIL. (%)	92.99	89.81	81.61	68.67	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	134	149	157	149	
AV. UTIL. OF TRANSPORT SYSTEM(%)	27.37	44.34	57.75	66.70	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS D			PROGRAM: DCON. OBJ		
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	237	389	502	566	
PARTS FINISHED	219	369	491	553	
BATCHES FINISHED	49	70	84	95	
BATCHES IN SYSTEM	21	22	22	21	
BATCHES WAITING OUT	77	55	41	30	
UNMANNED TOTAL MACHINE HOURS	10.32	8.67	13.58	11.47	
RUNTIME FOR M/C 1 (S.T.U.)	9364	10383	9630	10589	
RUNTIME FOR M/C 2 (S.T.U.)	9628	9817	9881	9895	
RUNTIME FOR M/C 3 (S.T.U.)	10195	10268	10064	8819	
RUNTIME FOR M/C 4 (S.T.U.)	9936	9109	11376	9877	
RUNTIME FOR M/C 5 (S.T.U.)	9593	9640	9508	9954	
RUNTIME FOR M/C 6 (S.T.U.)	9720	9843	9694	9855	
TOT. WORK PROCESSED (%)	22.50	31.17	41.22	46.87	
AV. PROCESS TIME (MINS)	61.64	37.96	29.96	26.06	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	27.93	37.71	49.15	57.49	
UTIL. FOR M/C 1 (%)	71.36	73.73	82.55	82.11	
UTIL. FOR M/C 2 (%)	18.94	24.22	26.59	30.04	
UTIL. FOR M/C 3 (%)	49.46	52.96	59.94	71.77	
UTIL. FOR M/C 4 (%)	19.04	39.65	64.69	79.42	
UTIL. FOR M/C 5 (%)	6.73	19.90	32.76	41.92	
UTIL. FOR M/C 6 (%)	2.03	15.82	28.38	39.71	
AV. MAN POWER UTIL. (%)	86.40	87.55	81.49	69.48	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	168	182	180	186	
AV. UTIL. OF TRANSPORT SYSTEM(%)	24.51	38.62	54.98	64.09	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS D		PROGRAM: DCON. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0		APC PALLET STATIONS 2	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471	FIXTURING FIX←TYP=2	
SHIFTS/DAY: (2)	PALLETS: (18)		SCHEDULE: (4)	MAX.QUEUE AT LD.STNS. (3)Per M/C	
MANPOWER	2	3	4	5	
PARTS MACHINED	537	790	884	914	
PARTS FINISHED	522	781	876	910	
BATCHES FINISHED	83	122	132	135	
BATCHES IN SYSTEM	14	10	7	5	
BATCHES WAITING OUT	50	15	8	7	
UNMANNED TOTAL MACHINE HOURS	5.28	10.47	8.33	6.78	
RUNTIME FOR M/C 1 (S.T.U.)	19966	19652	19626	19062	
RUNTIME FOR M/C 2 (S.T.U.)	17579	16630	14288	12322	
RUNTIME FOR M/C 3 (S.T.U.)	18914	17140	14945	13814	
RUNTIME FOR M/C 4 (S.T.U.)	19051	19806	19578	19495	
RUNTIME FOR M/C 5 (S.T.U.)	19085	19286	19694	19265	
RUNTIME FOR M/C 6 (S.T.U.)	19259	19744	19780	19776	
TOT. WORK PROCESSED (%)	49.51	79.93	87.78	89.64	
AV. PROCESS TIME (MINS)	53.02	35.52	30.52	28.37	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	31.16	51.07	58.07	61.59	
UTIL. FOR M/C 1 (%)	67.82	81.74	86.27	88.83	
UTIL. FOR M/C 2 (%)	24.56	25.97	27.11	31.44	
UTIL. FOR M/C 3 (%)	55.90	61.68	73.71	79.75	
UTIL. FOR M/C 4 (%)	19.86	64.10	69.43	74.49	
UTIL. FOR M/C 5 (%)	13.06	38.77	50.83	47.99	
UTIL. FOR M/C 6 (%)	5.79	34.17	41.06	47.05	
AV. MAN POWER UTIL. (%)	77.42	77.38	63.20	51.83	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	132	124	125	115	
AV. UTIL. OF TRANSPORT SYSTEM(%)	27.97	41.97	48.43	49.68	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS D	PROGRAM: DCON. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	529	724	904	909	
PARTS FINISHED	519	708	889	899	
BATCHES FINISHED	86	112	136	139	
BATCHES IN SYSTEM	20	14	6	6	
BATCHES WAITING OUT	41	21	5	2	
UNMANNED TOTAL MACHINE HOURS	5.93	12.42	13.43	16.40	
RUNTIME FOR M/C 1 (S.T.U.)	19607	20585	19942	19514	
RUNTIME FOR M/C 2 (S.T.U.)	19225	16604	14811	13420	
RUNTIME FOR M/C 3 (S.T.U.)	19760	16350	13363	13499	
RUNTIME FOR M/C 4 (S.T.U.)	18334	19293	19683	20936	
RUNTIME FOR M/C 5 (S.T.U.)	19409	20456	19899	19835	
RUNTIME FOR M/C 6 (S.T.U.)	19268	19128	19881	19472	
TOT. WORK PROCESSED (%)	48.30	71.70	91.75	92.74	
AV. PROCESS TIME (MINS)	54.63	38.82	29.75	29.34	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	30.12	45.82	61.25	62.05	
UTIL. FOR M/C 1 (%)	63.89	81.27	84.91	86.77	
UTIL. FOR M/C 2 (%)	15.04	29.19	32.72	32.18	
UTIL. FOR M/C 3 (%)	40.14	61.43	75.16	78.32	
UTIL. FOR M/C 4 (%)	33.02	43.00	74.09	69.66	
UTIL. FOR M/C 5 (%)	17.75	36.64	56.35	56.75	
UTIL. FOR M/C 6 (%)	10.90	23.42	44.27	48.63	
AV. MAN POWER UTIL. (%)	84.14	72.32	64.29	51.78	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	131	129	134	129	
AV. UTIL. OF TRANSPORT SYSTEM(%)	28.93	40.10	49.80	52.31	

COMPUTER SIMULATION RESULTS						T.K.D.
FMS TYPE: FMS D			PROGRAM: DCON. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471			FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C	
MANPOWER	2	3	4	5		
PARTS MACHINED	548	758	868	909		
PARTS FINISHED	531	741	849	900		
BATCHES FINISHED	88	114	126	136		
BATCHES IN SYSTEM	23	19	16	11		
BATCHES WAITING OUT	36	14	5	0		
UNMANNED TOTAL MACHINE HOURS	13.85	6.33	8.70	12.70		
RUNTIME FOR M/C 1 (S.T.U.)	19626	19805	19474	19855		
RUNTIME FOR M/C 2 (S.T.U.)	19348	18101	12255	18511		
RUNTIME FOR M/C 3 (S.T.U.)	19769	18305	17436	9529		
RUNTIME FOR M/C 4 (S.T.U.)	19171	19322	19632	19881		
RUNTIME FOR M/C 5 (S.T.U.)	17555	19568	19726	19325		
RUNTIME FOR M/C 6 (S.T.U.)	17768	19520	19935	19741		
TOT. WORK PROCESSED (%)	48.86	74.16	86.89	91.55		
AV. PROCESS TIME (MINS)	51.66	37.80	31.24	29.38		
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800		
AV. M/C UTIL. (%)	30.81	46.52	56.51	62.16		
UTIL. FOR M/C 1 (%)	59.69	84.46	81.63	85.28		
UTIL. FOR M/C 2 (%)	16.71	34.52	31.61	43.82		
UTIL. FOR M/C 3 (%)	31.01	37.53	63.18	66.42		
UTIL. FOR M/C 4 (%)	40.50	54.74	69.40	70.82		
UTIL. FOR M/C 5 (%)	21.83	38.06	49.11	54.50		
UTIL. FOR M/C 6 (%)	15.13	29.83	44.15	52.13		
AV. MAN POWER UTIL. (%)	88.26	74.91	63.08	51.79		
AV. WAITING W.I.P. (FOR MACHINING PARTS)	159	166	169	166		
AV. UTIL. OF TRANSPORT SYSTEM(%)	30.03	41.62	49.37	52.94		

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS D		PROGRAM: DCON. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (18)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (3)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	670	987	999	999	
PARTS FINISHED	658	986	999	999	
BATCHES FINISHED	104	145	147	147	
BATCHES IN SYSTEM	9	2	0	0	
BATCHES WAITING OUT	34	0	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	24018	23217	19643	19308	
RUNTIME FOR M/C 2 (S.T.U.)	21616	16021	13260	12595	
RUNTIME FOR M/C 3 (S.T.U.)	22226	16043	14024	13801	
RUNTIME FOR M/C 4 (S.T.U.)	23046	28695	24780	24345	
RUNTIME FOR M/C 5 (S.T.U.)	23449	28657	26546	23992	
RUNTIME FOR M/C 6 (S.T.U.)	23239	28475	25158	23375	
TOT. WORK PROCESSED (%)	63.70	97.88	100.00	100.00	
AV. PROCESS TIME (MINS)	51.34	35.74	30.88	29.38	
CLOCK AT FINISH (S.T.U.)	28800	28800	26605	24404	
AV. M/C UTIL. (%)	33.26	50.35	58.89	61.25	
UTIL. FOR M/C 1 (%)	70.50	72.93	86.20	87.69	
UTIL. FOR M/C 2 (%)	19.98	24.18	29.22	30.76	
UTIL. FOR M/C 3 (%)	47.57	68.67	78.55	79.82	
UTIL. FOR M/C 4 (%)	29.74	56.80	64.23	72.40	
UTIL. FOR M/C 5 (%)	18.35	38.17	50.06	50.27	
UTIL. FOR M/C 6 (%)	13.43	41.38	45.11	46.53	
AV. MAN POWER UTIL. (%)	66.60	62.30	51.12	44.60	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	115	105	89	83	
AV. UTIL. OF TRANSPORT SYSTEM(%)	24.31	38.78	43.04	46.81	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS D	PROGRAM: DCON. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	745	989	999	999	
PARTS FINISHED	741	999	999	999	
BATCHES FINISHED	115	147	147	147	
BATCHES IN SYSTEM	12	0	0	0	
BATCHES WAITING OUT	20	0	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	23085	20899	20814	19442	
RUNTIME FOR M/C 2 (S.T.U.)	18995	18364	13988	12293	
RUNTIME FOR M/C 3 (S.T.U.)	19288	17778	14523	12366	
RUNTIME FOR M/C 4 (S.T.U.)	28570	26951	23901	22753	
RUNTIME FOR M/C 5 (S.T.U.)	28601	27523	23372	22417	
RUNTIME FOR M/C 6 (S.T.U.)	28697	27603	24656	23141	
TOT. WORK PROCESSED (%)	73.08	100.0	100.0	100.0	
AV. PROCESS TIME (MINS)	49.41	34.81	30.34	28.13	
CLOCK AT FINISH (S.T.U.)	28800	27681	24734	23219	
AV. M/C UTIL. (%)	37.43	52.07	59.08	64.30	
UTIL. FOR M/C 1 (%)	73.35	81.02	81.35	87.09	
UTIL. FOR M/C 2 (%)	25.51	26.39	30.87	35.13	
UTIL. FOR M/C 3 (%)	52.07	56.50	72.79	85.49	
UTIL. FOR M/C 4 (%)	31.84	62.63	70.62	74.18	
UTIL. FOR M/C 5 (%)	22.26	43.63	54.77	51.23	
UTIL. FOR M/C 6 (%)	19.54	42.26	44.10	52.67	
AV. MAN POWER UTIL. (%)	74.37	64.98	54.24	45.21	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	113	105	98	93	
AV. UTIL. OF TRANSPORT SYSTEM(%)	27.21	41.47	46.33	49.43	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS D	PROGRAM: DCON. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	812	999	999	999	
PARTS FINISHED	796	999	999	999	
BATCHES FINISHED	124	147	147	147	
BATCHES IN SYSTEM	15	0	0	0	
BATCHES WAITING OUT	8	0	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	25582	19744	21645	19124	
RUNTIME FOR M/C 2 (S.T.U.)	23086	23617	12045	19702	
RUNTIME FOR M/C 3 (S.T.U.)	24868	11846	18848	8910	
RUNTIME FOR M/C 4 (S.T.U.)	28578	28412	27221	21765	
RUNTIME FOR M/C 5 (S.T.U.)	28683	28458	25174	20556	
RUNTIME FOR M/C 6 (S.T.U.)	28785	27406	24230	24983	
TOT. WORK PROCESSED (%)	79.43	100.0	100.0	100.0	
AV. PROCESS TIME (MINS)	49.13	34.91	32.32	28.79	
CLOCK AT FINISH (S.T.U.)	28800	28535	27280	25061	
AV. M/C UTIL. (%)	36.29	53.25	54.38	64.05	
UTIL. FOR M/C 1 (%)	66.19	85.76	78.23	88.54	
UTIL. FOR M/C 2 (%)	28.90	36.25	32.16	43.45	
UTIL. FOR M/C 3 (%)	33.05	53.43	58.45	71.03	
UTIL. FOR M/C 4 (%)	38.60	62.36	65.09	73.58	
UTIL. FOR M/C 5 (%)	32.24	41.53	48.37	53.46	
UTIL. FOR M/C 6 (%)	18.76	40.19	43.98	54.23	
AV. MAN POWER UTIL. (%)	81.36	64.37	49.39	42.49	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	144	136	131	116	
AV. UTIL. OF TRANSPORT SYSTEM(%)	30.22	40.08	41.88	45.66	

E.5: FMS E SIMULATION RESULTS

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS E	PROGRAM: COHC. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	6
PARTS MACHINED	277	413	519	580	595
PARTS FINISHED	261	387	507	558	580
BATCHES FINISHED	56	73	82	89	90
BATCHES IN SYSTEM	23	23	23	23	23
BATCHES WAITING OUT	68	51	42	25	34
UNMANNED TOTAL MACHINE HOURS	10.63	12.30	17.67	16.05	12.82
RUNTIME FOR M/C 1 (S.T.U.)	10359	11822	11733	11645	11097
RUNTIME FOR M/C 2 (S.T.U.)	10001	9774	9678	9687	9648
RUNTIME FOR M/C 3 (S.T.U.)	10109	9863	11114	10682	9732
RUNTIME FOR M/C 4 (S.T.U.)	9703	8971	8253	9692	9877
RUNTIME FOR M/C 5 (S.T.U.)	9800	9017	9646	9413	9865
RUNTIME FOR M/C 6 (S.T.U.)	9515	9377	9836	9807	9749
TOT. WORK PROCESSED (%)	26.55	38.36	46.03	52.07	52.81
AV. PROCESS TIME (MINS)	53.69	35.61	29.03	26.26	25.20
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	28800
AV. M/C UTIL. (%)	31.70	45.20	54.13	60.38	63.07
UTIL. FOR M/C 1 (%)	73.32	88.48	83.91	89.82	90.56
UTIL. FOR M/C 2 (%)	21.06	22.53	29.06	29.03	29.98
UTIL. FOR M/C 3 (%)	53.26	69.92	81.16	88.82	97.49
UTIL. FOR M/C 4 (%)	24.82	42.18	73.36	78.35	77.95
UTIL. FOR M/C 5 (%)	9.85	25.85	29.64	41.00	40.04
UTIL. FOR M/C 6 (%)	7.91	22.21	27.66	35.28	42.44
AV. MAN POWER UTIL. (%)	97.73	87.94	76.85	67.72	57.75
AV. WAITING W.I.P. (FOR MACHINING PARTS)	155	171	177	237	174
AV. UTIL. OF TRANSPORT SYSTEM(%)	12.20	19.60	26.96	31.60	33.37

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS E		PROGRAM: COHC. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	210	405	519	590	
PARTS FINISHED	185	382	506	571	
BATCHES FINISHED	46	68	81	94	
BATCHES IN SYSTEM	28	28	28	25	
BATCHES WAITING OUT	73	51	38	28	
UNMANNED TOTAL MACHINE HOURS	10.02	12.52	19.33	20.50	
RUNTIME FOR M/C 1 (S.T.U.)	9880	11523	11875	11450	
RUNTIME FOR M/C 2 (S.T.U.)	8501	9704	9804	9839	
RUNTIME FOR M/C 3 (S.T.U.)	7922	10325	10916	11178	
RUNTIME FOR M/C 4 (S.T.U.)	9772	8186	8928	9877	
RUNTIME FOR M/C 5 (S.T.U.)	9599	9095	9968	10084	
RUNTIME FOR M/C 6 (S.T.U.)	9638	8650	9668	9930	
TOT. WORK PROCESSED (%)	24.33	36.78	45.42	53.90	
AV. PROCESS TIME (MINS)	65.85	35.48	29.46	26.42	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	32.66	43.51	52.44	61.35	
UTIL. FOR M/C 1 (%)	75.15	89.30	85.06	89.87	
UTIL. FOR M/C 2 (%)	18.49	27.48	26.54	31.35	
UTIL. FOR M/C 3 (%)	74.44	73.59	74.80	87.31	
UTIL. FOR M/C 4 (%)	19.36	33.62	67.81	79.42	
UTIL. FOR M/C 5 (%)	7.50	23.74	34.95	41.35	
UTIL. FOR M/C 6 (%)	1.02	13.32	25.46	38.82	
AV. MAN POWER UTIL. (%)	89.43	84.38	75.98	69.78	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	188	236	235	236	
AV. UTIL. OF TRANSPORT SYSTEM(%)	8.57	18.58	27.79	33.12	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS E	PROGRAM: COHC. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2	
SHIFTS/DAY: (1)	PALLETS: (36)	SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (6)Per M/C	
MANPOWER	2	3	4	5	
PARTS MACHINED	234	362	532	572	
PARTS FINISHED	206	340	517	554	
BATCHES FINISHED	50	60	87	90	
BATCHES IN SYSTEM	33	30	31	29	
BATCHES WAITING OUT	64	57	29	28	
UNMANNED TOTAL MACHINE HOURS	10.85	16.77	20.83	22.37	
RUNTIME FOR M/C 1 (S.T.U.)	11274	11572	12312	11892	
RUNTIME FOR M/C 2 (S.T.U.)	6767	10064	9985	9962	
RUNTIME FOR M/C 3 (S.T.U.)	7235	10518	10817	10817	
RUNTIME FOR M/C 4 (S.T.U.)	9217	9179	8619	8248	
RUNTIME FOR M/C 5 (S.T.U.)	9685	9640	10042	10299	
RUNTIME FOR M/C 6 (S.T.U.)	9883	9804	9842	10226	
TOT. WORK PROCESSED (%)	27.56	35.22	47.14	50.93	
AV. PROCESS TIME (MINS)	57.76	41.97	28.96	26.85	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	36.17	39.67	54.25	59.26	
UTIL. FOR M/C 1 (%)	82.28	88.98	87.09	90.17	
UTIL. FOR M/C 2 (%)	16.91	32.09	26.71	32.42	
UTIL. FOR M/C 3 (%)	73.03	85.76	68.49	84.22	
UTIL. FOR M/C 4 (%)	24.26	16.86	70.24	73.40	
UTIL. FOR M/C 5 (%)	10.89	9.26	42.11	47.32	
UTIL. FOR M/C 6 (%)	9.63	5.07	30.86	28.02	
AV. MAN POWER UTIL. (%)	95.27	76.52	80.18	67.72	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	178	215	236	237	
AV. UTIL. OF TRANSPORT SYSTEM(%)	11.73	15.17	29.65	31.60	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS E	PROGRAM: COHC. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	581	745	841	892	
PARTS FINISHED	560	717	830	890	
BATCHES FINISHED	93	113	128	133	
BATCHES IN SYSTEM	22	12	11	8	
BATCHES WAITING OUT	32	22	8	6	
UNMANNED TOTAL MACHINE HOURS	4.98	10.13	17.67	11.03	
RUNTIME FOR M/C 1 (S.T.U.)	19688	18937	19141	18470	
RUNTIME FOR M/C 2 (S.T.U.)	19325	16619	15724	12669	
RUNTIME FOR M/C 3 (S.T.U.)	19160	17345	15677	13205	
RUNTIME FOR M/C 4 (S.T.U.)	18766	19637	20083	19914	
RUNTIME FOR M/C 5 (S.T.U.)	19438	19440	19818	19542	
RUNTIME FOR M/C 6 (S.T.U.)	18808	19440	19739	19356	
TOT. WORK PROCESSED (%)	57.14	70.65	85.80	89.60	
AV. PROCESS TIME (MINS)	49.56	37.39	32.75	28.91	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	35.74	45.87	55.92	62.31	
UTIL. FOR M/C 1 (%)	80.37	89.41	88.46	91.67	
UTIL. FOR M/C 2 (%)	11.97	25.98	27.46	34.08	
UTIL. FOR M/C 3 (%)	34.25	60.95	67.44	80.06	
UTIL. FOR M/C 4 (%)	45.06	44.69	61.39	74.48	
UTIL. FOR M/C 5 (%)	25.17	27.49	49.57	50.33	
UTIL. FOR M/C 6 (%)	17.59	26.70	41.18	43.26	
AV. MAN POWER UTIL. (%)	89.35	70.65	59.86	49.34	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	155	151	140	130	
AV. UTIL. OF TRANSPORT SYSTEM(%)	15.67	18.80	23.77	25.97	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS E	PROGRAM: COHC. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	540	798	866	871	
PARTS FINISHED	524	785	856	858	
BATCHES FINISHED	83	123	128	130	
BATCHES IN SYSTEM	21	15	12	11	
BATCHES WAITING OUT	43	9	7	6	
UNMANNED TOTAL MACHINE HOURS	12.77	18.42	13.80	13.55	
RUNTIME FOR M/C 1 (S.T.U.)	21022	18731	19936	18443	
RUNTIME FOR M/C 2 (S.T.U.)	16881	14778	12630	11590	
RUNTIME FOR M/C 3 (S.T.U.)	20118	18919	15681	13863	
RUNTIME FOR M/C 4 (S.T.U.)	17377	21472	19848	19737	
RUNTIME FOR M/C 5 (S.T.U.)	18348	19990	19920	19872	
RUNTIME FOR M/C 6 (S.T.U.)	17845	19758	19757	19462	
TOT. WORK PROCESSED (%)	53.25	81.63	88.91	89.28	
AV. PROCESS TIME (MINS)	51.66	35.60	31.11	29.55	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	32.87	51.23	58.31	61.86	
UTIL. FOR M/C 1 (%)	79.56	90.40	84.93	91.81	
UTIL. FOR M/C 2 (%)	22.95	26.21	30.67	33.43	
UTIL. FOR M/C 3 (%)	46.71	58.23	70.25	79.46	
UTIL. FOR M/C 4 (%)	22.77	57.41	68.64	69.03	
UTIL. FOR M/C 5 (%)	14.84	44.10	46.80	52.84	
UTIL. FOR M/C 6 (%)	10.40	31.03	48.54	44.60	
AV. MAN POWER UTIL. (%)	82.84	75.12	59.75	48.96	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	203	195	188	186	
AV. UTIL. OF TRANSPORT SYSTEM(%)	11.94	21.55	25.11	25.70	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS E		PROGRAM: COHC. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0		APC PALLET STATIONS 2	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (36)		SCHEDULE: (4)	MAX.QUEUE AT LD.STNS. (6)Per M/C	
MANPOWER	2	3	4	5	
PARTS MACHINED	484	781	824	856	
PARTS FINISHED	461	768	818	841	
BATCHES FINISHED	77	119	126	129	
BATCHES IN SYSTEM	27	20	14	14	
BATCHES WAITING OUT	43	8	7	4	
UNMANNED TOTAL MACHINE HOURS	10.58	9.68	13.05	17.47	
RUNTIME FOR M/C 1 (S.T.U.)	21051	19668	19125	19699	
RUNTIME FOR M/C 2 (S.T.U.)	19228	13151	12113	10950	
RUNTIME FOR M/C 3 (S.T.U.)	19556	19528	16286	19309	
RUNTIME FOR M/C 4 (S.T.U.)	19197	18754	19027	20404	
RUNTIME FOR M/C 5 (S.T.U.)	13980	19289	19541	19316	
RUNTIME FOR M/C 6 (S.T.U.)	13903	19282	19874	19525	
TOT. WORK PROCESSED (%)	47.73	81.20	84.92	88.83	
AV. PROCESS TIME (MINS)	55.22	35.11	32.15	31.89	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	29.88	52.14	56.70	56.80	
UTIL. FOR M/C 1 (%)	80.43	86.09	88.53	85.95	
UTIL. FOR M/C 2 (%)	14.42	26.89	29.19	32.29	
UTIL. FOR M/C 3 (%)	34.53	52.07	69.72	57.93	
UTIL. FOR M/C 4 (%)	21.50	66.79	65.83	67.74	
UTIL. FOR M/C 5 (%)	16.12	38.91	47.26	44.92	
UTIL. FOR M/C 6 (%)	12.27	42.09	39.66	51.96	
AV. MAN POWER UTIL. (%)	76.39	74.84	58.88	48.45	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	196	206	200	206	
AV. UTIL. OF TRANSPORT SYSTEM(%)	10.70	22.22	23.47	25.87	

COMPUTER SIMULATION RESULTS				T.K.D.	
FMS TYPE: FMS E		PROGRAM: COHC. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471	FIXTURING FIX←TYP=2	
SHIFTS/DAY: (3)	PALLETS: (24)		SCHEDULE: (4)	MAX.QUEUE AT LD.STNS. (4)Per M/C	
MANPOWER	2	3	4	5	6
PARTS MACHINED	769	999	999	999	999
PARTS FINISHED	763	999	999	999	999
BATCHES FINISHED	118	147	147	147	147
BATCHES IN SYSTEM	12	0	0	0	0
BATCHES WAITING OUT	17	0	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	22024	20250	19121	19042	18920
RUNTIME FOR M/C 2 (S.T.U.)	17642	16926	14032	14363	12652
RUNTIME FOR M/C 3 (S.T.U.)	18989	19289	14171	12691	12326
RUNTIME FOR M/C 4 (S.T.U.)	28519	26960	25520	24512	23682
RUNTIME FOR M/C 5 (S.T.U.)	28769	27321	24612	23321	22401
RUNTIME FOR M/C 6 (S.T.U.)	28728	26745	26454	24204	22759
TOT. WORK PROCESSED (%)	75.95	100.0	100.0	100.0	100.0
AV. PROCESS TIME (MINS)	47.03	34.41	31.01	29.56	28.21
CLOCK AT FINISH (S.T.U.)	28800	28320	26882	24962	24480
AV. M/C UTIL. (%)	39.64	52.34	58.84	61.73	64.23
UTIL. FOR M/C 1 (%)	76.88	83.61	88.55	88.92	89.49
UTIL. FOR M/C 2 (%)	24.48	25.51	30.77	33.74	34.13
UTIL. FOR M/C 3 (%)	55.67	54.81	74.60	79.14	85.77
UTIL. FOR M/C 4 (%)	33.30	62.61	70.78	73.69	74.21
UTIL. FOR M/C 5 (%)	25.88	46.56	47.75	53.48	53.02
UTIL. FOR M/C 6 (%)	21.62	40.95	40.58	41.39	48.78
AV. MAN POWER UTIL. (%)	73.19	61.51	49.72	42.25	35.58
AV. WAITING W.I.P. (FOR MACHINING PARTS)	125	115	107	101	97
AV. UTIL. OF TRANSPORT SYSTEM(%)	12.85	21.70	22.77	24.59	25.66

COMPUTER SIMULATION RESULTS				T.K.D.	
FMS TYPE: FMS E	PROGRAM: COHC. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471	FIXTURING FIX←TYP=2	
SHIFTS/DAY: (3)	PALLETS: (30)		SCHEDULE: (4)	MAX.QUEUE AT LD.STNS. (5)Per M/C	
MANPOWER	2	3	4	5	
PARTS MACHINED	704	987	999	999	
PARTS FINISHED	696	987	999	999	
BATCHES FINISHED	111	145	147	147	
BATCHES IN SYSTEM	15	2	0	0	
BATCHES WAITING OUT	21	0	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	20079	19700	19913	18660	
RUNTIME FOR M/C 2 (S.T.U.)	22758	12762	12295	11026	
RUNTIME FOR M/C 3 (S.T.U.)	27653	19076	16066	13872	
RUNTIME FOR M/C 4 (S.T.U.)	28786	28446	25604	24253	
RUNTIME FOR M/C 5 (S.T.U.)	28670	28029	23925	23371	
RUNTIME FOR M/C 6 (S.T.U.)	28670	28521	24228	23551	
TOT. WORK PROCESSED (%)	70.82	97.62	100.0	100.0	
AV. PROCESS TIME (MINS)	55.62	34.58	30.54	28.71	
CLOCK AT FINISH (S.T.U.)	28800	28800	26400	24482	
AV. M/C UTIL. (%)	34.81	51.84	58.20	62.62	
UTIL. FOR M/C 1 (%)	84.33	85.95	85.03	90.74	
UTIL. FOR M/C 2 (%)	17.02	30.36	31.51	35.14	
UTIL. FOR M/C 3 (%)	39.84	57.75	68.57	79.41	
UTIL. FOR M/C 4 (%)	31.74	56.24	68.64	72.46	
UTIL. FOR M/C 5 (%)	19.76	40.47	50.96	53.00	
UTIL. FOR M/C 6 (%)	16.15	40.29	44.52	44.97	
AV. MAN POWER UTIL. (%)	69.24	60.16	49.49	42.10	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	184	155	140	131	
AV. UTIL. OF TRANSPORT SYSTEM(%)	12.08	20.75	23.50	25.21	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS E		PROGRAM: COHC. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (36)		SCHEDULE: (4)	MAX.QUEUE AT LD.STNS. (6)Per M/C	
MANPOWER	2	3	4	5	
PARTS MACHINED	686	997	999	999	
PARTS FINISHED	683	996	999	999	
BATCHES FINISHED	108	146	147	147	
BATCHES IN SYSTEM	16	1	0	0	
BATCHES WAITING OUT	23	0	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	20354	19577	19586	19118	
RUNTIME FOR M/C 2 (S.T.U.)	20494	13796	11805	10805	
RUNTIME FOR M/C 3 (S.T.U.)	27659	21601	18837	15501	
RUNTIME FOR M/C 4 (S.T.U.)	28663	28780	25473	24625	
RUNTIME FOR M/C 5 (S.T.U.)	28565	26905	25643	23357	
RUNTIME FOR M/C 6 (S.T.U.)	28774	26967	23420	23578	
TOT. WORK PROCESSED (%)	56.30	34.51	31.22	29.28	
AV. PROCESS TIME (MINS)	63.33	36.92	33.96	31.76	
CLOCK AT FINISH (S.T.U.)	28800	28800	25671	24962	
AV. M/C UTIL. (%)	34.12	51.76	56.55	60.66	
UTIL. FOR M/C 1 (%)	83.19	86.49	86.45	88.57	
UTIL. FOR M/C 2 (%)	17.25	25.63	29.95	32.73	
UTIL. FOR M/C 3 (%)	41.05	52.56	60.27	73.25	
UTIL. FOR M/C 4 (%)	30.32	60.58	68.99	68.54	
UTIL. FOR M/C 5 (%)	18.70	44.21	47.17	51.05	
UTIL. FOR M/C 6 (%)	14.19	41.10	46.47	49.84	
AV. MAN POWER UTIL. (%)	68.60	60.97	50.89	41.68	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	181	163	151	139	
AV. UTIL. TRANSPORT SYSTEM(%)	11.87	21.29	24.58	25.53	

E.6: FMS F SIMULATION RESULTS

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS F	PROGRAM: CRGS. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	PALLETS: (18)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (3)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	81	120	165	190	
PARTS FINISHED	76	111	162	183	
BATCHES FINISHED	21	31	41	45	
BATCHES IN SYSTEM	18	18	18	18	
BATCHES WAITING OUT	108	98	88	84	
UNMANNED TOTAL MACHINE HOURS	3.87	4.55	5.48	5.25	
RUNTIME FOR M/C 1 (S.T.U.)	4208	4139	4262	4239	
RUNTIME FOR M/C 2 (S.T.U.)	3930	4162	3874	4147	
RUNTIME FOR M/C 3 (S.T.U.)	4310	4094	4200	4053	
RUNTIME FOR M/C 4 (S.T.U.)	3281	3907	3981	3962	
RUNTIME FOR M/C 5 (S.T.U.)	2970	3873	4171	3806	
RUNTIME FOR M/C 6 (S.T.U.)	3471	3622	4229	4249	
TOT. WORK PROCESSED (%)	10.54	12.65	15.80	17.13	
AV. PROCESS TIME (MINS)	68.43	49.58	37.45	32.18	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	31.01	37.58	45.80	50.56	
UTIL. FOR M/C 1 (%)	68.61	73.64	77.15	80.04	
UTIL. FOR M/C 2 (%)	14.38	12.13	14.58	19.98	
UTIL. FOR M/C 3 (%)	78.45	86.59	95.59	99.06	
UTIL. FOR M/C 4 (%)	20.97	30.82	47.53	60.78	
UTIL. FOR M/C 5 (%)	3.06	16.63	25.22	22.33	
UTIL. FOR M/C 6 (%)	0.58	5.66	14.76	24.19	
AV. MAN POWER UTIL. (%)	43.80	38.32	36.03	31.22	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	141	161	164	175	
AV. UTIL. OF TRANSPORT SYSTEM(%)	6.52	9.51	12.14	13.62	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS F		PROGRAM: CRGS. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0		APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471	FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)		PALLETS: (24)		SCHEDULE: (4)	MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	73	142	183	192	
PARTS FINISHED	71	141	179	186	
BATCHES FINISHED	24	36	44	48	
BATCHES IN SYSTEM	23	23	23	23	
BATCHES WAITING OUT	100	88	80	76	
UNMANNED TOTAL MACHINE HOURS	5.50	8.22	8.50	4.35	
RUNTIME FOR M/C 1 (S.T.U.)	4390	4231	4254	4241	
RUNTIME FOR M/C 2 (S.T.U.)	3067	3930	4135	4153	
RUNTIME FOR M/C 3 (S.T.U.)	4497	5156	5156	4336	
RUNTIME FOR M/C 4 (S.T.U.)	3740	3704	4012	3667	
RUNTIME FOR M/C 5 (S.T.U.)	4160	3976	4091	4081	
RUNTIME FOR M/C 6 (S.T.U.)	3737	3829	3822	3904	
TOT. WORK PROCESSED (%)	9.14	15.33	17.80	18.55	
AV. PROCESS TIME (MINS)	80.79	43.71	34.80	31.75	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	25.98	41.42	48.11	54.11	
UTIL. FOR M/C 1 (%)	65.08	82.68	86.01	82.48	
UTIL. FOR M/C 2 (%)	11.54	14.38	19.78	21.50	
UTIL. FOR M/C 3 (%)	54.28	94.28	94.28	100.0	
UTIL. FOR M/C 4 (%)	18.40	32.51	51.45	56.29	
UTIL. FOR M/C 5 (%)	6.03	16.98	22.32	22.96	
UTIL. FOR M/C 6 (%)	0.54	7.73	14.81	23.92	
AV. MAN POWER UTIL. (%)	39.72	43.64	38.71	33.69	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	124	158	172	173	
AV. UTIL. OF TRANSPORT SYSTEM(%)	5.47	10.69	13.13	13.59	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS F	PROGRAM: CRGS. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	87	136	196	206	
PARTS FINISHED	79	135	191	200	
BATCHES FINISHED	24	41	49	51	
BATCHES IN SYSTEM	29	29	29	29	
BATCHES WAITING OUT	94	77	69	67	
UNMANNED TOTAL MACHINE HOURS	6.52	6.82	8.28	8.48	
RUNTIME FOR M/C 1 (S.T.U.)	4506	4100	4194	4210	
RUNTIME FOR M/C 2 (S.T.U.)	2629	3953	4187	4186	
RUNTIME FOR M/C 3 (S.T.U.)	4967	4311	4884	4870	
RUNTIME FOR M/C 4 (S.T.U.)	3160	3461	3826	3979	
RUNTIME FOR M/C 5 (S.T.U.)	4091	3953	4171	4091	
RUNTIME FOR M/C 6 (S.T.U.)	4082	4100	4205	3883	
TOT. WORK PROCESSED (%)	11.39	15.31	19.42	20.01	
AV. PROCESS TIME (MINS)	67.34	43.89	32.48	30.61	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	31.11	45.12	53.77	55.48	
UTIL. FOR M/C 1 (%)	70.55	87.32	91.08	90.74	
UTIL. FOR M/C 2 (%)	13.47	19.71	21.33	21.33	
UTIL. FOR M/C 3 (%)	75.64	100.0	100.0	100.0	
UTIL. FOR M/C 4 (%)	16.33	29.82	58.44	60.52	
UTIL. FOR M/C 5 (%)	8.29	16.34	24.41	30.68	
UTIL. FOR M/C 6 (%)	2.40	9.68	19.17	21.12	
AV. MAN POWER UTIL. (%)	45.13	43.35	40.86	33.98	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	172	215	242	244	
AV. UTIL. OF TRANSPORT SYSTEM(%)	6.41	10.57	13.69	14.59	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS F	PROGRAM: CRGS. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (18)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (3)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	316	527	657	690	
PARTS FINISHED	298	517	633	676	
BATCHES FINISHED	60	84	99	105	
BATCHES IN SYSTEM	18	18	16	13	
BATCHES WAITING OUT	69	45	32	29	
UNMANNED TOTAL MACHINE HOURS	5.25	5.93	6.88	5.42	
RUNTIME FOR M/C 1 (S.T.U.)	14528	14163	14341	14158	
RUNTIME FOR M/C 2 (S.T.U.)	13485	13485	14119	13039	
RUNTIME FOR M/C 3 (S.T.U.)	13228	13718	13495	13408	
RUNTIME FOR M/C 4 (S.T.U.)	9036	13537	13417	13431	
RUNTIME FOR M/C 5 (S.T.U.)	9108	13353	13750	13835	
RUNTIME FOR M/C 6 (S.T.U.)	8693	13700	13464	13597	
TOT. WORK PROCESSED (%)	33.17	48.76	59.80	63.56	
AV. PROCESS TIME (MINS)	53.86	38.88	31.43	29.52	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	32.00	42.71	52.29	56.20	
UTIL. FOR M/C 1 (%)	77.66	82.67	87.45	88.58	
UTIL. FOR M/C 2 (%)	11.15	18.70	28.49	29.71	
UTIL. FOR M/C 3 (%)	45.74	54.40	74.32	79.95	
UTIL. FOR M/C 4 (%)	28.55	56.84	62.12	65.62	
UTIL. FOR M/C 5 (%)	17.19	25.11	30.36	35.71	
UTIL. FOR M/C 6 (%)	11.69	18.56	31.01	37.62	
AV. MAN POWER UTIL. (%)	56.50	54.61	50.09	40.84	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	149	144	130	123	
AV. UTIL. OF TRANSPORT SYSTEM(%)	10.49	16.03	19.70	20.72	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS F		PROGRAM: CRGS. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0		APC PALLET STATIONS 2	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	294	604	711	749	
PARTS FINISHED	277	595	692	700	
BATCHES FINISHED	54	92	103	111	
BATCHES IN SYSTEM	23	23	23	15	
BATCHES WAITING OUT	70	32	21	21	
UNMANNED TOTAL MACHINE HOURS	1.70	7.77	11.18	9.2	
RUNTIME FOR M/C 1 (S.T.U.)	13510	14801	14908	14855	
RUNTIME FOR M/C 2 (S.T.U.)	13676	13221	13467	13494	
RUNTIME FOR M/C 3 (S.T.U.)	13494	13262	13742	12529	
RUNTIME FOR M/C 4 (S.T.U.)	8335	13471	15003	14733	
RUNTIME FOR M/C 5 (S.T.U.)	9150	13608	14337	13631	
RUNTIME FOR M/C 6 (S.T.U.)	8624	14310	13814	13670	
TOT. WORK PROCESSED (%)	32.80	55.83	68.60	72.34	
AV. PROCESS TIME (MINS)	56.79	34.22	29.98	27.67	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	31.79	48.38	57.58	62.72	
UTIL. FOR M/C 1 (%)	82.08	85.75	85.14	92.54	
UTIL. FOR M/C 2 (%)	13.42	21.57	26.75	35.91	
UTIL. FOR M/C 3 (%)	53.51	59.80	68.39	80.17	
UTIL. FOR M/C 4 (%)	24.76	57.15	73.53	74.88	
UTIL. FOR M/C 5 (%)	11.56	30.94	52.24	48.76	
UTIL. FOR M/C 6 (%)	5.38	35.05	39.42	44.03	
AV. MAN POWER UTIL. (%)	52.72	60.86	52.45	42.77	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	149	156	141	126	
AV. UTIL OF TRANSPORT SYSTEM(%)	8.45	18.45	20.92	21.61	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS F	PROGRAM: CRGS. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	391	568	669	716	
PARTS FINISHED	385	564	655	702	
BATCHES FINISHED	68	89	104	108	
BATCHES IN SYSTEM	28	27	26	20	
BATCHES WAITING OUT	51	31	17	19	
UNMANNED TOTAL MACHINE HOURS	3.17	4.92	5.65	5.38	
RUNTIME FOR M/C 1 (S.T.U.)	13920	14323	14167	14144	
RUNTIME FOR M/C 2 (S.T.U.)	13338	13836	12039	11060	
RUNTIME FOR M/C 3 (S.T.U.)	13455	13536	12085	13367	
RUNTIME FOR M/C 4 (S.T.U.)	13027	13100	13676	13334	
RUNTIME FOR M/C 5 (S.T.U.)	13751	13198	13709	13859	
RUNTIME FOR M/C 6 (S.T.U.)	13412	13235	13914	13603	
TOT. WORK PROCESSED (%)	34.66	52.56	66.30	69.07	
AV. PROCESS TIME (MINS)	51.73	35.75	29.74	27.71	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	30.76	46.44	59.78	62.06	
UTIL. FOR M/C 1 (%)	71.10	86.23	91.39	93.11	
UTIL. FOR M/C 2 (%)	15.71	22.30	29.93	35.03	
UTIL. FOR M/C 3 (%)	46.64	58.92	72.25	80.20	
UTIL. FOR M/C 4 (%)	25.09	56.18	67.97	76.92	
UTIL. FOR M/C 5 (%)	16.47	31.79	47.38	47.72	
UTIL. FOR M/C 6 (%)	9.57	23.20	49.73	39.41	
AV. MAN POWER UTIL. (%)	63.70	58.59	49.46	42.27	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	201	209	204	178	
AV. UTIL. OF TRANSPORT SYSTEM(%)	11.15	16.81	20.39	19.85	

COMPUTER SIMULATION RESULTS				T.K.D.
FMS TYPE: FMS F	PROGRAM: CRGS. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471	FIXTURING FIX←TYP=2	
SHIFTS/DAY: (3)	PALLETS: (18)	SCHEDULE: (4)	MAX.QUEUE AT LD.STNS. (3)Per M/C	

MANPOWER	2	3	4	5	
PARTS MACHINED	745	960	999	999	
PARTS FINISHED	740	959	999	999	
BATCHES FINISHED	115	142	147	147	
BATCHES IN SYSTEM	9	4	0	0	
BATCHES WAITING OUT	23	1	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	23280	22136	19865	19343	
RUNTIME FOR M/C 2 (S.T.U.)	16528	17322	14928	13294	
RUNTIME FOR M/C 3 (S.T.U.)	18033	17420	14701	14346	
RUNTIME FOR M/C 4 (S.T.U.)	27506	28613	24656	24483	
RUNTIME FOR M/C 5 (S.T.U.)	28685	28725	26472	23270	
RUNTIME FOR M/C 6 (S.T.U.)	28678	28769	24448	23489	
TOT. WORK PROCESSED (%)	73.67	93.49	100.0	100.0	
AV. PROCESS TIME (MINS)	47.89	37.24	31.30	29.59	
CLOCK AT FINISH (S.T.U.)	28800	28800	26529	24539	
AV. M/C UTIL. (%)	38.93	47.84	57.84	60.59	
UTIL. FOR M/C 1 (%)	72.73	76.49	85.24	87.54	
UTIL. FOR M/C 2 (%)	23.44	22.36	28.93	29.14	
UTIL. FOR M/C 3 (%)	61.09	63.24	71.91	76.79	
UTIL. FOR M/C 4 (%)	32.92	53.31	64.55	71.99	
UTIL. FOR M/C 5 (%)	24.28	36.14	52.50	49.59	
UTIL. FOR M/C 6 (%)	19.15	35.52	43.93	48.48	
AV. MAN POWER UTIL. (%)	73.19	60.68	51.44	43.82	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	123	104	91	85	
AV. UTIL. OF TRANSPORT SYSTEM(%)	14.56	20.57	24.69	26.79	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS F		PROGRAM: CRGS. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0		APC PALLET STATIONS 2	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	623	999	999	999	
PARTS FINISHED	614	999	999	999	
BATCHES FINISHED	98	147	147	147	
BATCHES IN SYSTEM	11	0	0	0	
BATCHES WAITING OUT	38	0	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	22203	19747	18835	18561	
RUNTIME FOR M/C 2 (S.T.U.)	22277	17187	12023	12427	
RUNTIME FOR M/C 3 (S.T.U.)	22370	16519	13815	12559	
RUNTIME FOR M/C 4 (S.T.U.)	22685	27248	25144	23635	
RUNTIME FOR M/C 5 (S.T.U.)	21893	27256	25282	23357	
RUNTIME FOR M/C 6 (S.T.U.)	21805	27834	24540	22385	
TOT. WORK PROCESSED (%)	61.02	100.0	100.0	100.0	
AV. PROCESS TIME (MINS)	53.46	33.98	29.94	28.26	
CLOCK AT FINISH (S.T.U.)	28800	27907	25358	23691	
AV. M/C UTIL. (%)	33.05	53.78	60.68	64.21	
UTIL. FOR M/C 1 (%)	76.26	85.74	89.90	91.22	
UTIL. FOR M/C 2 (%)	19.38	28.20	32.22	34.75	
UTIL. FOR M/C 3 (%)	47.26	60.80	79.74	84.18	
UTIL. FOR M/C 4 (%)	27.72	61.95	67.13	71.42	
UTIL. FOR M/C 5 (%)	15.06	44.15	44.91	47.61	
UTIL. FOR M/C 6 (%)	12.59	41.82	50.20	56.08	
AV. MAN POWER UTIL. (%)	61.97	64.02	52.27	44.61	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	126	112	101	97	
AV. UTIL. OF TRANSPORT SYSTEM(%)	11.45	21.45	24.01	25.91	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS F	PROGRAM: CRGS. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	826	999	999	999	
PARTS FINISHED	822	999	999	999	
BATCHES FINISHED	127	147	147	147	
BATCHES IN SYSTEM	12	0	0	0	
BATCHES WAITING OUT	8	0	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	24435	19619	18904	18834	
RUNTIME FOR M/C 2 (S.T.U.)	21145	13371	11526	11702	
RUNTIME FOR M/C 3 (S.T.U.)	26605	17582	15903	14093	
RUNTIME FOR M/C 4 (S.T.U.)	28647	26975	25788	22744	
RUNTIME FOR M/C 5 (S.T.U.)	28665	24738	23099	21809	
RUNTIME FOR M/C 6 (S.T.U.)	28557	25531	24388	22760	
TOT. WORK PROCESSED (%)	84.26	100.0	100.0	100.0	
AV. PROCESS TIME (MINS)	47.84	31.99	29.93	28.01	
CLOCK AT FINISH (S.T.U.)	28800	27031	26400	22834	
AV. M/C UTIL. (%)	38.49	55.74	59.54	63.60	
UTIL. FOR M/C 1 (%)	69.29	86.30	89.57	89.90	
UTIL. FOR M/C 2 (%)	18.32	28.97	33.61	33.11	
UTIL. FOR M/C 3 (%)	41.41	62.65	69.27	78.17	
UTIL. FOR M/C 4 (%)	40.77	65.69	68.71	74.21	
UTIL. FOR M/C 5 (%)	35.25	44.02	46.42	52.22	
UTIL. FOR M/C 6 (%)	25.89	46.79	49.66	53.98	
AV. MAN POWER UTIL. (%)	78.28	64.51	49.30	45.80	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	174	137	138	127	
AV. UTIL. OF TRANSPORT SYSTEM(%)	15.94	20.83	22.73	25.66	

E.7: FMS G (2 AGVs) SIMULATION RESULTS

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/2 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	PALLETS: (18)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (3)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	246	364	431	553	
PARTS FINISHED	226	350	414	533	
BATCHES FINISHED	53	68	75	88	
BATCHES IN SYSTEM	18	18	18	18	
BATCHES WAITING OUT	76	61	54	41	
UNMANNED TOTAL MACHINE HOURS	8.12	10.60	15.93	22.63	
RUNTIME FOR M/C 1 (S.T.U.)	10268	10522	10052	10361	
RUNTIME FOR M/C 2 (S.T.U.)	9756	9439	9730	10057	
RUNTIME FOR M/C 3 (S.T.U.)	10238	9895	9797	11015	
RUNTIME FOR M/C 4 (S.T.U.)	8510	9746	11612	11538	
RUNTIME FOR M/C 5 (S.T.U.)	8509	10032	9980	10269	
RUNTIME FOR M/C 6 (S.T.U.)	8163	9780	9656	9709	
TOT. WORK PROCESSED (%)	26.78	33.80	41.11	49.23	
AV. PROCESS TIME (MINS)	56.35	40.81	35.28	28.46	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	32.97	40.55	48.60	55.68	
UTIL. FOR M/C 1 (%)	76.02	81.95	89.87	90.98	
UTIL. FOR M/C 2 (%)	15.42	18.10	21.32	25.47	
UTIL. FOR M/C 3 (%)	59.09	69.69	77.19	82.30	
UTIL. FOR M/C 4 (%)	30.32	35.30	52.14	66.68	
UTIL. FOR M/C 5 (%)	13.07	17.09	27.13	37.78	
UTIL. FOR M/C 6 (%)	3.92	21.15	23.95	30.85	
AV. MAN POWER UTIL. (%)	91.57	81.45	70.97	64.60	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	152	174	177	164	
AV. UTIL. OF TRANSPORT SYSTEM(%)	10.90	14.84	17.96	22.88	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/2 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	223	423	497	574	
PARTS FINISHED	200	402	484	562	
BATCHES FINISHED	50	71	78	89	
BATCHES IN SYSTEM	23	23	23	22	
BATCHES WAITING OUT	74	53	46	36	
UNMANNED TOTAL MACHINE HOURS	7.55	11.35	10.27	25.70	
RUNTIME FOR M/C 1 (S.T.U.)	10342	11317	10641	11470	
RUNTIME FOR M/C 2 (S.T.U.)	9713	9430	9626	9739	
RUNTIME FOR M/C 3 (S.T.U.)	10255	9737	10268	11286	
RUNTIME FOR M/C 4 (S.T.U.)	8786	9765	8537	11717	
RUNTIME FOR M/C 5 (S.T.U.)	9819	9762	9807	9741	
RUNTIME FOR M/C 6 (S.T.U.)	9675	9533	9531	9669	
TOT. WORK PROCESSED (%)	25.60	37.19	43.16	51.59	
AV. PROCESS TIME (MINS)	65.68	35.19	30.17	27.71	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	30.73	43.86	52.99	56.75	
UTIL. FOR M/C 1 (%)	77.41	87.00	84.84	89.55	
UTIL. FOR M/C 2 (%)	13.57	24.03	28.05	29.28	
UTIL. FOR M/C 3 (%)	56.19	68.88	78.20	86.47	
UTIL. FOR M/C 4 (%)	19.58	42.27	70.91	65.71	
UTIL. FOR M/C 5 (%)	12.80	25.60	31.45	36.60	
UTIL. FOR M/C 6 (%)	48.17	15.35	24.46	32.87	
AV. MAN POWER UTIL. (%)	91.12	88.95	75.07	66.71	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	141	166	170	183	
AV. UTIL. OF TRANSPORT SYSTEM(%)	10.52	17.36	21.00	24.80	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/2 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	296	438	506	543	
PARTS FINISHED	278	419	488	527	
BATCHES FINISHED	53	73	79	88	
BATCHES IN SYSTEM	28	28	28	28	
BATCHES WAITING OUT	66	46	40	31	
UNMANNED TOTAL MACHINE HOURS	11.43	14.85	17.48	25.75	
RUNTIME FOR M/C 1 (S.T.U.)	10197	11478	11438	11658	
RUNTIME FOR M/C 2 (S.T.U.)	9979	9482	9834	9600	
RUNTIME FOR M/C 3 (S.T.U.)	10835	10714	10861	10695	
RUNTIME FOR M/C 4 (S.T.U.)	9942	9417	8654	11545	
RUNTIME FOR M/C 5 (S.T.U.)	9643	9875	10040	9622	
RUNTIME FOR M/C 6 (S.T.U.)	9547	9694	9864	9752	
TOT. WORK PROCESSED (%)	28.91	37.41	44.63	49.60	
AV. PROCESS TIME (MINS)	50.80	34.62	29.99	28.95	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	33.91	42.96	52.40	55.32	
UTIL. FOR M/C 1 (%)	84.87	84.29	88.31	88.27	
UTIL. FOR M/C 2 (%)	22.71	28.12	24.51	27.36	
UTIL. FOR M/C 3 (%)	57.08	69.15	69.96	76.34	
UTIL. FOR M/C 4 (%)	25.95	38.36	60.95	67.94	
UTIL. FOR M/C 5 (%)	7.38	23.97	30.99	37.55	
UTIL. FOR M/C 6 (%)	5.46	13.85	30.66	34.43	
AV. MAN POWER UTIL. (%)	99.16	90.13	75.90	65.45	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	201	234	236	240	
AV. UTIL. OF TRANSPORT SYSTEM(%)	12.92	19.12	22.86	25.42	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/2 AGVs		PROGRAM: DAGV. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (18)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (3)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	529	745	841	870	
PARTS FINISHED	511	726	832	864	
BATCHES FINISHED	78	113	129	132	
BATCHES IN SYSTEM	14	11	8	6	
BATCHES WAITING OUT	55	23	10	9	
UNMANNED TOTAL MACHINE HOURS	4.40	11.03	11.00	7.87	
RUNTIME FOR M/C 1 (S.T.U.)	19540	19284	20137	19195	
RUNTIME FOR M/C 2 (S.T.U.)	19147	17222	16110	15030	
RUNTIME FOR M/C 3 (S.T.U.)	19435	18068	17090	15098	
RUNTIME FOR M/C 4 (S.T.U.)	19172	19416	19198	19722	
RUNTIME FOR M/C 5 (S.T.U.)	19321	19931	19714	19348	
RUNTIME FOR M/C 6 (S.T.U.)	19115	20053	19549	19392	
TOT. WORK PROCESSED (%)	49.94	72.51	85.59	87.89	
AV. PROCESS TIME (MINS)	54.69	38.25	33.23	30.97	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	31.03	45.97	54.58	58.32	
UTIL. FOR M/C 1 (%)	76.78	78.86	84.08	88.21	
UTIL. FOR M/C 2 (%)	20.23	22.49	24.05	28.73	
UTIL. FOR M/C 3 (%)	56.68	60.97	64.46	70.02	
UTIL. FOR M/C 4 (%)	18.84	49.97	65.01	67.71	
UTIL. FOR M/C 5 (%)	8.41	33.74	47.94	43.77	
UTIL. FOR M/C 6 (%)	5.25	29.78	41.97	51.49	
AV. MAN POWER UTIL. (%)	77.83	74.62	62.75	50.67	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	149	137	132	125	
AV. UTIL. OF TRANSPORT SYSTEM(%)	10.44	14.32	16.94	17.30	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/2 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471			FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (24)	SCHEDULE: (4)			MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	449	677	814	882	
PARTS FINISHED	429	662	801	877	
BATCHES FINISHED	71	105	126	135	
BATCHES IN SYSTEM	14	12	12	6	
BATCHES WAITING OUT	62	30	9	5	
UNMANNED TOTAL MACHINE HOURS	4.48	15.82	10.98	16.88	
RUNTIME FOR M/C 1 (S.T.U.)	19708	19340	18978	19108	
RUNTIME FOR M/C 2 (S.T.U.)	18429	17758	13520	13190	
RUNTIME FOR M/C 3 (S.T.U.)	18200	17788	13889	13192	
RUNTIME FOR M/C 4 (S.T.U.)	7938	20883	19848	20936	
RUNTIME FOR M/C 5 (S.T.U.)	9235	19631	19404	19501	
RUNTIME FOR M/C 6 (S.T.U.)	8632	19302	19560	19819	
TOT. WORK PROCESSED (%)	45.74	42.36	32.31	29.97	
AV. PROCESS TIME (MINS)	68.22	46.29	34.57	32.11	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	34.54	41.62	56.82	61.87	
UTIL. FOR M/C 1 (%)	82.77	87.55	89.22	88.61	
UTIL. FOR M/C 2 (%)	21.02	24.32	28.65	32.74	
UTIL. FOR M/C 3 (%)	60.53	59.43	79.31	80.14	
UTIL. FOR M/C 4 (%)	23.83	39.73	58.85	69.66	
UTIL. FOR M/C 5 (%)	12.31	22.88	46.30	52.52	
UTIL. FOR M/C 6 (%)	6.79	15.83	38.60	47.58	
AV. MAN POWER UTIL. (%)	71.28	68.29	61.13	51.93	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	138	146	138	141	
AV. UTIL. OF TRANSPORT SYSTEM(%)	10.04	14.44	17.40	19.28	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/2 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	556	748	838	875	
PARTS FINISHED	540	736	822	868	
BATCHES FINISHED	87	116	128	131	
BATCHES IN SYSTEM	26	16	12	10	
BATCHES WAITING OUT	34	15	7	6	
UNMANNED TOTAL MACHINE HOURS	7.03	10.35	15.83	13.43	
RUNTIME FOR M/C 1 (S.T.U.)	20239	19395	18907	18914	
RUNTIME FOR M/C 2 (S.T.U.)	19307	12746	12327	12229	
RUNTIME FOR M/C 3 (S.T.U.)	19174	19527	15618	15252	
RUNTIME FOR M/C 4 (S.T.U.)	19477	19230	20020	19429	
RUNTIME FOR M/C 5 (S.T.U.)	18939	19198	20075	19725	
RUNTIME FOR M/C 6 (S.T.U.)	19058	19321	19480	19753	
TOT. WORK PROCESSED (%)	54.23	75.89	85.30	89.88	
AV. PROCESS TIME (MINS)	52.25	36.57	31.75	30.09	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	33.33	49.03	57.03	60.49	
UTIL. FOR M/C 1 (%)	80.60	87.30	89.55	89.52	
UTIL. FOR M/C 2 (%)	14.64	30.39	31.43	31.68	
UTIL. FOR M/C 3 (%)	39.63	56.41	70.53	72.23	
UTIL. FOR M/C 4 (%)	32.29	51.67	61.58	71.23	
UTIL. FOR M/C 5 (%)	21.43	34.76	40.57	56.09	
UTIL. FOR M/C 6 (%)	11.37	33.65	48.50	42.19	
AV. MAN POWER UTIL. (%)	89.64	76.23	63.92	49.94	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	193	195	192	188	
AV. UTIL. OF TRANSPORT SYSTEM(%)	13.16	17.38	19.44	20.20	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/2 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2) (NO BATTERY CHANGE DURING SHIFT)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4		
PARTS MACHINED	588	809	840		
PARTS FINISHED	565	794	831		
BATCHES FINISHED	89	125	127		
BATCHES IN SYSTEM	23	14	12		
BATCHES WAITING OUT	35	8	8		
UNMANNED TOTAL MACHINE HOURS	6.28	11.50	11.83		
RUNTIME FOR M/C 1 (S.T.U.)	19991	19500	18543		
RUNTIME FOR M/C 2 (S.T.U.)	19641	14409	11871		
RUNTIME FOR M/C 3 (S.T.U.)	19398	19035	15947		
RUNTIME FOR M/C 4 (S.T.U.)	18217	19848	19848		
RUNTIME FOR M/C 5 (S.T.U.)	17741	19624	19613		
RUNTIME FOR M/C 6 (S.T.U.)	17787	19508	19606		
TOT. WORK PROCESSED (%)	57.81	82.66	85.57		
AV. PROCESS TIME (MINS)	47.95	34.59	31.38		
CLOCK AT FINISH (S.T.U.)	28800	28800	28800		
AV. M/C UTIL. (%)	36.32	52.31	57.64		
UTIL. FOR M/C 1 (%)	83.67	86.83	91.31		
UTIL. FOR M/C 2 (%)	18.34	26.89	32.63		
UTIL. FOR M/C 3 (%)	46.49	57.09	69.08		
UTIL. FOR M/C 4 (%)	34.52	59.94	63.20		
UTIL. FOR M/C 5 (%)	21.98	44.65	49.05		
UTIL. FOR M/C 6 (%)	12.94	38.46	40.58		
AV. MAN POWER UTIL. (%)	86.81	76.96	58.27		
AV. WAITING W.I.P. (FOR MACHINING PARTS)	199	198	193		
AV. UTIL. OF TRANSPORT SYSTEM(%)	13.72	18.54	19.40		

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/2 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471			FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (18)	SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (3)Per M/C	
MANPOWER	2	3	4	5	
PARTS MACHINED	647	885	999	999	
PARTS FINISHED	641	883	999	999	
BATCHES FINISHED	102	133	147	147	
BATCHES IN SYSTEM	9	6	0	0	
BATCHES WAITING OUT	36	8	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	23113	21870	20029	20225	
RUNTIME FOR M/C 2 (S.T.U.)	21464	14680	14923	13427	
RUNTIME FOR M/C 3 (S.T.U.)	21960	15850	15227	15017	
RUNTIME FOR M/C 4 (S.T.U.)	28649	28664	27854	25708	
RUNTIME FOR M/C 5 (S.T.U.)	28583	28516	26550	24835	
RUNTIME FOR M/C 6 (S.T.U.)	28577	28747	26287	24550	
TOT. WORK PROCESSED (%)	62.20	87.94	100.0	100.0	
AV. PROCESS TIME (MINS)	58.87	39.08	32.75	30.97	
CLOCK AT FINISH (S.T.U.)	28800	28800	27920	28800	
AV. M/C UTIL. (%)	31.26	47.41	55.48	57.92	
UTIL. FOR M/C 1 (%)	73.26	77.42	84.54	83.72	
UTIL. FOR M/C 2 (%)	18.05	26.39	25.96	28.85	
UTIL. FOR M/C 3 (%)	50.16	69.50	72.35	73.36	
UTIL. FOR M/C 4 (%)	22.81	47.98	63.28	65.43	
UTIL. FOR M/C 5 (%)	14.29	32.52	45.80	45.66	
UTIL. FOR M/C 6 (%)	90.00	30.66	40.96	50.47	
AV. MAN POWER UTIL. (%)	69.15	62.06	51.43	38.85	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	134	118	95	90	
AV. UTIL. OF TRANSPORT SYSTEM(%)	8.68	11.54	14.60	14.10	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/2 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	611	963	999	999	
PARTS FINISHED	595	958	999	999	
BATCHES FINISHED	95	140	147	147	
BATCHES IN SYSTEM	11	6	0	0	
BATCHES WAITING OUT	41	1	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	22748	19548	19078	18543	
RUNTIME FOR M/C 2 (S.T.U.)	23351	15054	13366	13455	
RUNTIME FOR M/C 3 (S.T.U.)	23195	17209	14542	13261	
RUNTIME FOR M/C 4 (S.T.U.)	22235	28781	26699	24194	
RUNTIME FOR M/C 5 (S.T.U.)	19896	28717	26587	24559	
RUNTIME FOR M/C 6 (S.T.U.)	20204	28736	26420	24083	
TOT. WORK PROCESSED (%)	60.43	96.85	100.0	100.0	
AV. PROCESS TIME (MINS)	53.86	35.84	31.70	29.55	
CLOCK AT FINISH (S.T.U.)	28800	28800	26788	28800	
AV. M/C UTIL. (%)	32.48	51.59	57.66	61.71	
UTIL. FOR M/C 1 (%)	74.43	86.62	88.75	91.31	
UTIL. FOR M/C 2 (%)	20.75	25.73	28.98	32.09	
UTIL. FOR M/C 3 (%)	43.30	64.01	75.75	79.72	
UTIL. FOR M/C 4 (%)	28.28	55.95	65.82	69.77	
UTIL. FOR M/C 5 (%)	17.65	38.65	47.52	46.03	
UTIL. FOR M/C 6 (%)	10.43	38.57	39.15	51.36	
AV. MAN POWER UTIL. (%)	64.43	63.58	53.61	38.70	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	114	117	110	103	
AV. UTIL OF TRANSPORT SYSTEM(%)	8.60	14.06	16.24	15.24	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/2 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	793	935	999	999	
PARTS FINISHED	788	932	999	999	
BATCHES FINISHED	123	139	147	147	
BATCHES IN SYSTEM	15	7	0	0	
BATCHES WAITING OUT	9	1	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	20951	20642	19445	18901	
RUNTIME FOR M/C 2 (S.T.U.)	19789	13040	12629	11820	
RUNTIME FOR M/C 3 (S.T.U.)	25375	21063	15926	15231	
RUNTIME FOR M/C 4 (S.T.U.)	28223	28696	25112	24907	
RUNTIME FOR M/C 5 (S.T.U.)	28758	28727	25248	23638	
RUNTIME FOR M/C 6 (S.T.U.)	28724	28637	25731	23663	
TOT. WORK PROCESSED (%)	80.41	95.44	100.0	100.0	
AV. PROCESS TIME (MINS)	47.86	37.65	31.05	29.57	
CLOCK AT FINISH (S.T.U.)	28800	28800	25762	28800	
AV. M/C UTIL. (%)	39.38	48.99	57.84	60.40	
UTIL. FOR M/C 1 (%)	80.82	82.03	87.08	89.58	
UTIL. FOR M/C 2 (%)	19.58	29.71	30.68	32.77	
UTIL. FOR M/C 3 (%)	43.41	52.30	69.17	72.33	
UTIL. FOR M/C 4 (%)	38.32	55.86	67.21	70.56	
UTIL. FOR M/C 5 (%)	25.81	40.04	48.10	48.30	
UTIL. FOR M/C 6 (%)	28.35	33.98	44.81	48.86	
AV. MAN POWER UTIL. (%)	82.19	63.62	54.58	38.45	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	160	163	143	136	
AV. UTIL OF TRANSPORT SYSTEM(%)	11.98	14.58	18.38	16.26	

E.8: FMS G (3 AGVs) SIMULATION RESULTS

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/3 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	TROLLEYS: (18)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (3)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	208	303	455	526	
PARTS FINISHED	189	283	435	504	
BATCHES FINISHED	49	61	81	86	
BATCHES IN SYSTEM	18	18	18	18	
BATCHES WAITING OUT	80	68	48	43	
UNMANNED TOTAL MACHINE HOURS	7.57	8.90	10.55	16.38	
RUNTIME FOR M/C 1 (S.T.U.)	10086	10804	10831	10143	
RUNTIME FOR M/C 2 (S.T.U.)	9647	9754	9616	9738	
RUNTIME FOR M/C 3 (S.T.U.)	10446	10221	10168	10160	
RUNTIME FOR M/C 4 (S.T.U.)	4927	6022	9104	11356	
RUNTIME FOR M/C 5 (S.T.U.)	4874	6413	9896	9982	
RUNTIME FOR M/C 6 (S.T.U.)	4990	6440	9700	9624	
TOT. WORK PROCESSED (%)	24.15	30.90	42.60	46.81	
AV. PROCESS TIME (MINS)	54.05	40.97	32.59	28.99	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	33.03	39.93	51.28	54.81	
UTIL. FOR M/C 1 (%)	73.32	75.88	89.08	89.07	
UTIL. FOR M/C 2 (%)	15.59	21.26	21.57	23.93	
UTIL. FOR M/C 3 (%)	57.92	80.41	69.68	75.31	
UTIL. FOR M/C 4 (%)	31.42	31.42	66.50	67.75	
UTIL. FOR M/C 5 (%)	14.57	19.96	29.75	42.84	
UTIL. FOR M/C 6 (%)	53.91	10.67	31.09	29.96	
AV. MAN POWER UTIL. (%)	83.78	71.82	75.26	63.72	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	158	191	167	167	
AV. UTIL. OF TRANSPORT SYSTEM(%)	6.72	9.70	13.00	14.44	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/3 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	TROLLEYS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	287	396	493	563	
PARTS FINISHED	263	383	473	548	
BATCHES FINISHED	51	72	77	88	
BATCHES IN SYSTEM	23	23	23	23	
BATCHES WAITING OUT	73	52	47	36	
UNMANNED TOTAL MACHINE HOURS	11.37	9.98	13.88	13.07	
RUNTIME FOR M/C 1 (S.T.U.)	10723	11265	11233	11128	
RUNTIME FOR M/C 2 (S.T.U.)	9774	9686	9844	9780	
RUNTIME FOR M/C 3 (S.T.U.)	10520	9789	10169	10119	
RUNTIME FOR M/C 4 (S.T.U.)	8443	9468	9897	8221	
RUNTIME FOR M/C 5 (S.T.U.)	9465	9650	9668	9959	
RUNTIME FOR M/C 6 (S.T.U.)	9388	9684	10074	9726	
TOT. WORK PROCESSED (%)	26.64	37.08	42.65	48.66	
AV. PROCESS TIME (MINS)	50.80	37.62	30.87	26.17	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	31.95	43.76	49.63	59.32	
UTIL. FOR M/C 1 (%)	64.96	89.21	87.64	88.47	
UTIL. FOR M/C 2 (%)	19.11	19.66	27.75	28.34	
UTIL. FOR M/C 3 (%)	56.57	70.45	92.42	88.69	
UTIL. FOR M/C 4 (%)	32.60	34.52	42.58	73.64	
UTIL. FOR M/C 5 (%)	12.10	23.05	26.19	41.49	
UTIL. FOR M/C 6 (%)	6.34	25.69	21.20	35.30	
AV. MAN POWER UTIL. (%)	99.04	88.74	72.19	65.90	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	143	174	168	178	
AV. UTIL OF TRANSPORT SYSTEM(%)	7.98	11.68	13.66	16.34	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/3 AGVs			PROGRAM: DAGV. OBJ		
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (1)	TROLLEYS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	249	469	509	571	
PARTS FINISHED	217	442	492	555	
BATCHES FINISHED	53	76	80	90	
BATCHES IN SYSTEM	28	28	28	25	
BATCHES WAITING OUT	66	43	39	32	
UNMANNED TOTAL MACHINE HOURS	14.67	13.15	16.77	27.25	
RUNTIME FOR M/C 1 (S.T.U.)	10337	11418	11498	11846	
RUNTIME FOR M/C 2 (S.T.U.)	8151	9777	9721	10092	
RUNTIME FOR M/C 3 (S.T.U.)	9574	10446	11006	11187	
RUNTIME FOR M/C 4 (S.T.U.)	9644	9468	9064	11545	
RUNTIME FOR M/C 5 (S.T.U.)	9642	9677	9672	9728	
RUNTIME FOR M/C 6 (S.T.U.)	9702	9720	9723	9671	
TOT. WORK PROCESSED (%)	26.92	39.63	45.60	53.19	
AV. PROCESS TIME (MINS)	57.28	32.25	29.81	28.05	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	33.12	45.98	52.91	58.14	
UTIL. FOR M/C 1 (%)	83.72	84.73	89.49	92.17	
UTIL. FOR M/C 2 (%)	15.58	26.13	27.85	30.57	
UTIL. FOR M/C 3 (%)	50.28	70.93	77.62	87.24	
UTIL. FOR M/C 4 (%)	26.75	39.97	66.79	67.94	
UTIL. FOR M/C 5 (%)	10.83	28.87	28.50	39.40	
UTIL. FOR M/C 6 (%)	11.55	25.26	27.18	31.53	
AV. MAN POWER UTIL. (%)	95.96	92.45	77.45	67.53	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	202	239	239	235	
AV. UTIL. OF TRANSPORT SYSTEM(%)	8.06	13.84	15.72	18.48	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/3 AGVs		PROGRAM: DAGV. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0		APC PALLET STATIONS 2	RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (18)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (3)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	520	748	831	845	
PARTS FINISHED	508	732	824	839	
BATCHES FINISHED	79	111	127	130	
BATCHES IN SYSTEM	11	10	9	7	
BATCHES WAITING OUT	57	26	11	10	
UNMANNED TOTAL MACHINE HOURS	5.82	15.05	11.27	10.85	
RUNTIME FOR M/C 1 (S.T.U.)	19499	20431	19974	19288	
RUNTIME FOR M/C 2 (S.T.U.)	17634	17870	14037	12970	
RUNTIME FOR M/C 3 (S.T.U.)	18277	18099	15416	14008	
RUNTIME FOR M/C 4 (S.T.U.)	19337	20908	19352	19371	
RUNTIME FOR M/C 5 (S.T.U.)	19212	19553	19433	19629	
RUNTIME FOR M/C 6 (S.T.U.)	19083	19142	19325	19855	
TOT. WORK PROCESSED (%)	49.01	72.74	83.90	85.81	
AV. PROCESS TIME (MINS)	54.35	38.77	32.35	31.10	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	31.35	44.82	55.52	58.51	
UTIL. FOR M/C 1 (%)	73.80	77.45	84.77	87.79	
UTIL. FOR M/C 2 (%)	21.97	21.68	27.60	29.87	
UTIL. FOR M/C 3 (%)	60.27	60.87	71.46	78.64	
UTIL. FOR M/C 4 (%)	19.57	55.70	68.59	68.52	
UTIL. FOR M/C 5 (%)	7.77	26.13	38.03	44.56	
UTIL. FOR M/C 6 (%)	4.72	27.09	42.70	41.70	
AV. MAN POWER UTIL. (%)	79.66	75.69	62.88	50.47	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	149	127	129	124	
AV. UTIL. OF TRANSPORT SYSTEM(%)	7.12	10.06	11.18	11.38	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/3 AGVs		PROGRAM: DAGV. OBJ			
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	556	708	841	863	
PARTS FINISHED	540	699	833	854	
BATCHES FINISHED	85	108	128	129	
BATCHES IN SYSTEM	21	13	11	10	
BATCHES WAITING OUT	41	26	8	8	
UNMANNED TOTAL MACHINE HOURS	9.0	8.08	13.83	11.68	
RUNTIME FOR M/C 1 (S.T.U.)	20647	20220	19349	18679	
RUNTIME FOR M/C 2 (S.T.U.)	19102	16794	15157	13406	
RUNTIME FOR M/C 3 (S.T.U.)	19056	16492	14003	13004	
RUNTIME FOR M/C 4 (S.T.U.)	17484	19029	19897	19737	
RUNTIME FOR M/C 5 (S.T.U.)	18987	19173	19390	19401	
RUNTIME FOR M/C 6 (S.T.U.)	19450	19376	19516	19272	
TOT. WORK PROCESSED (%)	54.35	68.30	85.81	88.51	
AV. PROCESS TIME (MINS)	51.59	39.22	31.90	29.98	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	33.81	44.23	57.57	61.58	
UTIL. FOR M/C 1 (%)	73.66	83.74	87.51	90.65	
UTIL. FOR M/C 2 (%)	15.14	28.86	31.97	32.21	
UTIL. FOR M/C 3 (%)	49.79	60.90	71.73	81.30	
UTIL. FOR M/C 4 (%)	34.63	44.43	65.22	67.93	
UTIL. FOR M/C 5 (%)	16.77	26.53	45.60	53.85	
UTIL. FOR M/C 6 (%)	12.89	20.94	43.42	43.56	
AV. MAN POWER UTIL. (%)	85.47	73.20	63.32	51.28	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	149	142	140	140	
AV. UTIL. OF TRANSPORT SYSTEM(%)	8.20	10.52	12.40	12.80	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/3 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (2)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	501	709	829	884	
PARTS FINISHED	481	693	818	870	
BATCHES FINISHED	80	111	126	132	
BATCHES IN SYSTEM	22	17	13	9	
BATCHES WAITING OUT	45	19	8	6	
UNMANNED TOTAL MACHINE HOURS	9.88	9.00	8.52	9.92	
RUNTIME FOR M/C 1 (S.T.U.)	20495	19595	19065	19567	
RUNTIME FOR M/C 2 (S.T.U.)	15610	14669	12513	11577	
RUNTIME FOR M/C 3 (S.T.U.)	19539	19114	15949	13663	
RUNTIME FOR M/C 4 (S.T.U.)	17972	19345	19848	19632	
RUNTIME FOR M/C 5 (S.T.U.)	19218	19121	19497	19255	
RUNTIME FOR M/C 6 (S.T.U.)	18195	19785	19356	19489	
TOT. WORK PROCESSED (%)	49.50	71.32	85.10	90.43	
AV. PROCESS TIME (MINS)	55.40	39.36	32.04	29.18	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	31.14	45.45	56.79	62.22	
UTIL. FOR M/C 1 (%)	75.19	85.36	88.81	86.53	
UTIL. FOR M/C 2 (%)	24.82	26.41	30.96	33.46	
UTIL. FOR M/C 3 (%)	47.59	56.86	69.07	80.63	
UTIL. FOR M/C 4 (%)	19.14	49.71	64.29	69.40	
UTIL. FOR M/C 5 (%)	13.81	33.57	48.99	50.91	
UTIL. FOR M/C 6 (%)	6.27	20.80	38.59	52.38	
AV. MAN POWER UTIL. (%)	79.90	73.12	61.86	50.63	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	211	197	193	184	
AV. UTIL. OF TRANSPORT SYSTEM(%)	8.06	11.32	12.96	13.86	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/3 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS MAN/MC ALLOCN.		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (18)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (3)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	700	970	999	994	
PARTS FINISHED	693	969	999	994	
BATCHES FINISHED	107	143	147	145	
BATCHES IN SYSTEM	10	3	0	2	
BATCHES WAITING OUT	30	1	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	28579	22419	19960	19365	
RUNTIME FOR M/C 2 (S.T.U.)	18377	18558	16235	14889	
RUNTIME FOR M/C 3 (S.T.U.)	20383	19741	17790	14590	
RUNTIME FOR M/C 4 (S.T.U.)	28610	28721	25543	24968	
RUNTIME FOR M/C 5 (S.T.U.)	28759	28714	25618	27022	
RUNTIME FOR M/C 6 (S.T.U.)	28775	28231	27627	23621	
TOT. WORK PROCESSED (%)	65.78	95.08	100.0	98.76	
AV. PROCESS TIME (MINS)	54.82	37.73	33.23	31.30	
CLOCK AT FINISH (S.T.U.)	28800	28800	27698	28800	
AV. M/C UTIL. (%)	32.88	46.94	54.26	57.66	
UTIL. FOR M/C 1 (%)	57.53	75.53	84.83	87.44	
UTIL. FOR M/C 2 (%)	21.08	20.88	23.86	29.00	
UTIL. FOR M/C 3 (%)	54.05	55.80	61.92	72.46	
UTIL. FOR M/C 4 (%)	25.08	52.55	62.31	63.75	
UTIL. FOR M/C 5 (%)	16.89	39.75	47.29	49.96	
UTIL. FOR M/C 6 (%)	14.73	37.15	45.33	43.35	
AV. MAN POWER UTIL. (%)	77.51	67.72	53.57	40.79	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	138	112	96	91	
AV. UTIL. OF TRANSPORT SYSTEM(%)	6.40	9.14	10.08	9.64	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/3 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS MAN/MC ALLOCN.		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (24)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (4)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	778	771	926	994	
PARTS FINISHED	771	755	926	994	
BATCHES FINISHED	121	118	140	145	
BATCHES IN SYSTEM	13	12	7	2	
BATCHES WAITING OUT	13	17	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	22549	19843	18977	18871	
RUNTIME FOR M/C 2 (S.T.U.)	26639	20650	16235	13343	
RUNTIME FOR M/C 3 (S.T.U.)	28350	20287	15636	14558	
RUNTIME FOR M/C 4 (S.T.U.)	27371	19461	13381	25697	
RUNTIME FOR M/C 5 (S.T.U.)	28758	20111	28547	24983	
RUNTIME FOR M/C 6 (S.T.U.)	28739	20109	28597	22761	
TOT. WORK PROCESSED (%)	78.95	76.79	90.32	99.63	
AV. PROCESS TIME (MINS)	52.19	39.06	32.77	30.23	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	36.45	46.33	55.40	59.69	
UTIL. FOR M/C 1 (%)	75.09	85.33	89.22	89.72	
UTIL. FOR M/C 2 (%)	18.19	23.47	29.85	32.36	
UTIL. FOR M/C 3 (%)	34.94	49.51	64.24	72.62	
UTIL. FOR M/C 4 (%)	39.52	47.56	59.61	66.93	
UTIL. FOR M/C 5 (%)	29.50	36.90	50.77	50.52	
UTIL. FOR M/C 6 (%)	21.46	35.22	38.74	45.97	
AV. MAN POWER UTIL. (%)	86.24	54.34	49.61	39.88	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	136	122	129	108	
AV. UTIL. OF TRANSPORT SYSTEM(%)	7.44	7.32	9.50	10.12	

COMPUTER SIMULATION RESULTS					T.K.D.
FMS TYPE: FMS G/3 AGVs	PROGRAM: DAGV. OBJ				
SALES/ WORKLOAD MULTIA =1.25 MULTIB =4.0 BT←SIZE =1.0	APC PALLET STATIONS 2		RANDOMISED SEQUENCE RANDST=1 RNSEED=29471		FIXTURING FIX←TYP=2
SHIFTS/DAY: (3)	PALLETS: (30)		SCHEDULE: (4)		MAX.QUEUE AT LD.STNS. (5)Per M/C
MANPOWER	2	3	4	5	
PARTS MACHINED	731	901	998	998	
PARTS FINISHED	727	898	998	998	
BATCHES FINISHED	115	135	145	145	
BATCHES IN SYSTEM	15	8	2	2	
BATCHES WAITING OUT	17	4	0	0	
UNMANNED TOTAL MACHINE HOURS	-	-	-	-	
RUNTIME FOR M/C 1 (S.T.U.)	21836	19150	18631	18531	
RUNTIME FOR M/C 2 (S.T.U.)	16876	14723	13811	12079	
RUNTIME FOR M/C 3 (S.T.U.)	25778	18711	15636	14749	
RUNTIME FOR M/C 4 (S.T.U.)	28600	28743	24867	24234	
RUNTIME FOR M/C 5 (S.T.U.)	28651	28767	24109	24257	
RUNTIME FOR M/C 6 (S.T.U.)	28650	28694	24768	23830	
TOT. WORK PROCESSED (%)	72.09	91.97	99.71	99.71	
AV. PROCESS TIME (MINS)	51.43	38.51	30.52	29.48	
CLOCK AT FINISH (S.T.U.)	28800	28800	28800	28800	
AV. M/C UTIL. (%)	35.72	49.09	58.83	60.85	
UTIL. FOR M/C 1 (%)	77.54	88.42	89.78	90.26	
UTIL. FOR M/C 2 (%)	22.96	26.31	28.05	32.07	
UTIL. FOR M/C 3 (%)	42.73	58.87	70.45	74.69	
UTIL. FOR M/C 4 (%)	30.13	48.90	67.88	69.65	
UTIL. FOR M/C 5 (%)	22.76	38.89	46.89	52.01	
UTIL. FOR M/C 6 (%)	18.20	33.14	49.94	46.41	
AV. MAN POWER UTIL. (%)	79.14	63.14	48.77	39.37	
AV. WAITING W.I.P. (FOR MACHINING PARTS)	186	169	143	137	
AV. UTIL OF TRANSPORT SYSTEM(%)	7.74	9.46	10.92	11.10	

APPENDIX F

INVESTMENT COSTS OF ALTERNATIVE SYSTEMS

CONTENTS Page

APPENDIX F

F.1: FMS A - MANUAL CNC CELL

	ITEM	QUANTITY	UNIT COST (£)	COST (£)	TOTAL (£)
(1)	Machine Tool Costs				
	KTM Hoz. M/c ctr.	1	70,000	70,000	
	Wadkin V4-6 Vert.M/c Ctr.	2	46,980	93,960	
	Wadkin V5-10 Vert.M/c Ctr.	3	68,040	204,120	
	Indexer	1	6,000	6,000	
					374,080
(2)	Inspection Costs				
	Coord. Meas. M/c	1	20,000	20,000	
					20,000
(3)	Aux. Equip. Costs				
	Vacuum Suction Pump	1	500	500	
	Wash Station	1	10,000	10,000	
					10,500
(4)	Tooling Equipment				
	Tool Presetting M/c	1	18,000	18,000	
	Tooling Package/KTM	1	4,900	4,900	
	Tooling Pack/V4-6	3	4,000	12,000	
	Tooling Pack/V5-10	6	4,900	29,400	
					64,300
(5)	Fixture Costs				
	Grid Plates	6	1,000	6,000	
	Dedicated Fixtures	69	300	20,700	
	Modular Fixtures	63	500	31,500	
					58,200
(6)	Material Handling Costs				
	Hoists	6	300	1,800	
	Trolleys (parts+fixtures)	24	75	1,800	
	Tool Trolleys	12	150	1,800	
					5,400
(7)	Part Programming Costs				
	147 parts programs	636 hrs	£15/hr	9,540	
					9,540
(8)	Commissioning + Engineering Costs				
	6 man-weeks		£1000/ man week	6,000	6,000
(9)	Computer Costs				
	Hardware (2 disc/micro)	1	2,000	2,000	
	Software (preprocessing)			1,500	
					3,500
	INVESTMENT COST less,				551,520
(10)	Grant	26%			143,395
	TOTAL INVESTMENT COST				408,125

APPENDIX F

F.2: FMS B - MANUAL CNC CELL WITH 1 APC PER MACHINE

	ITEM	QUANTITY	UNIT COST (£)	COST (£)	TOTAL (£)
(1)	Machine Tool Costs				374,080
(2)	Inspection Costs				20,000
(3)	Aux. Equip. Costs				10,500
(4)	Tooling Equipment Costs				64,300
(5)	Fixture Costs				
	Grid Plates	12	1,000	12,000	
	Ded. and Mod. Fixtures			52,200	
					64,200
(6)	Material Handling Costs				
	Pallet Shuttles (Twin)	6	22,000	132,000	
	Hoists	6	300	1,800	
	Trolleys (Parts+Fixtures)	24	75	1,800	
	Tool Trolleys	12	150	1,800	
					137,400
(7)	Part Programming Costs				9,540
(8)	Commissioning + Engineering Costs				
	12 man weeks	12	£1000/ man week	12,000	12,000
(9)	Computer Costs				3,500
	INVESTMENT COST				695,520
	less,				
(10)	Grant	26%			180,835
	TOTAL INVESTMENT COST				£514,685

APPENDIX F

F.3: FMS C - MANUAL CNC CELL WITH 2 APC PER MACHINE

	ITEM	QUANTITY	UNIT COST	4 PALLET SHUTTLE COST	TOTAL
(1)	Machine Tool Costs				374,080
(2)	Inspection Equipment Costs				20,000
(3)	Aux. Equip. Costs				10,500
(4)	Tooling Equipment Costs				64,300
(5)	Fixture Costs				
	Grid Plates	24	1,000	24,000	
	Ded. + Mod. Fixtures			52,200	
					76,200
(6)	Material Handling Costs				
	Pallet Shuttles (Twin)	12	20,000	240,000	
	Hoists	6	300	1,800	
	Trolleys (parts + fixtures)	24	75	1,800	
	Tool Trolleys	12	150	1,800	
					245,400
(7)	Part Programming Costs				9,540
(8)	Commissioning & Engineering Costs				
	12 man weeks	12	1000/wk	12,000	
					12,000
(9)	Computer Costs				3,500
	INVESTMENT COST				815,520
	less,				
(10)	Grant	26%			212,035
	TOTAL INVESTMENT COST				603,485

F.4: FMS D - CONVEYOR SYSTEM (1 APC)

	ITEM	QUANTITY	UNIT COST	COST	TOTAL
(1)	Machine Tool Costs				374,080
(2)	Inspection Equip Costs				20,000
(3)	Aux. Equip. Costs				10,500
(4)	Tooling Equipment Costs				64,300
(5)	Fixture Costs				52,200
	Baseplates = (38 x £300) +(26 x £500) =				24,400
(6)	Pallet Costs				
	KTM Pallets	3	500	1,500	
	Wadkin Pallets	15	1,500	22,500	
					24,000
(7)	Material Handling Costs				
	Conveyor Modules	54	2,500	135,000	
	Turntables	8	3,000	24,000	
	Telescopic Forks	11	7,000	77,000	
	Pallet Shuttles	6	22,000	132,000	
	Control System	78 M.E.	£450/M.E. + 8000	43,100	
	Part Trolleys	12	75	900	
	Tool Trolleys	12	150	1,800	
	Alignment Devices	6	500	3,000	
					416,800
(8)	Part Programming Costs				9,540
(9)	Commissioning + Engineering Cost				
	30 man weeks	30	1000/man week	30,000	30,000
(10)	Load/Unload Stations				
	Pallet Storage Stations	18	2,000	36,000	
	Fixturing Tables	3	2,200	6,600	
	Wash Station Connection	1	1,600	1,600	
	Transfer Devices	21	300	6,300	
					50,500
(11)	Conveyor Installation Cost	76	65	4,940	
	84 Units	84	60	5,040	
	Fixture Devices			400	
					5,440
(12)	Computer Costs				
	Hardware			30,000	
	Software	20 man-weeks	1,000/man-week	20,000	
					50,000
	INVESTMENT COST less,				1,131,760
(13)	Grant	26%			294,258
	TOTAL INVESTMENT COST				837,502

APPENDIX F

F.5: FMS E - STACKER CRANE SYSTEM (1 APC)

	ITEM	QUANTITY	UNIT COST (£)	COST (£)	TOTAL (£)
(1)	Machine Tool Costs				374,080
(2)	Inspection Equip. Costs				20,000
(3)	Aux. Equipment Costs				10,500
(4)	Tooling Equipment Costs				64,300
(5)	Fixture Costs				52,200
	Fix. Base Plates				24,400
(6)	Pallet Costs	30			40,000
(7)	Part Programming Costs				9,540
(8)	Material Handling Costs				
	Pallet Shuttles	6	22,000	132,000	
	Auto Stacker Crane (Rails, Busbars+Commn.Equip.)	1	100,000	100,000	
	End Buffers	2	1000/pair	2,000	
	Racking	30	100/hole	3,000	
	Fencing	100 m	25/m	2,500	
	Gates	11	500	5,500	
	Pick + Deposit	3	2000	6,000	
	Part Trolleys	12	75	900	
	Tool Trolleys	12	150	1,800	
					253,700
(9)	Installation Costs				
	Top + Bottom Rail	80 m	250/m + 1000	21,000	21,000
(10)	Commissionaing Costs				
	25 man weeks	25	1000	25,000	25,000
(11)	Computer Costs				
	IBM AT-X	1	6000	6,000	
	Appln. Software			10,000	
	Infrared Data Link (Installed)			1,500	
	PLC for Stacker Crane + M/c Interlocks			1,000	
	PLC Software			5,000	
	Installation (Power Distribution & Cabling)			5,000	
					28,500
(12)	Load/Unload Stations				
	Conveyor (12 modules)	12	2000	24,000	
	Fixturing Tables	6	3000	18,000	
					42,000
	INVESTMENT COST				965,220
	less,				
(13)	Grant				250,957
	TOTAL INVESTMENT COST				£714,263

APPENDIX F

F.6: FMS F - RAIL GUIDED SHUTTLE (1 APC)

	ITEM	QUANTITY	UNIT COST (£)	COST (£)	TOTAL (£)
(1)	Machine Tool Costs				374,080
(2)	Inspection Equip. Costs				20,000
(3)	Aux. Equipment Costs				10,500
(4)	Tooling Equipment Costs				64,300
(5)	Fixture Costs				52,200
	Fix. baseplates				24,400
(6)	Pallet Costs	24			32,000
(7)	Part Programming Costs				9,540
(8)	Material Handling Costs				
	Rail Shuttle (9 meq)	1	8,500	8,500	
	Rails	2x40m	300/m +2000	26,000	
	Pallet Shuttles	6	22,000	132,000	
	Racking	24 posn.	150	2,600	
	End buffers	1	1000/pair	1,000	
	Fencing	100m	20/m	2,000	
	Gates	14	500	7,000	
	Part Trolleys	12	75	900	
	Tool Trolleys	12	150	1,800	
					182,800
(9)	Installation Costs				
	Erection of stores			2,100	
	Erection of rails	80m	250/m +1000	21,000	23,100
(10)	Computer Costs				
	As stacker crane (floor cabling only)				26,500
(11)	Load/Unload Stations				
	Fixture Tables	3	3000	9,000	
					9,000
(12)	Commissioning Costs				
	24 man weeks	24	1000	24,000	
					24,000
	INVESTMENT COST				852,420
	less,				
(13)	Grant	26%			221,629
	TOTAL INVESTMENT COST				£630,791

F.7: FMS G - AGV SYSTEM (1 APC)

	ITEM	QUANTITY	UNIT COST (£)	COST (£)	TOTAL (£)
(1)	Machine Tool Costs				374,080
(2)	Inspection Equip. Costs				20,000
(3)	Aux. Equipment Costs				10,500
(4)	Tooling Equipment Costs				64,300
(5)	Fixture Costs				52,200
	Fix Base plates				24,400
(6)	Pallet Costs	30			40,000
(7)	Part Programming Costs				9,540
(8)	Material Handling Costs				
	AGV's	2	30,000	60,000	
	Tracks	120m	280/m	33,600	
	In Process Stalls	30	400	12,000	
	Automation + Control			40,000	
	Pallet Positioning Device	12	10,000	120,000	
	Pallet Shuttles	6	22,000	132,000	
	Fencing + Gates			11,000	
	Part Trolleys	12	75	900	
	Tool Trolleys	12	150	1,800	
	Batteries + Charging Equip.			5,000	
					416,300
(9)	Installation Cost				10,000
(10)	Computer Costs				
	Hardware			30,000	
	Software			20,000	
					50,000
(11)	Load/Unload Stations				
	3 positions	3	6,000	18,000	
					18,000
(12)	Commissioning Costs				
	25 man weeks	25	1,000	25,000	
					25,000
	INVESTMENT COST				£1,114,320
	less,				
(13)	Grant	26%			289,723
	TOTAL INVESTMENT COST				824,597

APPENDIX G

MANUFACTURING OPERATING COST ESTIMATE

CONTENTS

G.1: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS A

MANPOWER LEVEL: 2 (SHIFT = 2)

IN PROCESS STALLS NO: 24

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3754	3867	3982	4102	4225	4352	4482
LABOUR	5	40000	42000	44100	46305	48620	51051	53604
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		2662	5325	7987	10650	13312	15974	18637
MAINTENANCE: COMP. EQUIP.	4	200	208	216	225	234	243	253
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		4607	4951	5306	5671	6047	6436	6836
(A) TOTAL DIRECT COSTS		96739	103973	111422	119091	126997	135148	143557
INDIRECT COSTS:								
INSURANCE	4	1838	1912	1988	2068	2151	2237	2326
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		11838	12412	13013	13644	14306	14999	15727
(C) OPERATING COST		108577	116385	124435	132735	141303	150147	159284
(D) LESS TAX BENEFIT		35711	26783	20087	15066	11299	8474	6356
TOTAL OPERATING COST		72866	89602	104348	117669	130004	141673	152928
DISCOUNTED TOTAL OPERATING COST		72866	80005	83185	83757	82617	80385	77473

G.1: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS A

MANPOWER LEVEL: 3 (SHIFT = 2)

IN PROCESS STALLS NO: 24

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3795	3909	4026	4147	4271	4399	4531
LABOUR	5	60000	63000	66150	69458	72930	76577	80406
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		2662	5325	7987	10650	13312	15974	18637
MAINTENANCE: COMP. EQUIP.	4	200	208	216	225	234	243	253
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		5609	6003	6410	6831	7265	7714	8179
(A) TOTAL DIRECT COSTS		117782	126067	134616	143449	152570	161999	171752
INDIRECT COSTS:								
INSURANCE	4	1838	1912	1988	2068	2151	2237	2326
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		11838	12412	13013	13644	14306	14999	15727
(C) OPERATING COST		129620	138479	147629	157093	166876	176998	187479
(D) LESS TAX BENEFIT		35711	26783	20087	15066	11299	8474	6356
TOTAL OPERATING COST		93909	111696	127542	142027	155577	168524	181123
DISCOUNTED TOTAL OPERATING COST		93909	99733	101679	101094	98869	95621	91756

G.1: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS A

MANPOWER LEVEL: 4 (SHIFT = 2)

IN PROCESS STALLS NO: 24

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3734	3846	3961	4080	4202	4328	4458
LABOUR	5	80000	84000	88200	92610	97241	102103	107208
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		2662	5325	7987	10650	13312	15974	18637
MAINTENANCE: COMP. EQUIP.	4	200	208	216	225	234	243	253
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		6606	7050	7509	7985	8477	8987	9515
(A) TOTAL DIRECT COSTS		138718	148051	157700	167688	178024	188725	199817
INDIRECT COSTS:								
INSURANCE	4	1838	1912	1988	2068	2151	2237	2326
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		11838	12412	13013	13644	14306	14999	15727
(C) OPERATING COST		150556	160463	170713	181332	192330	203724	215544
(D) LESS TAX BENEFIT		35711	26783	20087	15066	11299	8474	6356
TOTAL OPERATING COST		114845	133680	150626	166266	181331	195250	209188
DISCOUNTED TOTAL OPERATING COST		114845	119361	120080	118347	115043	110785	105973

G.2: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS B

MANPOWER LEVEL: 2 (SHIFT = 2)

IN PROCESS STALLS NO: 24

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3754	3867	3983	4102	4225	4352	4482
LABOUR	5	40000	42000	44100	46305	48620	51051	53604
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		3352	6705	10057	13410	16762	20114	23467
MAINTENANCE: COMP. EQUIP.	4	200	208	216	225	234	243	253
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		4641	5020	5409	5809	6220	6643	7078
(A) TOTAL DIRECT COSTS		97463	105422	113592	121989	130619	139495	148630
INDIRECT COSTS:								
INSURANCE	4	2318	2411	2508	2608	2712	2821	2934
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		12318	12911	13533	14184	14867	15583	16335
(C) OPERATING COST		109781	118333	127125	136173	145486	155078	164965
(D) LESS TAX BENEFIT		45035	33776	25332	18999	14249	10687	8015
TOTAL OPERATING COST		64746	84557	101793	117174	131237	144391	156950
DISCOUNTED TOTAL OPERATING COST		64746	75501	81150	83405	83401	81928	79510

G.2: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS B

MANPOWER LEVEL: 3 (SHIFT = 2)

IN PROCESS STALLS NO: 24

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3795	3909	4026	4147	4271	4399	4531
LABOUR	5	60000	63000	66150	69458	72930	76577	80406
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		3352	6705	10057	13410	16762	20114	23467
MAINTENANCE: COMP. EQUIP.	4	200	208	216	225	234	243	253
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		5643	6072	6514	6969	7438	7921	8420
(A) TOTAL DIRECT COSTS		118506	127516	136790	146347	156193	166346	176823
INDIRECT COSTS:								
INSURANCE	4	2318	2411	2508	2608	2712	2821	2934
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		12318	12911	13533	14184	14867	15583	16335
(C) OPERATING COST		130824	140427	150323	160531	171060	181929	193158
(D) LESS TAX BENEFIT		45035	33776	25332	18999	14249	10687	8015
TOTAL OPERATING COST		85789	106651	124991	141532	156811	171242	185143
DISCOUNTED TOTAL OPERATING COST		85789	95229	99644	100742	99654	97163	93793

G.2: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS B

MANPOWER LEVEL: 4 (SHIFT = 2)

IN PROCESS STALLS NO: 24

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3732	3844	3959	4078	4200	4326	4456
LABOUR	5	80000	84000	88200	92610	97241	102103	107208
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		3352	6705	10057	13410	16762	20114	23467
MAINTENANCE: COMP. EQUIP.	4	200	208	216	225	234	243	253
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		6640	7119	7613	8123	8650	9194	9756
(A) TOTAL DIRECT COSTS		139440	149498	159872	170584	181645	193072	204886
INDIRECT COSTS:								
INSURANCE	4	2318	2411	2508	2608	2712	2821	2934
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		12318	12911	13533	14184	14867	15583	16334
(C) OPERATING COST		151758	162409	173405	184768	196512	208655	221220
(D) LESS TAX BENEFIT		45035	33776	25332	18999	14249	10687	8015
TOTAL OPERATING COST		106723	128633	148073	165769	182863	197968	213205
DISCOUNTED TOTAL OPERATING COST		106724	114857	118045	117994	115828	112327	108009

G.3: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS C

MANPOWER LEVEL: 2 (SHIFT = 2)

IN PROCESS STALLS NO: 24

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3754	3867	3983	4102	4225	4352	4482
LABOUR	5	40000	42000	44100	46305	48620	51051	53604
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		3952	7905	11857	15810	19762	23714	27667
MAINTENANCE: COMP. EQUIP.	4	200	208	216	225	234	243	253
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		4671	5080	5499	5929	6370	6823	7288
(A) TOTAL DIRECT COSTS		98093	106682	115482	124509	133769	143275	153040
INDIRECT COSTS:								
INSURANCE	4	2718	2827	2940	3058	3180	3307	3440
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		12718	13327	13965	14634	15335	16069	16841
(C) OPERATING COST		110811	120009	129447	139143	149104	159345	169881
(D) LESS TAX BENEFIT		52805	39604	29703	22277	16708	12531	9398
TOTAL OPERATING COST		58006	80405	99744	116866	132396	146814	160483
DISCOUNTED TOTAL OPERATING COST		58006	71794	79517	83185	84138	83302	81300

G.3: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS C

MANPOWER LEVEL: 3 (SHIFT = 2)

IN PROCESS STALLS NO: 24

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3795	3909	4026	4147	4271	4399	4531
LABOUR	5	60000	63000	66150	69458	72930	76577	80406
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		3952	7905	11857	15810	19762	23714	27667
MAINTENANCE: COMP. EQUIP.	4	200	208	216	225	234	243	253
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		5673	6132	6604	7089	7588	8101	8630
(A) TOTAL DIRECT COSTS		119136	128776	138680	148867	159343	170126	181233
INDIRECT COSTS:								
INSURANCE	4	2718	2827	2940	3058	3180	3307	3440
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		12718	13327	13965	14634	15335	16069	16841
(C) OPERATING COST		131854	142103	152645	163501	174678	186195	198074
(D) LESS TAX BENEFIT		52805	39604	29703	22277	16708	12531	9398
TOTAL OPERATING COST		79049	102499	122942	141225	157970	173664	188676
DISCOUNTED TOTAL OPERATING COST		79049	91522	98011	100523	100390	98538	95583

G.3: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS C

MANPOWER LEVEL: 4 (SHIFT = 2)

IN PROCESS STALLS NO: 24

	ΔC%/Yr.	END OF YEAR: 1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3732	3844	3959	4078	4200	4326	4456
LABOUR	5	80000	84000	88200	92610	97241	102103	107208
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		3952	7905	11857	15810	19762	23714	27667
MAINTENANCE: COMP. EQUIP.	4	200	208	216	225	234	243	253
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		6670	7179	7703	8243	8800	9374	9966
(A) TOTAL DIRECT COSTS		140070	150758	161762	173104	184795	196852	209296
INDIRECT COSTS:								
INSURANCE	4	2718	2827	2940	3058	3180	3307	3440
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		12718	13327	13965	14634	15335	16069	16841
(C) OPERATING COST		158788	164085	175727	187738	200130	212921	226137
(D) LESS TAX BENEFIT		52805	39604	29703	22277	16708	12531	9398
TOTAL OPERATING COST		99983	124481	146024	165461	183422	200390	216739
DISCOUNTED TOTAL OPERATING COST		99984	111149	116412	117775	116564	113702	109798

G.4: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS D

MANPOWER LEVEL: 2 (SHIFT = 2)

IN PROCESS STALLS NO: 18

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3754	3867	3983	4102	4225	4352	4482
LABOUR	5	40000	42000	44100	46305	48620	51051	53604
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		5184	10368	15552	20736	25919	31103	36287
MAINTENANCE: COMP. EQUIP.	4	3000	3120	3245	3375	3510	3650	3796
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		4873	5349	5835	6333	6842	7362	7896
(A) TOTAL DIRECT COSTS		102327	112326	122542	132989	143674	154610	165811
INDIRECT COSTS:								
INSURANCE	4	3773	3923	4080	4244	4413	4590	4773
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		13773	14423	15105	15820	16568	17352	18174
(C) OPERATING COST		116100	126749	137647	148809	160242	171962	183985
(D) LESS TAX BENEFIT		73281	54961	41221	30916	23187	17390	13042
TOTAL OPERATING COST		42819	71788	96426	117893	137055	154572	170943
DISCOUNTED TOTAL OPERATING COST		42819	64100	76872	83916	87098	87705	86599

G.4: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS D

MANPOWER LEVEL: 3 (SHIFT = 2)

IN PROCESS STALLS NO: 18

	ΔC%/Yr.	END OF YEAR: 1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4461	4548	4685	4825	4970	5119	5273
POWER	3	3795	3909	4026	4147	4271	4399	4531
LABOUR	5	60000	63000	66150	69458	72930	76577	80406
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		5184	10368	15552	20736	25919	31103	36287
MAINTENANCE: COMP. EQUIP.	4	3000	3120	3245	3375	3510	3650	3796
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		5875	6401	6940	7493	8059	8641	9238
(A) TOTAL DIRECT COSTS		123370	134420	145740	157347	169247	181462	194004
INDIRECT COSTS:								
INSURANCE	4	3773	3923	4080	4244	4413	4590	4773
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		13773	14423	15105	15820	16568	17352	18174
(C) OPERATING COST		137143	148843	160845	173167	185815	198814	212178
(D) LESS TAX BENEFIT		73281	54961	41221	30916	23187	17390	13042
TOTAL OPERATING COST		63862	93882	119624	142251	162628	181424	199136
DISCOUNTED TOTAL OPERATING COST		63862	83828	95365	101253	103351	102940	100882

G.4: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS D

MANPOWER LEVEL: 4 (SHIFT = 2)

IN PROCESS STALLS NO: 18

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3732	3844	3959	4078	4200	4326	4456
LABOUR	5	80000	84000	88200	92610	97241	102103	107208
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		5184	10368	15552	20736	25919	31103	36287
MAINTENANCE: COMP. EQUIP.	4	3000	3120	3245	3375	3510	3650	3796
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		6872	7448	8039	8647	9271	9914	10575
(A) TOTAL DIRECT COSTS		144304	156402	168822	181584	194699	208188	222068
INDIRECT COSTS:								
INSURANCE	4	3773	3923	4080	4244	4413	4590	4773
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		13773	14423	15105	15820	16568	17352	18174
(C) OPERATING COST		158077	170825	183927	197404	211267	225540	240242
(D) LESS TAX BENEFIT		73281	54961	41221	30916	23187	17390	13042
TOTAL OPERATING COST		84796	115864	142706	166488	188080	208150	227200
DISCOUNTED TOTAL OPERATING COST		84796	103455	113766	118506	119525	118104	115099

G.5: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS E

MANPOWER LEVEL: 2 (SHIFT = 2)

IN PROCESS STALLS NO: 30

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3754	3867	3983	4102	4225	4352	4482
LABOUR	5	40000	42000	44100	46305	48620	51051	53604
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		4406	8812	13218	17624	22029	26435	30841
MAINTENANCE: COMP. EQUIP.	4	1350	1404	1460	1519	1579	1642	1708
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		4751	5185	5629	6084	6551	7029	7519
(A) TOTAL DIRECT COSTS		99777	108890	118217	127772	137562	147601	157900
INDIRECT COSTS:								
INSURANCE	4	3217	3346	3480	3619	3764	3914	4071
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		13217	13846	14505	15195	15919	16676	17472
(C) OPERATING COST		112994	122736	132722	142967	153481	164277	175372
(D) LESS TAX BENEFIT		62498	46874	35155	26366	19775	14831	11123
TOTAL OPERATING COST		50496	75862	97567	116601	133706	149446	164249
DISCOUNTED TOTAL OPERATING COST		50496	67737	77781	82997	84970	84796	83208

G.5: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS E

MANPOWER LEVEL: 3 (SHIFT = 2)

IN PROCESS STALLS NO: 30

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3795	3909	4026	4147	4271	4399	4531
LABOUR	5	60000	63000	66150	69458	62930	76577	80406
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		4406	8812	13218	17624	22029	26435	30841
MAINTENANCE: COMP. EQUIP.	4	1350	1404	1460	1519	1579	1642	1708
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		5753	6237	6734	7244	7768	8307	8862
(A) TOTAL DIRECT COSTS		120820	130984	141415	152130	163135	174452	186094
INDIRECT COSTS:								
INSURANCE	4	3217	3346	3480	3619	3764	3914	4071
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		13217	13846	14505	15195	15919	16676	17472
(C) OPERATING COST		134037	144830	155920	167325	179054	191128	203566
(D) LESS TAX BENEFIT		62498	46874	35155	26366	19775	14831	11123
TOTAL OPERATING COST		71539	97956	120765	140959	159279	176297	192443
DISCOUNTED TOTAL OPERATING COST		71539	87465	96275	100334	101223	100032	97491

G.5: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS E

MANPOWER LEVEL: 4 (SHIFT = 2)

IN PROCESS STALLS NO: 30

	ΔC%/Yr.	END OF YEAR: 1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3732	3844	3959	4078	4200	4326	4456
LABOUR	5	80000	84000	88200	92610	97241	102103	107208
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		4456	8912	13368	17824	22280	26735	31191
MAINTENANCE: COMP. EQUIP.	4	1350	1404	1460	1519	1579	1642	1708
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		6750	7284	7833	8398	8980	9580	10198
(A) TOTAL DIRECT COSTS		141754	152966	164497	176367	188588	201178	214157
INDIRECT COSTS:								
INSURANCE	4	3217	3346	3480	3619	3764	3914	4071
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		13217	13846	14505	15195	15919	16676	17472
(C) OPERATING COST		154971	166812	179002	191562	204507	217854	231629
(D) LESS TAX BENEFIT		62498	46874	35155	26366	19775	14831	11123
TOTAL OPERATING COST		92473	119938	143847	165196	184732	203023	220506
DISCOUNTED TOTAL OPERATING COST		92473	107093	114676	117587	117397	115196	111708

G.6: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS F

MANPOWER LEVEL: 2 (SHIFT = 2)

IN PROCESS STALLS NO: 24

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3754	3867	3983	4102	4225	4352	4482
LABOUR	5	40000	42000	44100	46305	48620	51051	53604
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		3846	7693	11539	15386	19232	23078	26925
MAINTENANCE: COMP. EQUIP.	4	1150	1196	1244	1294	1345	1399	1455
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		4713	5119	5535	5961	6399	6849	7311
(A) TOTAL DIRECT COSTS		98979	107497	116228	125186	134379	143821	153523
INDIRECT COSTS:								
INSURANCE	4	2841	2955	3073	3196	3324	3457	3595
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		12841	13455	14908	14772	15479	16219	16996
(C) OPERATING COST		111820	120952	130326	139958	149858	160040	170519
(D) LESS TAX BENEFIT		55194	41396	31047	23285	17464	13098	9823
TOTAL OPERATING COST		56626	79556	99279	116673	132394	146942	160696
DISCOUNTED TOTAL OPERATING COST		56626	71035	79146	83048	84137	83375	81408

G.6: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS F

MANPOWER LEVEL: 3 (SHIFT = 2)

IN PROCESS STALLS NO: 24

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3795	3909	4026	4147	4271	4399	4531
LABOUR	5	60000	63000	66150	69458	72930	76577	80406
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		3846	7693	11539	15386	19232	23078	26925
MAINTENANCE: COMP. EQUIP.	4	1150	1196	1244	1294	1345	1399	1455
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		5715	6171	6639	7121	7617	8127	8653
(A) TOTAL DIRECT COSTS		120022	129591	139425	149544	159953	170672	181716
INDIRECT COSTS:								
INSURANCE	4	2841	2955	3073	3196	3324	3457	3595
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		12841	13455	14908	14772	15479	16219	16996
(C) OPERATING COST		132863	143046	153523	164316	175432	186891	198712
(D) LESS TAX BENEFIT		55194	41396	31047	23285	17464	13098	9823
TOTAL OPERATING COST		77669	101650	122476	141031	157968	173793	188889
DISCOUNTED TOTAL OPERATING COST		77669	90763	97639	100385	100389	98611	95691

G.6: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS F

MANPOWER LEVEL: 4 (SHIFT = 2)

IN PROCESS STALLS NO: 24

	ΔC%/Yr.	END OF YEAR: 1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3732	3844	3959	4078	4200	4326	4456
LABOUR	5	80000	84000	88200	92610	97241	102103	107208
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		3846	7693	11539	15386	19232	23078	26925
MAINTENANCE: COMP. EQUIP.	4	1150	1196	1244	1294	1345	1399	1455
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		6712	7218	7739	8275	8829	9400	9989
(A) TOTAL DIRECT COSTS		140956	151573	162508	173781	185405	197398	209779
INDIRECT COSTS:								
INSURANCE	4	2841	2955	3073	3196	3324	3457	3595
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		12841	13455	14098	14772	15479	16219	16996
(C) OPERATING COST		153797	165028	176606	188553	200884	213617	226775
(D) LESS TAX BENEFIT		55194	41396	31047	23285	17464	13098	9823
TOTAL OPERATING COST		98603	123632	145559	165268	183420	200519	216952
DISCOUNTED TOTAL OPERATING COST		98603	110391	116041	117638	116563	113775	109908

G.7: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS G

MANPOWER LEVEL: 2 (SHIFT = 2)

IN PROCESS STALLS NO: 30

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3754	3867	3983	4102	4225	4352	4482
LABOUR	5	40000	42000	44100	46305	48620	51051	53604
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		5099	10198	15297	20396	25495	30593	35692
MAINTENANCE: COMP. EQUIP.	4	3000	3120	3245	3375	3510	3650	3796
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		4868	5340	5823	6316	6820	7337	7866
(A) TOTAL DIRECT COSTS		102237	112147	122275	132632	143228	154075	165186
INDIRECT COSTS:								
INSURANCE	4	3714	3863	4017	4178	4345	4519	4700
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		13714	14363	15042	15754	16500	17281	18101
(C) OPERATING COST		115951	126510	137317	148386	159728	171356	183287
(D) LESS TAX BENEFIT		72152	54114	40586	30439	22829	17122	12842
TOTAL OPERATING COST		43799	72396	96731	117947	136899	154234	170445
DISCOUNTED TOTAL OPERATING COST		43799	64642	77114	83955	86999	87513	86347

G.7: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS G

MANPOWER LEVEL: 3 (SHIFT = 2)

IN PROCESS STALLS NO: 30

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3795	3909	4026	4147	4271	4399	4531
LABOUR	5	60000	63000	66150	69458	72930	76577	80406
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		5099	10198	15297	20396	25495	30593	35692
MAINTENANCE: COMP. EQUIP.	4	3000	3120	3245	3375	3510	3650	3796
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		5870	6392	6927	7476	8038	8616	9209
(A) TOTAL DIRECT COSTS		123280	134241	145472	156990	168802	180927	193380
INDIRECT COSTS:								
INSURANCE	4	3714	3863	4017	4178	4345	4519	4700
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		13714	14363	15042	15754	16500	17281	18101
(C) OPERATING COST		136994	148604	160514	172744	185302	198208	211481
(D) LESS TAX BENEFIT		72152	54114	40586	30439	22829	17122	12842
TOTAL OPERATING COST		64842	94490	119928	142305	162473	181086	198639
DISCOUNTED TOTAL OPERATING COST		64842	84370	95608	101292	103251	102748	100630

G.7: MANUFACTURING OPERATING COST ESTIMATE

SYSTEM: FMS G

MANPOWER LEVEL: 4 (SHIFT = 2)

IN PROCESS STALLS NO: 30

		END OF YEAR:						
	ΔC%/Yr.	1	2	3	4	5	6	7
DIRECT COSTS:								
HEAT, LIGHT, RATES	3	4416	4548	4685	4825	4970	5119	5273
POWER	3	3732	3844	3959	4078	4200	4326	4456
LABOUR	5	80000	84000	88200	92610	97241	102103	107208
SUPERVISION	5	27000	28350	29767	31256	32819	34460	36183
MAINTENANCE: MACHINES		5099	10198	15297	20396	25495	30593	35692
MAINTENANCE: COMP. EQUIP.	4	3000	3120	3245	3375	3510	3650	3796
CONSUMABLES: TOOLS	4	7200	7488	7787	8099	8423	8760	9110
CONSUMABLES: CUTTING FLUID.	4	900	936	973	1012	1053	1095	1139
SWARF & WASTE DISPOSAL	5	6000	6300	6615	6946	7293	7658	8041
CONTINGENCIES		6867	7439	8026	8630	9250	9888	10545
(A) TOTAL DIRECT COSTS		144214	156223	168554	181227	194254	207652	221443
INDIRECT COSTS:								
INSURANCE	4	3714	3863	4017	4178	4345	4519	4700
LABOUR	5	10000	10500	11025	11576	12155	12762	13401
(B) TOTAL INDIRECT COSTS		13714	14363	15042	15754	16500	17281	18101
(C) OPERATING COST		157928	170586	183596	196981	210754	224933	239544
(D) LESS TAX BENEFIT		72152	54114	40586	30439	22829	17122	12842
TOTAL OPERATING COST		85776	116472	143010	166542	187925	207811	226702
DISCOUNTED TOTAL OPERATING COST		85776	103998	114009	118544	119426	117912	114847

APPENDIX H

SCHEDULE OF OPERATING COSTS AND TAX BENEFIT

Page

APPENDIX H

H.1: PROFILE OF OPERATING COST ELEMENTS

(1) HEAT, LIGHT AND RATES

An overhead recovery rate for heat, light and rates apportioned to the prismatic machining cell area has been estimated at £1.15 per hour for two shift operation. For three shift operation, a saving of 6% for higher consumption levels has been assumed, so that the corresponding rate is £1.08 per hour. Thus, the annual costs for 2 and 3 shifts per day operation is

Heat, Light and Rates cost = Total hours per week x no. of weeks per year x Rate

For 2 shifts/day, Annual Cost = 80 (hrs) x 48 (wks) x 1.15 (£)
= £4,416

For 3 shifts/day, Annual Cost = 120 (hrs) x 48 (wks) x 1.08 (£)
= £6,221

(2) POWER

MACHINE TOOLS

The cost of power consumption by machine tools (C_m) is given by

$$C_m = \frac{T.s.U_m \quad N\, P_m\, r}{U_o}$$

where, T = No. of hours per week per shift (40 hrs)

s = No. of shifts per day

U_m = Average percentage machine utilisation (from simulation)

U_o = Percentage Output Level (from simulation)

N = No. of 2 week batch production periods per year (24)

P_m = Total Machine Tool rating in kW

r = £0.03/kWhr (commercial rate from East Midlands Electricity Board).

Electrical Ratings of Machine Tools Equipment:-

One KTM Hoz. Machine Centre	@ 15 kW	= 15 kW.
Two V4-6 Vert. Machine Centres	@ 11.5 kW	= 23 kW.
Three V5-10 Vert. Machine Centres	@ 18 kW	= 54 kW.
Sub Total		= 92 kW.
Six A.P.C.s(2 pallet stations each)	@ 0.5 kW	= 3 kW.
Six A.P.C.s(4 pallet stations each)	@ 1 kW	= 6 kW.

AUXILIARY EQUIPMENT

The costs of power consumption by auxiliary equipment, C_a, (for example Washing, Inspection, and Tool Presetting machines), is estimated at 10% of machine tool power consumption. Thus

$$C_a = 0.1\ C_m$$

MATERIAL HANDLING EQUIPMENT

Costs of power consumption by transporters in automated systems is given by, C_t, where

$$C_t = \frac{T_s\ U_t\ \ N\ P_t\ r}{U_o}$$

U_T = Percentage utilisation of transport system (from simulation)

P_t = Power Rating of transport system (kW).

The other variables have been defined under machine tools.

Electrical Ratings of Transport Systems:

Conveyor System = 78 motor equivalent @ 0.4 kW each.

Stacker Crane = 15 kW

Rail Guided Shuttle = 8 kW

AGV Battery Recharge (approx) = 4.5 kW

COMPUTER AND CONTROL EQUIPMENT

The computer equipment in the manual systems (FMS A, B and C) has an estimated rating of 1 kW and is assumed to have a utilisation rate of 50%. Thus the power costs, C_C, is given by

C_C = 1920 x 0.5 x (shifts/day) x 1 x £0.03

In automated systems (FMS D, E, F and G), the power costs of computer and control equipment is estimated at the rate of 10% of material handling power consumption costs, C_T, i.e.

$$C_C = 0.1\ C_T$$

(3) DIRECT LABOUR

Wages for direct labour are estimated at £10,000 per man per annum.

(4) SUPERVISION

Supervision consists of salaries paid to one Cell Supervisor, and one Cell Planner at £15000 and £12000 per year respectively.

(5) MAINTENANCE

Mechanical Equipment

The maintenance costs for mechanical equipment is calculated at a rate of d% of the Investment Cost (CI) excluding Grant (less programming, computer, engineering and installation costs). This cost element is assumed to increase linearly over the 7 year time span as per schedule below.

Year	1	2	3	4	5	6	7
d %	0.5	1.0	1.5	2.0	2.5	3.0	3.5
SYSTEM	A	B	C	D	E	F	G
CI	£532480	£670480	£790480	£1036780	£881180	£769280	£1019780

Computer Equipment

The cost of this item is in the form of a maintenance contract with the suppliers,and is estimated at 10% of the computer equipment costs.

(6) CONSUMABLES:TOOLS

For the output level simulated, the cost of cutting tools was estimated at the rate of £1200 per machine annually. The total cost of this item per year is therefore £7200.

(7) CONSUMABLES:CUTTING FLUID

This cost element was estimated at the rate of £150 per machine, resulting in an annual cost of £900 for the prismatic machining cell.

(8) SWARF AND WASTE DISPOSAL

This activity is performed manually by the cell attendant (representing unskilled labour) whose wages are £6000 per year.

(9) CONTINGENCIES

This element has been estimated at the rate of 5% of the direct costs which is obtained by adding cost items (1) to (8) described previously.

(10) INSURANCE

This indirect cost is estimated at 1/3% of the Investment Cost (excluding Grant) of the prismatic machining cell.

(11) INDIRECT LABOUR

This consists of one tool presetter with remuneration estimated at £10000 per year.

APPENDIX H

H.2: TAX BENEFIT ON WRITING DOWN ALLOWANCE

FMS A:

YEAR	WRITING DOWN ALLOWANCE	(X0.25)	ALLOWANCE TAXED	(X0.35)	TAX SAVED
1	408,125		102,031		35,711
2	306,094		76,524		26,783
3	229,570		57,392		20,087
4	172,178		43,045		15,066
5	129,133		32,283		11,299
6	96,850		24,213		8,474
7	72,637		18,159		6,536

FMS B:

1	512,095		128,024		44,808
2	384,071		96,018		33,606
3	288,053		72,013		25,205
4	216,040		54,010		18,904
5	162,030		40,508		14,178
6	121,522		30,381		10,633
7	91,141		22,785		7,975

FMS C:

1	603,485		150,871		52.805
2	452,614		113,154		39,604
3	339,460		84,865		29,703
4	254,595		63,649		22,277
5	190,946		47,737		16,708
6	143,209		35,802		12,531
7	107,407		26,852		9,398

FMS D:

1	837,502		209,376		73,281
2	628,126		157,032		54,961
3	471,094		117,774		41,221
4	353,320		88,330		30,916
5	264,990		66,248		23,187
6	198,742		49,686		17,390
7	149,056		37,264		13,042

FMS E:

YEAR	WRITING DOWN ALLOWANCE		ALLOWANCE TAXED		TAX SAVED
		(X0.25)		(X0.35)	
1	630,791		157,698		55,194
2	473,093		118,273		41,396
3	354,820		88,705		31,047
4	266,115		66,529		23,285
5	199,586		49,897		17,464
6	149,689		37,422		13,098
7	112,267		28,067		9,823

FMS F:

YEAR	WRITING DOWN ALLOWANCE	ALLOWANCE TAXED	TAX SAVED
1	717,223	179,306	62,757
2	537,917	134,479	47,068
3	403,438	100,860	35,301
4	302,578	75,645	26,476
5	226,933	56,733	19,857
6	170,200	42,550	14,893
7	127,650	31,913	11,169

FMS G:

YEAR	WRITING DOWN ALLOWANCE	ALLOWANCE TAXED	TAX SAVED
1	824,597	206,149	72,152
2	618,448	154,612	54,114
3	463,836	115,959	40,586
4	347,877	86,969	30,439
5	260,908	65,227	22,829
6	195,681	48,920	17,122
7	146,761	36,690	12,842

APPENDIX I

CASH OUTFLOWS FOR SYSTEMS WITH EQUAL MANPOWER LEVELS

CONTENTS

APPENDIX I

I.1.: ANNUAL CASH OUTFLOWS FOR EQUAL MANPOWER LEVELS

ANNUAL CASH FLOWS (£)

SYSTEM	FMS A	FMS B	FMS C	FMS D	FMS E	FMS F	FMS G
2 MEN							
C INV	-408,125	-514,685	-603,485	-837,502	-714,263	-630,791	-824,597
C OP,Yr.1	- 72,866	- 64,746	- 58,006	- 42,819	- 50,496	- 56,626	- 43,799
Yr.2	- 89,602	- 84,557	- 80,405	- 71,788	- 75,862	- 79,556	- 72,396
Yr.3	-104,348	-101,793	- 99,744	- 96,426	- 97,567	- 99,279	- 96,731
Yr.4	-117,669	-117,174	-116,866	-117,893	-116,601	-116,673	-117,947
Yr.5	-130,004	-131,237	-132,396	-137,055	-133,706	-132,394	-136,899
Yr.6	-141,673	-144,391	-146,814	-154,572	-149,446	-146,942	-154,234
Yr.7	-152,928	-156,950	-160,483	-170,943	-164,249	-160,696	-170,445

ANNUAL CASH FLOWS (£)

SYSTEM	FMS (A)	FMS (B)	FMS (C)	FMS (D)	FMS (E)	FMS (F)	FMS (G)
3 MEN							
C INV	-408,125	-514,685	-603,485	-837,502	-714,263	-630,791	-824,597
C OP,Yr.1	- 93,909	- 85,789	- 79,049	- 63,862	- 71,539	- 77,669	- 64,842
Yr.2	-111,696	-106,651	-102,499	- 93,882	- 97,956	-101,650	- 94,490
Yr.3	-127,542	-124,991	-122,942	-119,624	-120,765	-122,476	-119,928
Yr.4	-142,027	-141,532	-141,225	-142,251	-140,959	-141,031	-142,305
Yr.5	-155,577	-156,811	-157,970	-162,628	-159,279	-157,968	-162,473
Yr.6	-168,524	-171,242	-173,664	-181,424	-176,297	-173,793	-181,086
Yr.7	-181,123	-185,143	-188,676	-199,136	-192,443	-188,889	-198,639

ANNUAL CASH FLOWS (£)

SYSTEM	FMS (A)	FMS (B)	FMS (C)	FMS (D)	FMS (E)	FMS (F)	FMS (G)
4 MEN							
C INV	-408,125	-514,685	-603,485	-837,502	-714,263	-630,791	-824,597
C OP,Yr.1	-114,845	-106,723	- 99,983	- 84,796	- 92,473	- 98,603	- 85,776
Yr.2	-133,680	-128,633	-124,481	-115,864	-119,938	-123,632	-116,472
Yr.3	-150,626	-148,073	-146,024	-142,706	-143,847	-145,559	-143,010
Yr.4	-166,266	-165,769	-165,461	-166,488	-165,196	-165,268	-166,542
Yr.5	-181,331	-182,863	-183,422	-188,080	-184,732	-183,420	-187,925
Yr.6	-195,250	-197,968	-200,390	-208,150	-203,023	-200,519	-207,811
Yr.7	-209,180	-213,205	-216,739	-227,200	-220,506	-216,952	-226,702

APPENDIX I

I.2.: NPV CASH OUTFLOWS FOR EQUAL MANPOWER LEVELS (£)

SYSTEM							
2 MEN	FMS A	FMS B	FMS C	FMS D	FMS E	FMS F	FMS G
C_{INV}	-408,125	-514,685	-603,485	-837,502	-714,263	-630,791	-824,597
C_{OP},Yr.1	- 65,062	- 57,812	- 51,794	- 38,233	- 45,088	- 50,561	- 39,108
Yr.2	- 71,431	- 67,409	- 64,099	- 57,229	- 60,477	- 63,422	- 57,714
Yr.3	- 74,275	- 72,456	- 70,998	- 68,636	- 69,448	- 70,667	- 68,853
Yr.4	- 74,779	- 74,464	- 74,268	- 74,921	- 74,146	- 74,146	- 74,955
Yr.5	- 73,764	- 74,464	- 75,121	- 77,765	- 75,865	- 75,120	- 77,676
Yr.6	- 71,772	- 73,148	- 74,376	- 78,306	- 75,709	- 74,441	- 78,135
Yr.7	- 69,169	- 70,988	- 72,586	- 77,318	- 74,290	- 72,683	- 77,092
TOTAL NPV	-908377	-1005426	-1086727	-1309910	-1189286	-1111831	-1298430
3 MEN	FMS (A)	FMS (B)	FMS (C)	FMS (D)	FMS (E)	FMS (F)	FMS (G)
C_{INV}	-408,125	-514,685	-603,485	-837,502	-714,263	-630,791	-824,597
C_{OP},Yr.1	- 83,851	- 76,601	- 70,583	- 57,022	- 63,877	- 69,351	- 57,897
Yr.2	- 89,044	- 85,022	- 81,712	- 74,843	- 78,091	- 81,035	- 75,327
Yr.3	- 90,784	- 88,969	- 87,510	- 85,148	- 85,961	- 87,178	- 85,365
Yr.4	- 90,258	- 89,944	- 89,748	- 90,401	- 89,579	- 89,625	- 90,435
Yr.5	- 88,274	- 88,975	- 89,632	- 92,275	- 90,375	- 89,631	- 92,187
Yr.6	- 85,374	- 86,751	- 87,978	- 91,909	- 89,312	- 88,044	- 91,738
Yr.7	- 81,922	- 83,740	- 85,338	- 90,069	- 87,042	- 85,434	- 89,844
TOTAL NPV	-1017632	-1114687	-1195986	-1419169	-1298500	-1221089	-1407390
4 MEN	FMS (A)	FMS (B)	FMS (C)	FMS (D)	FMS (E)	FMS (F)	FMS (G)
C_{INV}	-408,125	-514,685	-603,485	-837,502	-714,263	-630,791	-824,597
C_{OP},Yr.1	-102,545	- 95,293	- 89,275	- 75,714	- 82,569	- 88,043	- 76,589
Yr.2	-106,570	-102,546	- 99,236	- 92,367	- 95,615	- 98,559	- 92,851
Yr.3	-107,216	-105,398	-103,940	-101,578	-102,390	-103,609	-101,795
Yr.4	-105,662	-105,346	-105,150	-105,803	-104,982	-105,028	-105,837
Yr.5	-102,887	-103,756	-104,074	-106,717	-104,817	-104,073	-106,629
Yr.6	- 98,914	-100,291	-101,518	-105,449	-102,851	-101,583	-105,277
Yr.7	- 94,612	- 96,433	- 98,031	-102,763	- 99,735	- 98,127	-102,537
TOTAL NPV	-1126531	-1223748	-1304709	-1527893	-1407222	-1329813	-1516112

APPENDIX J

NPV CASH OUTFLOWS FOR INCREMENTAL AUTOMATION

CONTENTS

J.1 NPV FOR TWO STAGE INCREMENTAL AUTOMATION

J.1.1: CASH OUTFLOWS FOR FMS C

(For minimum assured output 52.5%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	A	A	A	B	B	C	C	C
C_{INV} (£)	-408125	0	0	-113050	0	- 99945	0	0
C_{OP} (£)	0	-114845	-133680	-124991	-141532	-132396	-146814	-160483
C_{TOT} (£)	-408125	-114845	-133680	-238041	-141532	-232341	-146814	-160483
C_{D} (£)	-408125	-102545	-106570	-170149	- 89944	-131830	- 74376	- 72586

(For Output Range 42-58%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	A	A	A	B	B	C	C	C
C_{INV} (£)	-408125	0	0	-113050	0	- 99945	0	0
C_{OP} (£)	0	- 93909	-111696	-101793	-117174	-132396	-146814	-160483
C_{TOT} (£)	-408125	- 93909	-111696	-214843	-117174	-232341	-146814	-160483
C_{D} (£)	-408125	- 83851	- 89044	-152925	- 74464	-131830	- 74376	- 72586

J.1.2: CASH OUTFLOWS FOR FMS D

(For minimum assured output 52.5%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	A	A	A	B	B	D	D	D
C_{INV} (£)	-408125	0	0	-113050	0	-363333	0	0
C_{OP} (£)	0	-114845	-133680	-124991	-141532	-162628	-181424	-199136
C_{TOT} (£)	-408125	-114845	-133680	-238041	-141532	-525961	-181424	-199136
C_{D} (£)	-408125	-102545	-106570	-170149	- 89944	-298430	- 91909	- 90069

(For Output Range 42-58%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	A	A	A	B	B	D	D	D
C_{INV} (£)	-408125	0	0	-113050	0	-363333	0	0
C_{OP} (£)	0	- 93909	-111696	-101793	-117174	-137055	-154572	-170943
C_{TOT} (£)	-408125	- 93909	-111696	-214843	-117174	-500388	-154572	-170943
C_{D} (£)	-408125	- 83851	- 89044	-152925	- 74464	-283920	- 78306	- 77318

J.1.3: CASH OUTFLOWS FOR FMS E

(For minimum assured output 52.5%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	A	A	A	B	B	E	E	E
C_{INV} (£)	-408125	0	0	-113050	0	-224627	0	0
C_{OP} (£)	0	-114845	-133680	-124991	-141532	-133706	-149446	-164249
C_{TOT} (£)	-408125	-114845	-133680	-238041	-141532	-358333	-149446	-164249
C_{D} (£)	-408125	-102545	-106570	-170149	- 89944	-203318	- 75709	- 74290

(For Output Range 42-58%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	A	A	A	B	B	E	E	E
C_{INV} (£)	-408125	0	0	-113050	0	-224627	0	0
C_{OP} (£)	0	- 93909	-111696	-101793	-117174	-133706	-149446	-164249
C_{TOT} (£)	-408125	- 93909	-111696	-214843	-117174	-358333	-149446	-164249
C_{D} (£)	-408125	- 83851	- 89044	-152925	- 74464	-203318	- 75709	- 74290

J.1.4: CASH OUTFLOWS FOR FMS F

(For minimum assured output 52.5%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	A	A	A	B	B	F	F	F
C_{INV} (£)	-408125	0	0	-113050	0	-130678	0	0
C_{OP} (£)	0	-114845	-133680	-124991	-141532	-157968	-173793	-188889
C_{TOT} (£)	-408125	-114845	-133680	-238041	-141532	-288646	-173793	-188889
C_{D} (£)	-408125	-102545	-106570	-170149	- 89944	-163778	- 88044	- 85434

(For Output Range 42-58%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	A	A	A	B	B	F	F	F
C_{INV} (£)	-408125	0	0	-113050	0	-130678	0	0
C_{OP} (£)	0	- 93909	-111696	-101793	-117174	-157968	-173793	-188889
C_{TOT} (£)	-408125	- 93909	-111696	-214843	-117174	-288646	-173793	-188889
C_{D} (£)	-408125	- 83851	- 89044	-152925	- 74464	-163778	- 88044	- 85434

J.1.5: CASH OUTFLOWS FOR FMS G

(For minimum assured output 52.5%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	A	A	A	B	B	G	G	G
C_{INV} (£)	-408125	0	0	-113050	0	-348809	0	0
C_{OP} (£)	0	-114845	-133680	-124991	-141532	-136899	-154234	-170445
C_{TOT} (£)	-408125	-114845	-133680	-238041	-141532	-485708	-154234	-170445
C_{D} (£)	-408125	-102545	-106570	-170149	- 89944	-275591	- 78135	- 77092

(For Output Range 42-58%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	A	A	A	B	B	G	G	G
C_{INV} (£)	-408125	0	0	-113050	0	-348809	0	0
C_{OP} (£)	0	- 93909	-111696	-101793	-117174	-136899	-154234	-170445
C_{TOT} (£)	-408125	- 93909	-111696	-214843	-117174	-485708	-154234	-170445
C_{D} (£)	-408125	- 83851	- 89044	-152925	- 74464	-275591	- 78135	- 77092

J.2 NPV FOR SINGLE STAGE INCREMENTAL AUTOMATION

J.2.1: CASH OUTFLOWS FOR FMS C

(For minimum assured output 52.5%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	B	B	B	C	C	C	C	C
C_{INV} (£)	-514685	0	0	- 88800	0	0	0	0
C_{OP} (£)	0	-132825	-140427	- 99746	-116866	-132396	-146814	-160481
C_{TOT} (£)	-514685	-132825	-140427	-188546	-116866	-132396	-146814	-160481
C_D (£)	-514685	-118599	-111948	-134207	- 74268	- 75121	- 74376	- 72586

(For Output Range 42-58%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	B	B	B	C	C	C	C	C
C_{INV} (£)	-514685	0	0	- 88800	0	0	0	0
C_{OP} (£)	0	- 64747	- 84557	- 99746	-116866	-132396	-146814	-160481
C_{TOT} (£)	-514685	- 64747	- 84557	-188546	-116866	-132396	-146814	-160481
C_D (£)	-514685	- 57813	- 67409	-134207	- 74268	- 75121	- 74376	- 72586

J.2.2: CASH OUTFLOWS FOR FMS D

(For minimum assured output 52.5%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	B	B	B	D	D	D	D	D
C_{INV} (£)	-514685	0	0	-322817	0	0	0	0
C_{OP} (£)	0	-132825	-140427	- 96427	-117892	-137055	-154573	-170943
C_{TOT} (£)	-514685	-132825	-140427	-419244	-117892	-137055	-154573	-170943
C_{D} (£)	-514685	-118599	-111948	-298418	- 74920	- 77765	- 78307	- 77318

(For Output Range 42-58%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	B	B	B	D	D	D	D	D
C_{INV} (£)	-514685	0	0	-322817	0	0	0	0
C_{OP} (£)	0	- 64747	- 84557	- 96427	-117892	-137055	-154573	-170943
C_{TOT} (£)	-514685	- 64747	- 84557	-419244	-117892	-137055	-154573	-170943
C_{D} (£)	-514685	- 57813	- 67409	-298418	- 74920	- 77765	- 78307	- 77318

J.2.3: CASH OUTFLOWS FOR FMS E

(For minimum assured output 52.5%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	B	B	B	E	E	E	E	E
C_{INV} (£)	-514685	0	0	-199578	0	0	0	0
C_{OP} (£)	0	-132825	-140427	- 97568	-116601	-133706	-149447	-164249
C_{TOT} (£)	-514685	-132825	-140427	-297146	-116601	-133706	-149447	-164249
C_{D} (£)	-514685	-118599	-111948	-211509	- 74100	- 75865	- 75710	- 74290

(For Output Range 42-58%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	B	B	B	E	E	E	E	E
C_{INV} (£)	-514685	0	0	-199578	0	0	0	0
C_{OP} (£)	0	- 64747	- 84557	- 97568	-116601	-133706	-149447	-164249
C_{TOT} (£)	-514685	- 64747	- 84557	-297146	-116601	-133706	-149447	-164249
C_{D} (£)	-514685	- 57813	- 67409	-211509	- 74100	- 75865	- 75710	- 74290

J.2.4: CASH OUTFLOWS FOR FMS F

(For minimum assured output 52.5%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	B	B	B	F	F	F	F	F
C_{INV} (£)	-514685	0	0	-116106	0	0	0	0
C_{OP} (£)	0	-132825	-140427	- 99280	-116673	-132394	-146942	-160695
C_{TOT} (£)	-514685	-132825	-140427	-215386	-116673	-132394	-146942	-160695
C_{D} (£)	-514685	-118599	-111948	-153312	- 74146	- 75120	- 74441	- 72682

(For Output Range 42-58%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	B	B	B	F	F	F	F	F
C_{INV} (£)	-514685	0	0	-116106	0	0	0	0
C_{OP} (£)	0	- 64747	- 84557	- 99280	-116673	-132394	-146942	-160695
C_{TOT} (£)	-514685	- 64747	- 84557	-215386	-116673	-132394	-146942	-160695
C_{D} (£)	-514685	- 57813	- 67409	-153312	- 74146	- 75120	- 74441	- 72682

J.2.5: CASH OUTFLOWS FOR FMS G

(For minimum assured output 52.5%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	B	B	B	G	G	G	G	G
C_{INV} (£)	-514685	0	0	-309912	0	0	0	0
C_{OP} (£)	0	-132825	-140427	- 96732	-117947	-136899	-154235	-170444
C_{TOT} (£)	-514685	-132825	-140427	-406644	-117947	-136899	-154235	-170444
C_D (£)	-514685	-118599	-111948	-289449	- 74955	- 77676	- 78135	- 77092

(For Output Range 42-58%)

YEAR	0	1	2	3	4	5	6	7
SYSTEM	B	B	B	G	G	G	G	G
C_{INV} (£)	-514685	0	0	-309912	0	0	0	0
C_{OP} (£)	0	- 64747	- 84557	- 96732	-117947	-136899	-154235	-170444
C_{TOT} (£)	-514685	- 64747	- 84557	-406644	-117947	-136899	-154235	-170444
C_D (£)	-514685	- 57813	- 67409	-289449	- 74955	- 77676	- 78135	- 77092