COMPUTERISED CONTROL
OF
CELLULAR MANUFACTURING SYSTEMS

MONTAJ MUSTAKIM

Doctor of Philosophy

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SUMMARY

This thesis reviews the existing manufacturing control techniques and identifies their practical drawbacks when applied in a high variety, low and medium volume environment. It advocates that the significant drawbacks inherent in such systems, could impair their applications in such a manufacturing environment. The key weaknesses identified in the system were: capacity insensitive nature of Material Requirements Planning (MRP); the centralised approach to planning and control applied in Manufacturing Resources Planning (MRP II); the fact that Kanban can only be used in repetitive environments ; Optimised Production Techniques's (OPT) inability to deal with transient bottlenecks etc. On the other hand, cellular systems offer advantages in simplifying the control problems of manufacturing and the thesis reviews systems designed for cellular manufacturing including Distributed Manufacturing Resources Planning (DMRP) and Flexible Manufacturing Systems (FMS) controllers.

It advocates that a newly developed cellular manufacturing control methodology, which is fully automatic, capacity sensitive and responsive, has the potential to resolve the core manufacturing control problems discussed above. It's development is envisaged within the framework of a DMRP environment, in which each cell is provided with its own MRP II system and decision making capability. It is a cellular based, closed loop control system, which revolves on single level Bills-Of-Material (BOM) structure and hence provides better traceability between shop level scheduling activities and the relevant entries in the Master Production Schedule (MPS). This enhances the prospect of undertaking rapid response to changes in the status of manufacturing resources and incoming enquiries. In addition, it also permits automatic evaluation of capacity and due date constraints and facilitates the automation of MPS within such a system.

A prototype cellular manufacturing control model, was developed to demonstrate the underlying principles and operational logic of the cellular manufacturing control methodology, based on the above concept. This was shown to offer significant advantages from the prospective of complete automation of all operational planning and control functions. Results of relevant tests proved that the model is capable of producing reasonable due date and undertake automation of MPS. The overall performance of the model proved satisfactory and acceptable.

KEYWORDS : Cellular Manufacturing Systems, Distributed Manufacturing Resources Planning, Production Control, Material Requirements Planning

In the name of God, The Compassionate, The Merciful

To

My Mother

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FIGURES

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ABBREVIATIONS

APICS	American Production and Inventory Control Society
BOM	Bills-Of-Material
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CIM	Computer Integrated Manufacturing
CM	Cellular Manufacturing
CMS	Cellular Manufacturing Systems
COCMACS	COmputerised Cellular MAnufacturing Control System
CRP	Capacity Requirements Planning
DB	Database
DD	Due Date
DOS	Disk Operating System
DP	Data Processing
DMRP	Distributed Manufacturing Resources Planning
FCS	Finite Capacity Scheduling
FMC	Flexible Manufacturing (Machining) Cell
FMS	Flexible Manufacturing Systems
FSA	Finite Scheduling Algorithm
GT	Group Technology
JIT	Just-In-Time
KB	Knowledge Base
LAN	Local Area Network
MB	Mega Byte
MHz	Mega Hertz
MOD	Module

MPS	Master Production Schedule
MRP	Material Requirements Planning
MRP II	Manufacturing Resources Planning
MS-DOS	Micro-Soft Disk Operating System
OPT	Optimised Production Techniques
OS	Operating System
PBC	Periodic Batch Control
PC	Personal Computer
RAM	Random Access Memory
RCCP	Rough Cut Capacity Planning
TBasic	Turbo Basic
TPascal	Turbo Pascal
WC	Work Centre
WIP	Work-In-Progress

CHAPTER 1

Introduction

This thesis reviews the resource planning and control problems in manufacturing and it examines the major attributes of such problems and the practical implications for the future development of manufacturing control systems. It also explores the development of a manufacturing control methodology that has the potential to offer total automation of all operational activities.

1.1 An Introduction to the Research Problem

Over the years, manufacturing systems have become increasingly complex, in order to cope with the increase in product variety and complexity. This has major implications for the management of manufacturing systems. For example, high product variety increases the complexity of the factory plant layout, since it must accommodate numerous route options within the system. This leads to an attendent increase in the complexity of work flow patterns and work-in-progress [Lewis, F. A. 1973]. Complex material flow poses a serious physical progress control problem [Burbidge, J.L. 1971]. As a result, this increases the throughput time of products [Rolstadas, A 1988] and enhances the prospect of inflating the manufacturing lead time. This also increases the likelihood of extended completion or due date of products manufactured within the system, thus resulting in late delivery.

The increase in product variety and complexity has a major implication for the nature of resource planning because it entails management of large volumes of data and more complex calculation of material or capacity requirements. The complexity stems, in part, from multi-level Bills-Of-Material (BOM) and a significant degree of parts commonality between products. These characteristics affect the ease with which control information can flow between the levels in the system hierarchy. Information flow up the system is difficult since the complex product structure hinders traceability between shop floor activities and higher level planning such as Master Production Scheduling (MPS).

As discussed earlier, the presence of high product variety and complexity poses a major resource allocation problem since it is relatively difficult to schedule non identical parts as compared with a families of identical parts due to different manufacturing resource requirements. For example, the set-up requirements (e.g. change overs) for high variety items are much greater compared to families of parts. The scheduling process is therefore relatively complex and the calculation of precise manufacturing lead time or due date is problematic in such an environment.

The characteristics of manufacturing systems discussed above, have a significant influence on the planning and control systems used in such an environment. Many manufacturing control systems have been developed (e.g. Material Requirements Planning (MRP), Manufacturing Resources Planning (MRP II), Optimised Production Techniques (OPT), Flexible Manufacturing Systems (FMS) controllers, Distributed Manufacturing Resources Planning (DMRP)) and implemented in manufacturing industries. Some of them are tailor made for specific applications (e.g. FMS process controllers) whereas, others were developed for a much broader application (e.g. MRP, MRP II, OPT). These systems can be broadly classified under manual (e.g. Kanban), semi-automatic (e.g. MRP II, DMRP) and automatic control systems (e.g. FMS controllers). Generally, fully automatic control systems have been implemented only in low level, process control applications. These may respond to status changes, arising from low level inputs (e.g. machine breakdown) but they are limited in their ability to provide a similar function for top level inputs such as incoming orders or enquiries. Furthermore, these systems attempt only low level replanning in response to system status changes and they do not trigger replanning of systems higher up the control hierarchy (i.e. MPS). For example, an FMS breakdown will not affect material purchasing plans.

Most of the current control systems involve a significant degree of manual intervention. For example, in MRP, modification of the highest level plan (i.e. MPS) is always performed manually. However, the ultimate aim of control system development should be complete automation of all aspects of operation of the manufacturing control system.

The practical implications for the manufacturing control system would be to eliminate all major forms of human intervention in the management of such a system, in particular, in response to changes in the status of manufacturing resources or in the key inputs into the factory. In this context, changes in the status of manufacturing environment arise from disturbances on the shop floor (i.e. machine breakdown) whereas of the major inputs to the system, the most significant is incoming orders or customer enquiries.

An automatic control system would provide a better prospect of dealing with the dynamics of the manufacturing environment, that is, it would enable such a system to replan all the relevant activities if necessary in response to status change. This would also be capable of providing rapid response (e.g. accurate and realistic due date) for any new orders or incoming enquiries. In this context, realistic due date implies that there is a high probability that the products can be delivered in time as demanded by the prospective customer.

Although some of the existing manufacturing control systems, have some of the capabilities required to fulfill the above requirements, none can offer the potential for full automation in the context discussed above and this is attributed to the inherent limitations in existing manufacturing systems and control philosophy (e.g. centralised top-down concept, open-loop control structure) adopted in the current manufacturing control systems. The main aim of the thesis is to develop a control system architecture that has the capability to offer automation of all operational control activities as discussed above.

1.2 Research Objectives

The main objective of the research is to develop a manufacturing control system methodology that could automate the operational control function. In this context, the prospective methodology should be capable of providing the following control functions:-

- rapid response to changes in the manufacturing environment, arising from top level inputs (e.g. incoming customer orders or enquiries) and bottom level inputs (i.e. changes in the status of manufacturing resources) and

- offer inherent flexibility in the means of decision making, so that the control mechanism can match a variety of manufacturing environments.

CHAPTER 2

Review of Manufacturing Control Problems

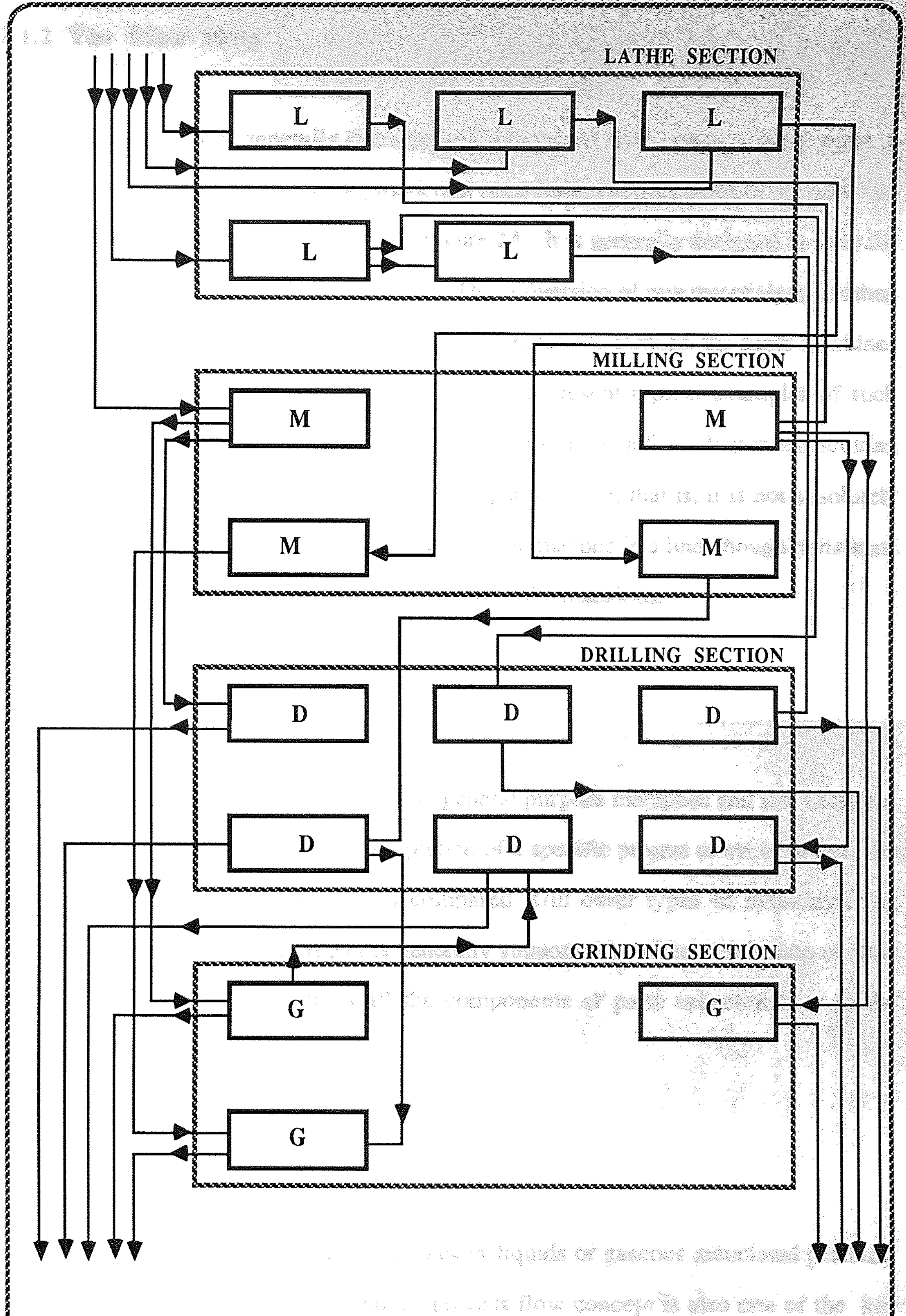
This chapter discusses the major control problems associated with manufacturing systems. It explores the key factors that influence the control problems and their implications on operational planning and control of such systems.

2.1 Traditional Manufacturing Systems

Manufacturing systems can be classified into four traditional categories, namely, the job, flow, project and continuous shops respectively, each having unique and distinct characteristics from the other [Huang, P.Y. et. al 1985]. The following sections discuss the characteristics of each system.

2.1.1 The Job Shop

The job shop is the oldest of the traditional manufacturing systems in which the transformation of the raw materials to finished products follow different sequences and through different machines or processes. It is characterised by flexible general purpose machines, high product variety and highly skilled operators. It requires a great deal of manual material handling, involves a lot of indirect labour and the lot sizes range from small to medium [Black, J.T. 1983]. A typical job shop environment based on functional layout is illustrated in Figure 1. Machining is carried out in a machine shop which is arranged in a standard functional manner where the lathes, milling and drilling machines are arranged according to the types of operations which they perform.



[TYPES OF MACHINE LAYOUT (AFTER LEWIS)]
[COMPLEX WORK FLOW AND HIGH VOLUME OF WORK-IN-PROGRES]

FIGURE 1 A TYPICAL FUNCTIONAL LAYOUT

2.1.2 The Flow Shop

The flow shop is generally characterised by product flow layout, special purpose single function machines with long production runs, constant process times per unit, etc. A typical flow line layout is illustrated in Figure 2A. It is generally designed to cater for products which are made in large quantities. The conversion of raw materials to finished products normally follow the same sequence of operations through the same machines with practically no backtracking. Transfer lines represent typical examples of such systems where the mode of control is fully computerised. In a flow shop manufacturing environment, it is permissible for a part to jump a machine, that is, it is not absolutely necessary that every part must be processed by each machine in a line, though parts must travel in the same order of sequence of operation of the machines.

2.1.3 The Project Shop

The project shop is characterised by general purpose machines and it is designed with specific objective such as the completion of a specific project or set of orders. Its application is therefore quite limited compared with other types of manufacturing systems. In most cases, the project is generally supported by either a job shop or flow shop system which manufactures all the components or parts subassemblies to the project.

2.1.4 The Continuous Shop

The continuous shop is designed to cater liquids or gaseous associated products made in large volumes. The continuous process flow concept is also one of the key features of the Just-In-Time (JIT) production systems where the parts processing and movements are designed ideally to flow like water through the production system. It is generally characterised by small in-process inventories, continuous flow process etc.

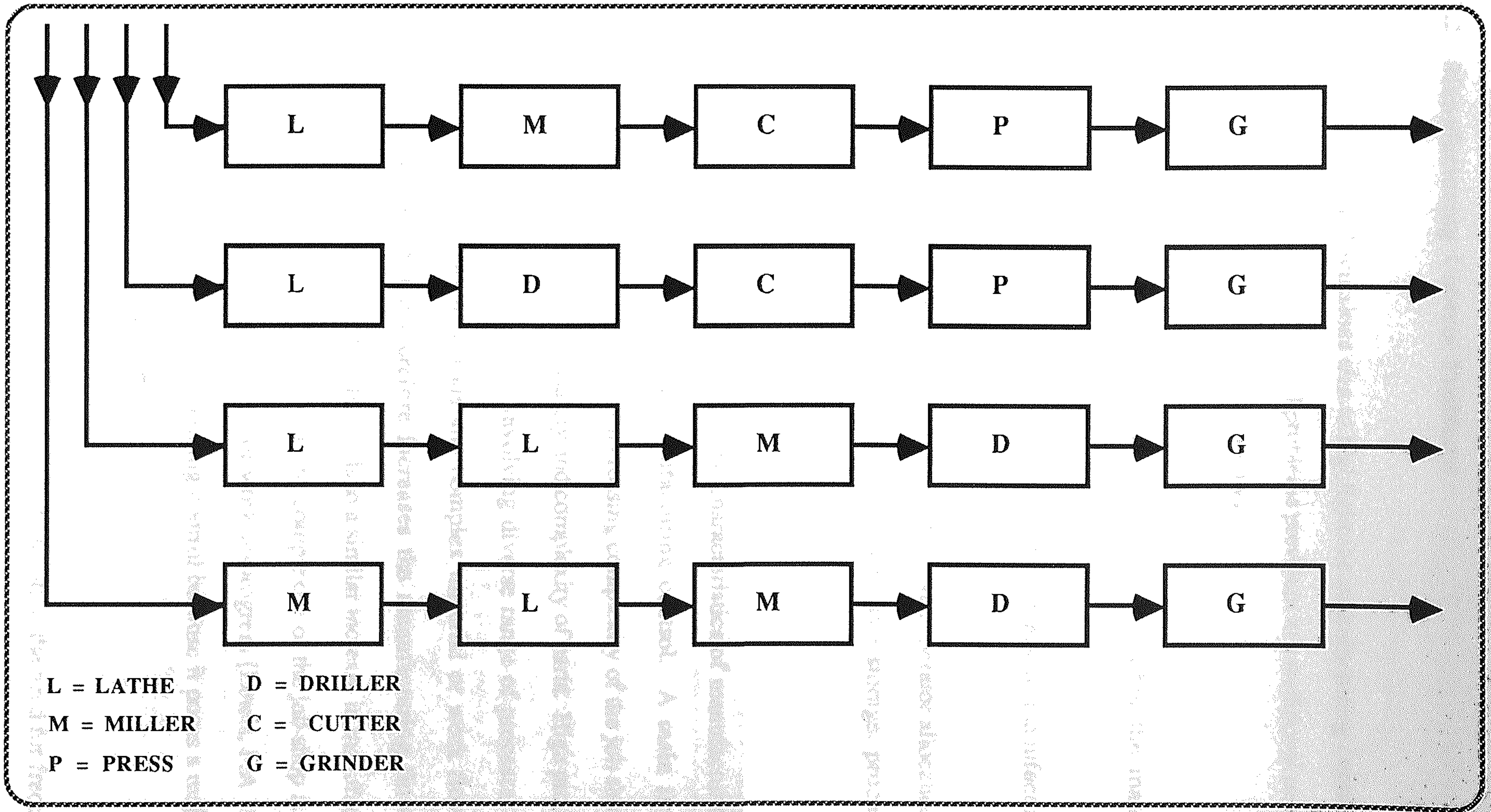


FIGURE 2A - A TYPICAL FLOW LINE LAYOUT

2.2 Manufacturing Control Problems

The following discussions aim to highlight the manufacturing control problems and their attributes. The major control problems prevalent in a traditional manufacturing environment can be broadly classified as follows :-

- material flow (i.e., movement of material within the manufacturing environment) ;
- information flow (i.e., monitoring and feedback of manufacturing status and incoming enquiries) ;
- resource allocation/utilisation (i.e., jobs, parts, operator allocation), and
- database management or processing (i.e., data storage, processing, data accuracy/integrity), etc.

These problems are influenced by the characteristics of manufacturing systems which have major implications for manufacturing control. A main factor which contributes to such problems is the ever increasing complexity of the job shop, which is attributed to an increase in product variety and complexity of parts. High product variety offers a wide range of route options involving diverse range of processes in various sequences. This presents numerous and complex material or work flow patterns through the shop floor and therefore increases the manufacturing flow time and work-in-progress. As a result, this also leads to a similar increase in manufacturing lead times and due date. As shown in Figure 1, the complexity of the job shop is influenced by complex work flow and high volume of work-in-progress [Lewis, F.A 1973]. This has a practical implication for manufacturing control because it poses a major material and physical progress control problems.

The manufacture of high product variety often entails the need for frequent change overs from one product variety to the other. For example, the set-up requirements (e.g.

change over frequency) are much higher as compared to identical or family of parts. This leads to an increase in the total flow times through the system, since more time is lost in change overs from one part type to the other [Kekre, Sunder 1987]. As a result, this leads to extended manufacturing lead time, completion or due date. In a major review of job shop problems, Ballakur, A. et. al [1984] wrote :-

> "The flow of production orders through a job shop is one of the most complex type of flow structures in manufacturing systems. The network of job routing poses a challenge in understanding and controlling job shops. Likewise, product mix, machine capacities and capabilities, variations in operation processing times, and labour assignment to machines, etc., are other factors adding to the complexity of the job shop control system. The conflicting interactions of various activities and the resulting dilemma on the shop floor can be visualised through the following example (see Figure 2B). The orders arriving in the shop have due dates associated with them, usually based on customer needs and plant workload. Consider the case of the job shop where due dates are being missed, perhaps due to work input demand being greater than the work capacity of the shop. The management intentionally increases the operation of the lead times and therefore releases the orders to the shop somewhat earlier. This corrective action increases the number of jobs in the shop, causing increased machine/work centre loads, queues, and queue waiting times. Now, the increased workload only increases congestion, extends job throughput times, and ultimately results in more jobs missing due dates."

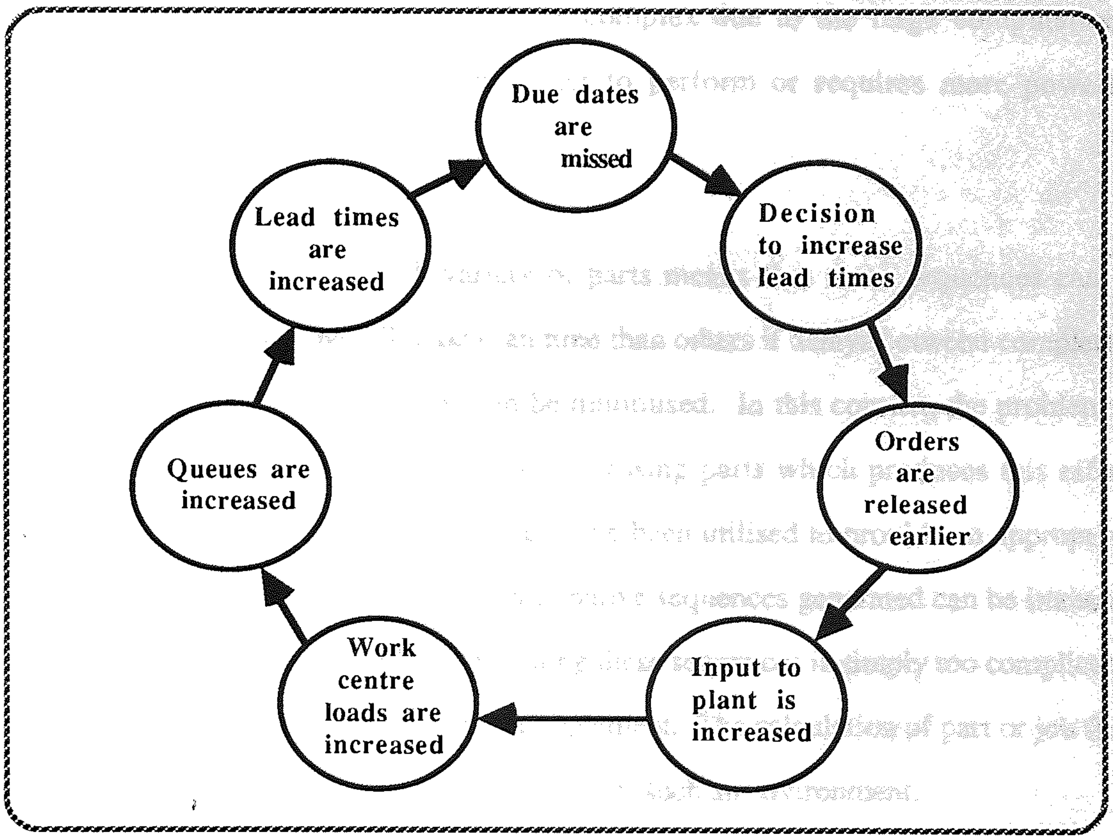


FIGURE 2B THE VICIOUS CIRCLE

Although, batch sizes could be increased to offset the long change over or set-up time, this often leads to an increase in work-in-progress. In connection with this matter, Schaffer, G. [1980a, 1980b] wrote:-

> " For an average batch type production shop, a part spends only 5% of its time on the machine tool. The remaining 95% of the time is spent waiting for moves from one machine to the other or waiting for machines to become free for processing. The large amount of waiting times increases the manufacturing lead times and gives rise to substantial work-in-progress inventories. It also becomes difficult to keep track of parts when there is excessive material handling ".

The processing of high product variety entails the need for a wide range of tools, fixtures, jigs, etc. This requires the maintenance of an accurate bill of tool inventories, manufacturing data, Bills-Of-Material (BOM), etc. High product variety and complexity has a major implication for the nature of resource planning because this entails the processing of large volumes of manufacturing data. Maintaining data accuracy and integrity under such conditions will be difficult. The Material Requirements Planning (MRP) calculation becomes increasingly complex due to the large computational requirements and thus takes much longer to perform or requires more powerful computing resources.

The processing of a high variety of parts means that some sequences can be generated with a lower overall makespan time than others if delays between completing one operation and starting the next can be minimised. In this context, the problem of sequencing is to determine the order of processing parts which produces this effect. Although operational research techniques have been utilised to provide an appropriate solution to the problem, the number of alternative sequences generated can be immense and the actual process involved in generating these sequences is simply too complicated for the shop scheduler to understand and implement. The calculation of part or job flow time and productivity are therefore difficult under such an environment.

In a review of related matter, Browne, J [1988] wrote :-

> " On the other hand the complex manufacturing systems associated with process based layouts in traditional batch production systems lead to extremely difficult scheduling problems and are arguably responsible for the extreme inefficiency of batch production systems where it has been shown that a batch typically spends 95% of its time on the shop floor in non-productive queuing and storage activities".

The combination of complex and long process routes increases the complexity of job flow through the shop. For example, parts spend much longer time on the shop floor than originally anticipated by the scheduler, thus resulting in a significant increase in the manufacturing lead time than was originally anticipated. In such an environment the shopfloor becomes immensely difficult to schedule manually and this impairs the prospect of achieving accurate and realistic due dates.

It was cited [Rolstadas, A. 1988] that the material flow through a traditional manufacturing system based on a functional layout is complex and results in long throughput time. The impact of manufacturing layout was also highlighted by Burbidge, J.L [1971] who wrote :-

> " The traditional method for organising factories was 'process organisation'. Organisational units specialised in particular processes .... because of different parts use different combinations of processes in different sequences, this creates extremely complex material flow systems through which the control of material flow is very difficult ".

This has complications for due date accuracy since, if it is difficult to trace the movement of orders and batches of goods at the shopfloor level, then the control system will not be able to provide a rapid response to changes in the manufacturing status because the accuracy of progress data available may be limited.

The manufacturing control problems are also compounded by the loss of valuable production time due to inefficient utilisation of manufacturing resources. Studies by Hollier, R.H [1980] and Dudley, N.A [1970] have shown that any undue emphasis on high machine utilisation leads to excessive work-in-progress and long throughput time. Similarly, studies by Gallagher, C.C et. al [1986] suggests that long and uncertain throughput times are the source of due date (delivery) problems which commonly exist in small batch manufacture. In a review of the limitations of current control systems, Spooner, P.D [1985] wrote :-

> "The batch manufacturing industry, generally suffers from problems of not meeting delivery dates, inefficient use of men and machines and too much stock. Taken together, these indicate a process which is out of control. If stock levels, both work-in-progress and finished goods are reduced significantly, a lot more emphasis is placed on the control process................. Constraints are often applied to the control available by the type of machinery in use. A lot of these plants have machines with large setting times, which has dictated the use of large batches, to minimise setting overheads. This can lead to large levels of work-in-progress and a very inflexible system."

2.3 Implications for Manufacturing Control

The problems inherent in existing manufacturing systems have a major implication for manufacturing control systems since they influence the operational planning and control functions. A schematic view of traditional manufacturing control system is shown in Figure 3. The complexity of the shop floor (i.e. complex work flow) coupled with large database system, based on multi-level BOM structure renders a major control problem because it is difficult to establish any link between the downstream activities (i.e. shop level scheduling) and the relevant entries at the high level plan (i.e. Master Production Schedule (MPS)). Therefore, this hinders the process of closing the loop between these levels (i.e. infinite/finite scheduling and the MPS) in the control system hierarchy. As a result, it is difficult to establish a truly closed loop feedback control system and to undertake dynamic control functions in response to top and bottom level inputs respectively. This has a major implication on decision making functions at the high level plan since it limits management's ability to replan (i.e. reschedule all its manufacturing operations in response to changes in the manufacturing environment).

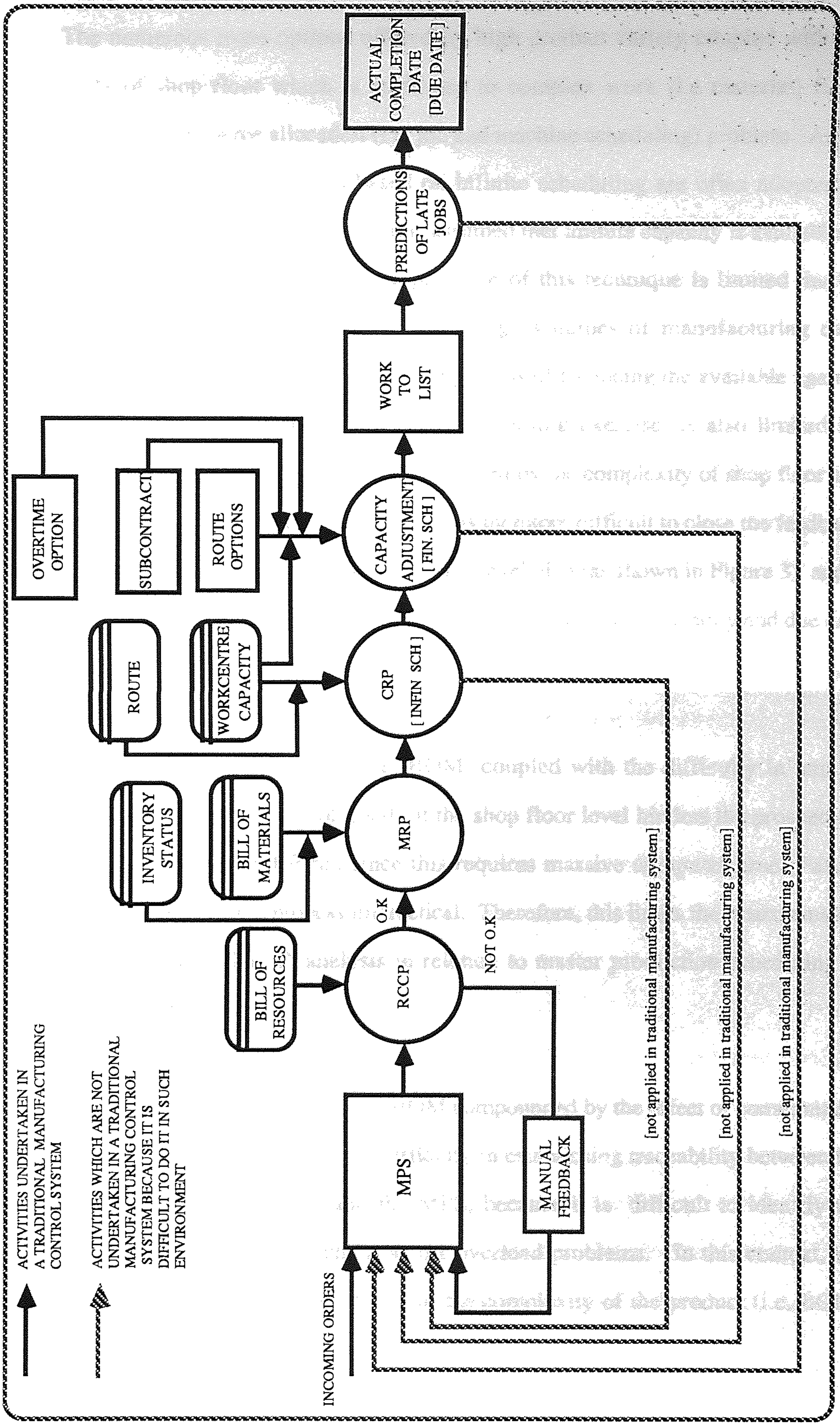


FIGURE 3 SCHEMATIC VIEW OF A TYPICAL TRADITIONAL MANUFACTURING [CONTROL] SYSTEM

The numerous route options offered by high product variety coupled with the complexity of shop floor which is attributed to complex work (i.e material) flow, presents a serious resource allocation (i.e. job and machine scheduling) problem. As an alternative, simplistic techniques based on infinite scheduling are often adopted to resolve such problems. In this context, it is assumed that infinite capacity is available at all the work centres. However, the application of this technique is limited due to massive computer time required to process large volumes of manufacturing data associated with the high product variety. The process of balancing the available against required capacity, as implied in the finite scheduling exercise, is also limited by problems (i.e. material and information flow) posed by the complexity of shop floor and time required to undertake such an exercise. It is therefore difficult to close the feedback loop between the downstream activities and high level plan (as shown in Figure 3) and it limits the management's ability to undertake dynamic evaluation of capacity and due date constraints.

The complexity of database (i.e. BOM) coupled with the difficulty in tracing movement of orders or batches of goods at the shop floor level hinders the prospect of undertaking a complete MRP run since this requires massive computer time [Fox, B 1983a] and this renders the process impractical. Therefore, this limits the management's ability to undertake 'what if" analysis in relation to master production scheduling or detailed capacity planning.

The complexity of the multi level BOM compounded by the effect of commonality and lot sizing policies, leads to severe difficulty in establishing traceability between the shop level scheduling activities and the MPS, because it is difficult to identify the relevant entries in the MPS which cause the overload problems. In this context, the problem of closing the loop is attributed to the complexity of the product (i.e. BOM) structure.

The computational requirements associated with the processing of large volumes of data used in the bill of resources are generally high due to procurement of high product variety. However, this is offset by some simplistic assumptions used in the Rough Cut Capacity Planning (RCCP) referred to in Figure 3. In this context, these assumptions include ignoring work-in-progress, lot sizing rules and shop control policies and lead time offsets. In brief, it adopts a global view which makes the system efficient and therefore feasible, but the benefits of rapid analysis and generation of the MPS are offset by a lesser degree of accuracy. Under such circumstances, the Rough Cut Capacity Planning (RCCP) technique is followed by the Capacity Requirements Planning (CRP) process and overtime is used to accommodate the MPS. The assumption that local replanning can overcome any capacity problems which emerge from CRP may not always prove feasible.

In addition, traditional manufacturing systems embark on the utilisation of skilled but non multi-disciplinary work force. This implies that the operators in such environments generally perform only one type of operation [Huang, P.Y. et. al 1985]. The scope of utilisation of the work force and the overall system efficiency are normally low. In this context, it was cited [Spooner, P.D 1985] that traditional manufacturing environment generally suffers from the problems of inefficient use of manufacturing resources (e.g. men and machine).

As discussed above, the problems inherent in traditional manufacturing systems, have major implications for manufacturing control, since it limits the system's ability to undertake automatic rescheduling of all manufacturing activities, in response to changes in the status of manufacturing resources, arising from 'top level' inputs (i.e., incoming enquiries) and changes arising 'bottom level' inputs (i.e., machine breakdown). This hinders the control system's ability to provide automation of MPS in a dynamic manufacturing environment.

2.4 Concluding Remarks

The above discussions have demonstrated that the problems inherent in traditional manufacturing systems, have serious implications for manufacturing control problems because these affect the operation of control systems and in particular it hinders the prospect of undertaking rapid evaluation of capacity and due date constraints in response to changes in the status of manufacturing environment.

In view of these limitations, there is a need for a practical and realistic manufacturing concept and control system architecture. However, any prospective solution should consider the advantages offered by the concept of cellular manufacturing because it has the potential to minimise the complexity of manufacturing systems and the corresponding control problems. Hence, this warrants a review of the cellular manufacturing concept and the relevant control techniques applied in such systems.

CHAPTER 3

Developments in Cellular Manufacturing Control

3.1 An Introduction to Cellular Manufacturing

The discussions in this chapter provide a formal introduction to cellular manufacturing systems, their characteristics and impact on manufacturing control. It reviews the different manufacturing control concepts applied in such a system, namely, centralised, hybrid and distributed systems. Subsequently, it highlights the key problems related to above control systems and their implications on the operation and control of the overall system.

3.1.1 Group Technology

Group Technology [G.T] is a complete manufacturing system where families of similar components are processed in groups of non-identical machines and the technical and economical advantages of mass production extended to jobbing and mass production. Thornley, R.H.[1972] defined Group Technology as :-

> " Group Technology or Part Family Manufacturing is a method of achieving some degree of mass production technology in the batch production industry ".

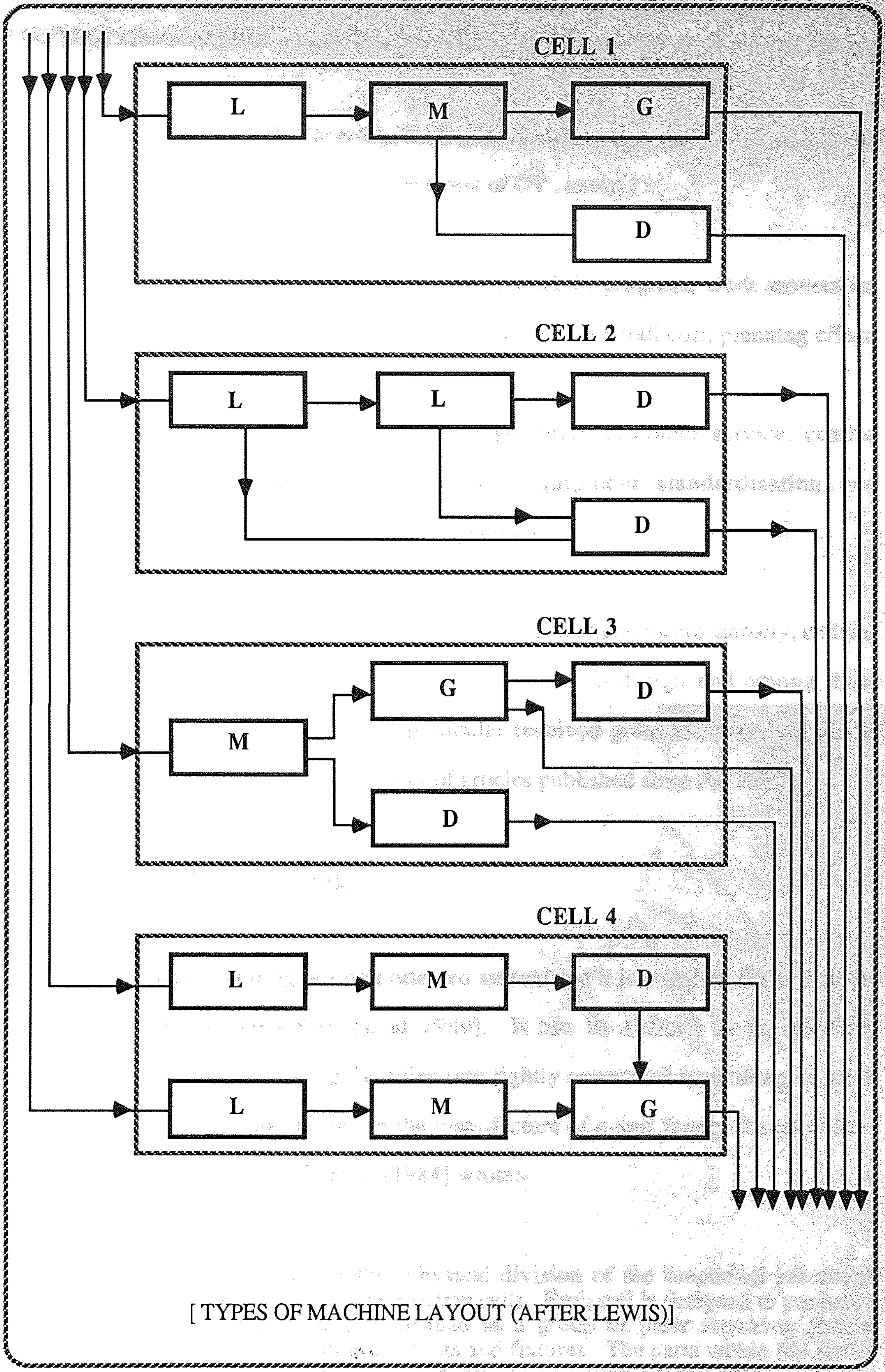
Burbidge, J.L [1975] defined Group Technology as :-

> " A new approach to batch production based on group layout and the simplification of material flow. It seeks to achieve batch production, the same advantages as those obtained with line layout in the batch production industry ".

Group Technology had its origins in the U.S.S.R. and it was mooted in the 1940's by a leading Russian engineer, namely, Mitrofanov, S.P.[1966] who made significant inroads into the aspects of job simplification and reduction of set-up times. Opitz, H.A [1970,1971] of Aachen Technical University advanced the concept of GT in Germany in the early 1960's and produced the Opitz part coding system based on such concept. Professor Burbidge, J.L. [1969] of United Kingdom promoted the concept of G.T. in the 1960's at the International Centre for Advanced Technical and Vocational Training, Turin, Italy. In Great Britain a government supported Group Technology Centre was established in the 1960's and the concept was also advanced by the British Institution of Production Engineers. Since then the advancement and application of the GT spread to other parts of the world, namely, United States of America, Europe, Japan etc.

The concept of GT was also initiated at the University of Manchester's Institute of Science and Technology (U.M.I.S.T) by Connolly, R. et. al [1970, 1971] and subsequent work was undertaken at the Mechanical and Production Engineering Department of Aston University by Professor Thornley, R.H [1972]. Furthermore, a commercial part coding or classification package, called CAMAC [Computer Aided MAnufacturing Classification System] which was based on GT concept, was developed at Aston University by Love, D.M [1986a] .

A typical GT manufacturing layout is shown in Figure 4. The GT concept provides a significant improvement in many aspects of manufacturing, namely, planning, control and productivity of manufacturing systems. Its major contributions are simplified work flow, reduced work-in-progress [Lewis, F.A. 1973], minimum set-up time, better loading and scheduling of parts. Baldwin, K.I et. al [1975] and Athersmith, D et. al [1972] claimed that the concept of group manufacture produced significant reduction of greater than 24% on work-in-process and 39% on transportation distance. The authors also claimed that the 24% reduction in work-in-process implies a 24% reduction in throughput time. Gallagher, C.C. et.al [1986] advocated that GT provides manufacturing rationalisation, simplifies the needs for Material Requirements Planning



[TYPES OF MACHINE LAYOUT (AFTER LEWIS)]

FIGURE 4 GROUP TECHNOLOGY LAYOUT - SIMPLE WORK FLOW AND LOW VOLUME OF WORK-IN-PROGRESS

(MRP) and scheduling (i.e. less parts or routes).

As shown in Figure 5, Thornley, R.H. [1972] cited that a number of significant benefits can be derived from the implementation of GT , namely :-

- reduction in setting time, down time, work-in-progress, work movement, overall production times, finished parts stocks, overall cost, planning effect, paper work, etc., and
- an increase in productivity, order potential, customer service, costing accuracy, reliability of estimates, equipment standardisation and rationalisation, effect of machine operation.

The GT concept embraces three major aspects of manufacturing, namely, cellular manufacturing, part classification and coding and set-up design and among these subsets, cellular manufacturing has in particular received great attention and this is particularly more evident from the number of articles published since the 1960's.

3.1.2 Cellular Manufacturing

Cellular manufacturing is a part oriented system and it is based on GT principles for its part families [Teng,S.H. et. al 1989]. It can be defined as the physical segregation of the manufacturing facilities into tightly controlled machining or work cells, where each cell is specialised in the manufacture of a part family which utilises similar machinery. Greene, T.J. et. al [1984] wrote:-

> " Cellular manufacturing is the physical division of the functional job shop's manufacturing machinery into production cells. Each cell is designed to produce a part family. A part family is defined as a group of parts requiring similar machinery, machine operations and jigs and fixtures. The parts within the family are transformed from raw material to finished part within a single cell".

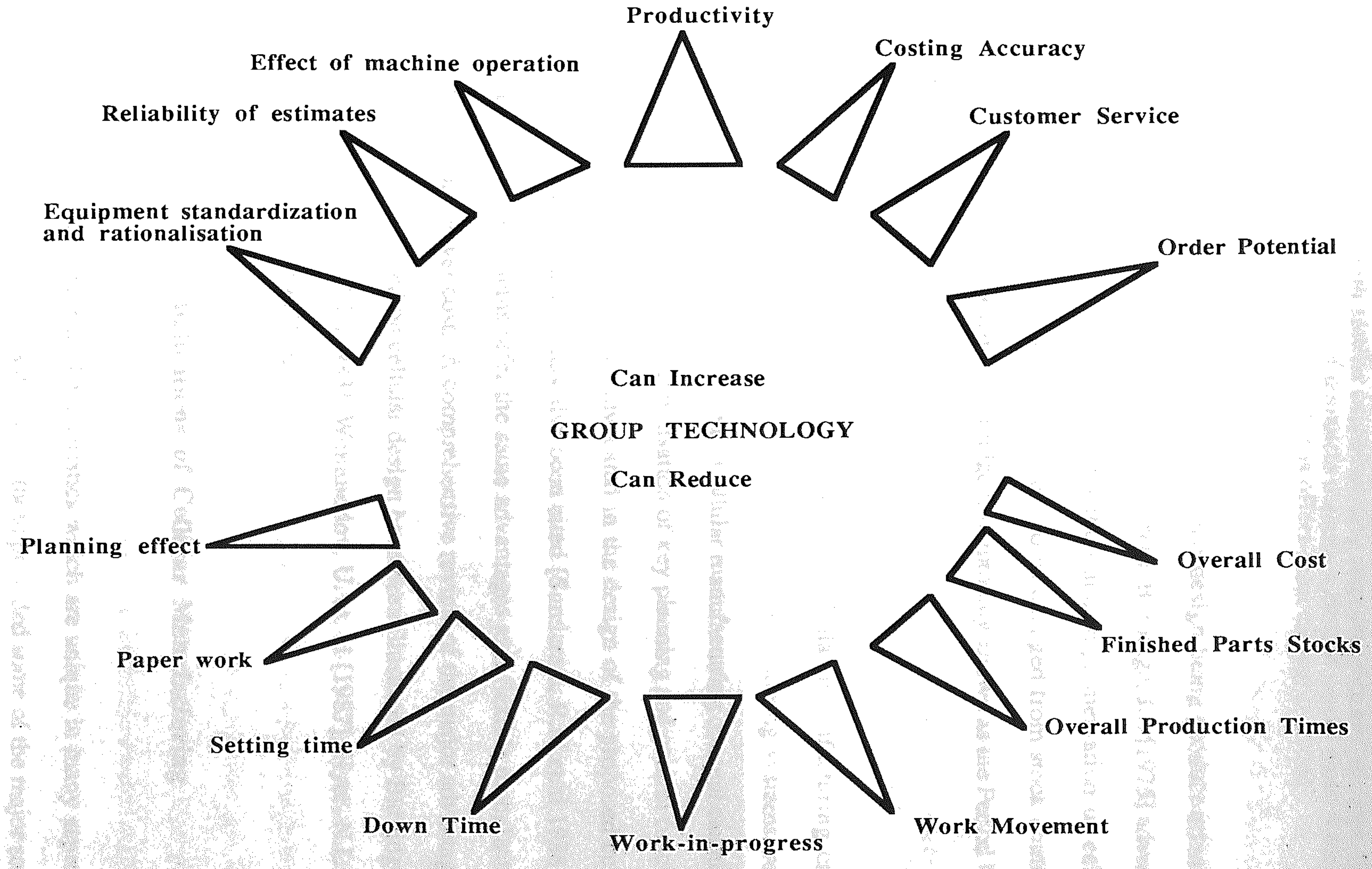


FIGURE 5 GENERAL ACHIEVEMENTS OF GROUP TECHNOLOGY [AFTER THORNLEY]

Rolstadas, A. [1988] wrote :-

> "Cellular manufacturing is based on two fundamentals, namely, the grouping of parts into families with similar manufacturing requirements and the grouping of machines into cells capable of complete manufacturing of one or more families of parts. Each cell is a 'flow line' and thus offers short throughput time".

Schonberger, R.J [1984] stressed that cellular design being product orientated, makes Just-In-Time (JIT) production possible whereas Burbidge, J.L [1975] advocated that the prerequisite for the successful application and implementation of cellular manufacture is that the production control needs to be changed from stock control to flow control. The concept mooted by Burbidge is commonly known as the Period Batch Control (PBC).

The underlying reasons for the popularity of cellular manufacturing can be attributed to its ability to simplify the complexity of manufacturing systems, reduce product variety, reduce product mixture etc. Cellular manufacturing concept can also be used to strengthen the notion of decentralisation of key planning and control functions. This feature has been very strongly advocated in the design of the proposed cellular manufacturing control model. It has also been cited [Sundaram, R.M.et.al 1988] that cellular manufacturing systems offer the same advantages as a flexible manufacturing system but at a much lower cost. A comprehensive review of the major advantages of manufacturing systems based on cellular design have been illustrated by Burbidge, J.L [1975, 1971, 1988], Black, J.T [1983], Wemmerlov, U. et. al [1987], Hyer, N.L et. al [1982], Greene, T.J. et al [1984] etc.

3.2 Characteristics and Implications of Cellular Manufacturing

Cellular manufacturing has characteristics which are unique in many aspects as compared to other manufacturing systems and these provided some of the major sources of attractions of such a concept in many manufacturing industries. The following discussions highlight the fundamental characteristics of cellular manufacturing concept.

Cellular concept has the potential to simplify the complexity of manufacturing systems and the corresponding control problems. For example, it can be taken to strengthen the concept of decentralisation of planning and control functions. This entails that each cell is only required to maintain Bills-Of-Material (BOM), inventory records, routing and other associated data relevant to the product range manufactured within the cell. This simplifies the database system, improves the integrity of data and provides a more accurate and realistic data to drive the entire cell. Decentralisation of planning and control functions facilitates the organisation of the manufacturing system into tightly controlled cellular units. This enables all the manufacturing activities to be performed within the cell and require no external interaction.

The process of decentralisation of planning and control activities enables each cell to exercise greater degree of freedom in managing local activities and thus, facilitates the implementation of the concept of cell ownership. The cell manager may then be regarded as the 'owner' of a manufacturing business unit (the cell) and may be measured against broader performance objectives than would be common in conventional manufacturing systems. Hence, this provides the cell management with greater degree of autonomy over its manufacturing activities.

The application of cellular concept in conventional manufacturing systems can lead to the development of an autonomous cell in which each cell is provided with its own Manufacturing Resources Planning (MRP II) software. This simplifies the BOM, database and improves the management of the cell. In addition, it provides greater management flexibility since changes in production can be implemented with less changeover and set-up time [Huang, P.Y. et. al 1985].

The degree of ownership and autonomy resulting from decentralisation of planning and control functions provides each cell with greater degree of accountability over the management of manufacturing activities. Thus, instead of being responsible for one process as in the job shop manufacturing system, the supervisor of the cell is responsible for all the operations needed for a part family.

Cellular concept also enhances the simplification of manufacturing systems into cells and facilitates the complete manufacture of a family of parts, assemblies or finished products within the cell. This permits the use of simpler routings and databases which enable the implementation of a more structured material flow within the system than is implied in a job shop manufacturing environment. This is attributed to the simple layout of manufacturing facilities reflected by the process routes of part families.

The operation of the cell can be undertaken with the aid of a specific set of data related to the product or part range. This can be exploited to strengthen the notion of simplified material flow which contributes to a major reduction in manufacturing lead time. The simpler material and information flow accrued from the implementation of cellular manufacturing system has the potential to provide the benefits of reduced work-in-progress and throughput times [Burner, L. et. al 1980]. This enables cell management to derive the benefits of Just-In-Time (JIT) production. Therefore parts are delivered to the work cells when needed and not otherwise. Furthermore, cellular concept also offers greater opportunities in improving manufacturing performances even in circumstances unsuited to Kanban or other material flow control systems. This is more evident from reduced set-up time and work-in-progress and minimum shop floor utilisation around the processing centres [Zisk, B.I. 1983] that can be derived from the application of such concept. This has the potential to minimise the complexity of local control problems, which is significantly lesser than is implied in a conventional manufacturing system. As a result, there is a better prospect of achieving minimum throughput or flow time under such environment.

The relatively small number of product range manufactured in each cell can be exploited to strengthen the benefits of less changeovers and set-up times and hence changes in production can be accommodated without much difficulty [Huang, P.Y.et.al 1985]. This implies that retooling of machines is only essential when changing from one lot (families) of components to another. This provides a significant reduction in set-up times and dramatically alters the economics of lot or batch production to permit economic production of very small lots [Bing Liu 1988].

Similarly, the smaller product range or part families manufactured in cells, requires each cell to maintain bills of data that are relevant to the specific part family. The BOM is therefore much simpler in structure and size and this naturally improves data integrity, storage of accurate and realistic data and enhances the overall management of database system. The concept of predefined product range although in this context the product may actually be a component or an assembly, permits the design of manufacturing facilities to reflect the process routes of parts family manufactured in a cell. The application of such a concept in a conventional manufacturing environment, provides the potential to simplify some of the core manufacturing control problems discussed in the previous chapter.

The concept of flexibility has gained great popularity with the development and implementation of Flexible Manufacturing Systems (FMS) and other programmable automated manufacturing systems [Wemmerlov,U.et.al 1987]. Although flexibility can be classified under different categories (e.g. volume, product mix, routing), it is the routing flexibility that is of particular importance to cellular manufacturing since it provides the potential to use simpler alternate routes and hence structured material flow within each cell.

Cellular manufacturing systems incorporate characteristics of conventional manufacturing systems, namely flexible machine types from job shop, product flow layout from flow shop, small lot sizes from the job shop and small in-process inventories from the continuous flow shop. It is therefore common to find that a typical cellular manufacturing system employs flexible, general purpose machines where the set-up times are usually shorter due to the similarity of parts produced in the same cell [Sridharan,V.et.al 1987/1990].

A major strength of the cellular concept is its potential to provide each cell with greater degrees of freedom and flexibility in decision making with regard to the implementation and execution of various manufacturing policies. This enables each cell to adopt policies that suits its local needs. Similarly, the multi-disciplinary work force used in a cellular manufacturing environment provides each cell with a flexible labour force and a greater degree of flexibility and freedom in the assignment of operators to various manufacturing resources. Operators can therefore be alternated among key machines to keep the manufacturing system functional and this is anticipated to provide an indirect saving in labour costs [Huang, P.Y. et. al 1985].

The smooth material and information flow within the cellular manufacturing system generally improves the utilisation of high investment machinery to 80 - 90 % as compared to 10 - 15% rate common in most traditional manufacturing systems [Zisk, B.I.1983]. This is influenced by the application of flexible, general purpose machines, reduced set-up times and improved material flow and this provides a better opportunity of achieving higher productivity.

3.3 Background to Cellular Manufacturing Control

The methods of control applied in cellular manufacturing systems can be classified under centralised, distributed (discussed in Chapter 4) and hybrid control systems. Despite the numerous advantages offered by these systems, practically all of them have limitations in their ability to provide automatic evaluation and regulation of key operational and control parameters, namely, the due date and Master Production Schedule (MPS). This shortcoming is attributed to a number of factors which are elaborated in great detail in the following discussions.

3.4 The Centralised Approach to Cellular Manufacturing Control

Manufacturing control systems are concerned with all the resources needed to fulfil a given production schedule. The major concerns are therefore control of materials, people, plant, etc. Most of the well known 'systems', namely, Optimised Production Techniques (OPT), Material Requirements Planning (MRP), Manufacturing Resources Planning (MRP II) and Kanban are generally concerned with control of material flow from suppliers and within the factory. The following discussions highlight control systems which are based on a centralised approach to planning and control. It also discusses the drawbacks of such systems and the practical implications for operational planning and control.

3.4.1 The Optimised Production Techniques [OPT] Philosophy

The Optimised Production Techniques's concept was developed by the Goldratt, E. [1981] brothers of Creative Output Incorporated. It is a sophisticated shop floor control system based on finite loading procedures. It resolves manufacturing resource problems by stressing special emphasis on a subset of work centres (bottleneck) and it performs such tasks by using a sophisticated bottleneck 'optimising' algorithm for planning and scheduling production. A comprehensive review of OPT concept is provided by Goldratt, E [1981] and Jacobs, F.R [1983].

The OPT concept is believed to have the capability to offer 'optimised' throughput whilst minimising inventory and operating expense [King, J.R. 1979]. Despite these advantages, it is claimed [Love, D.M. 1988c] to have some shortcomings, namely, it resolves capacity constraints by concentrating on a predefined bottleneck but could not cope with transient overloads. In this context, transient overloads normally occur when a work station, which on average has ample capacity, is unable to make the programme demanded in the required time frame.

Capacity constraints which may occur at a bottleneck operation, at the 'downstream' level may cause serious loss in throughput. Since OPT finite schedules only the bottleneck operation, it cannot spot such problems. Furthermore, OPT uses infinite scheduling procedure on non bottleneck and this provides only an 'average' view of work centre load status.

Vollman,T.E. [1986] cited that OPT is truly difficult to understand and analyse the schedules produced by the secret algorithm and often requires substantial faith. It is a concept which adopts a centralised approach to planning and control and therefore difficult to institute the concept of ownership and control of key system parameters. Although OPT is capable of generating a practical due date or MPS based on the current manufacturing status, it does not provide automation of MPS.

3.4.2 The Manufacturing Resources Planning (MRP II) System

Material Requirements Planning (MRP) and its derivative MRP II are typical computerised inventory planning and control systems. MRP recognises the need for a materials management system that takes into account the specific timing of demands for materials at all levels of manufacture. As shown in Figure 6, MRP begins with a master schedule of demand for each finished goods. It uses a manufacturing oriented explosion to break the demand for the product into its primary sub-assemblies.

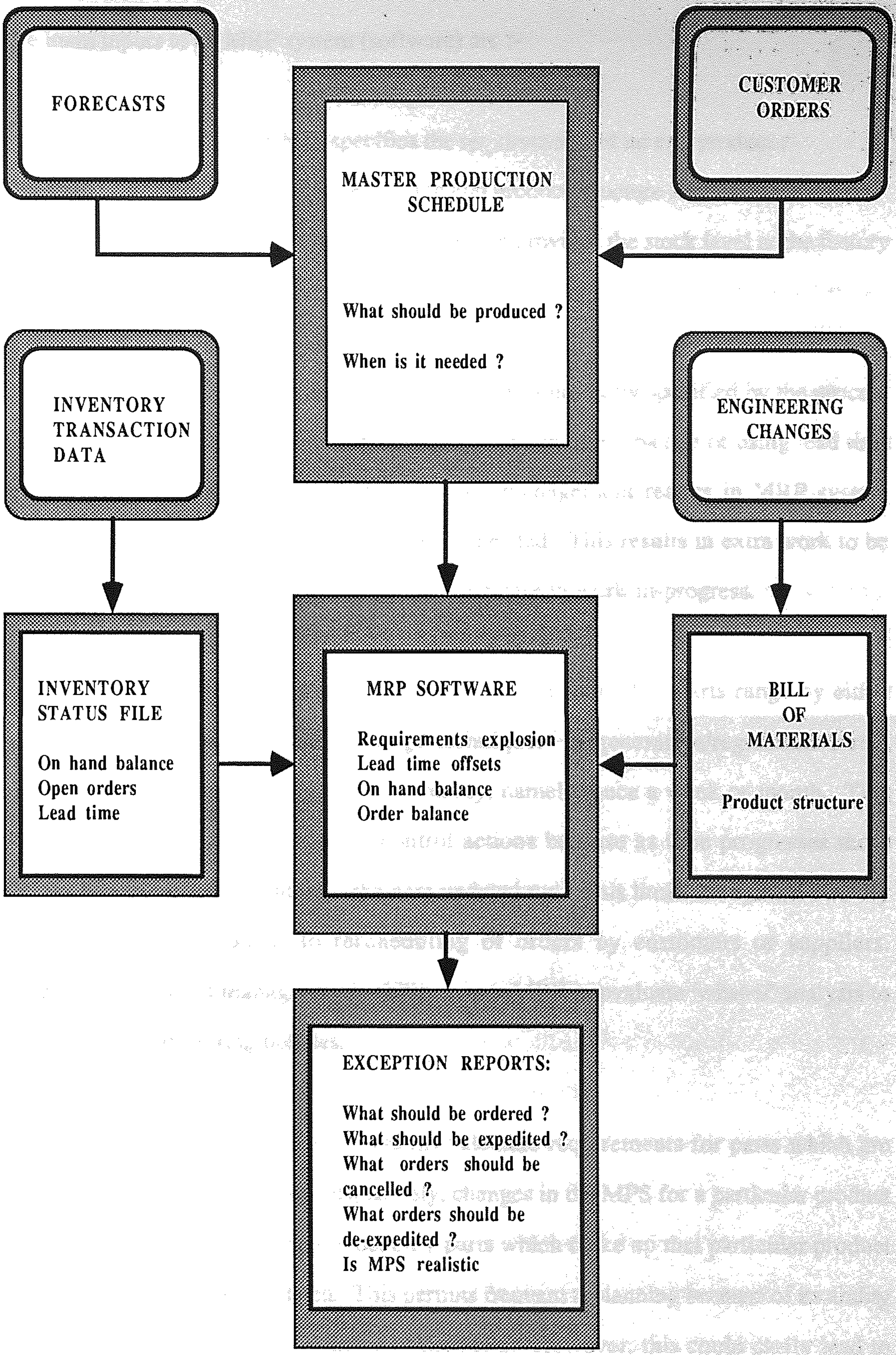


FIGURE 6 AN OVERVIEW OF MRP MECHNISM

The main inputs to an MRP system (software) are :-

- the MPS which specifies the requirements of an end product ;
- the BOM which defines the end product structure and
- the inventory status system which provides the stock level at the factory and outstanding orders.

Standard MRP system uses the lead time offset normally specified by the process plan to calculate the launch date for an order. The common practice of using lead time offsets based on estimation provided by shop management results in MRP system generating earlier launch dates than are really needed. This results in extra work to be released to the shopfloor, thus resulting in an increase in work-in-progress.

MRP system calculates the requirements for the complete parts range by either generative (regenerative) or net change technique. In generative/regenerative run, required parts are calculated only occasionally, namely, once a week or month. This often results in the deterioration of control actions because as time progresses these actions become less relevant until the next updated run. This limits the system's ability to provide rapid response to rescheduling of orders by customers or suppliers. Infrequent runs limit management's ability to use MRP to evaluate 'what-if' analysis to alternative manufacturing policies.

Conversely, the net-change systems calculate requirements for parts which are directly affected by external events, namely, changes in the MPS for a particular product requirement's date. In this technique, only parts which make up that particular product will have their status recalculated. This permits frequent replanning because of its ability to provide rapid response to changes in the MPS. However, this could easily lead to excessive number of order actions, which could result in the cancellation of previously established action. Such a phenomenon is known as ' nervousness ' and it is dampened by batching the inputs into the system.

MRP is a typical deterministic materials control system because it assumes no changes in the manufacturing environment. For example, the lead time used in such a system takes no account of the dynamics of shopfloor activities. It makes no attempt to evaluate the practical implications of work load status on throughput time of the orders concerned. The effectiveness of MRP depends on accuracy of input data and if deficiencies exist in the inputs or the calculation assumptions, then this will also impair the quality of MRP results. Similarly, the planned order release, launch date and due dates will also suffer.

Standard MRP is a typical centralised based planning and control system, in both a logical and computing sense. This delegates the responsibility for MRP policies with a central function and therefore the management has little influence over key policies which affect the performance of the system. MRP has a number of limitations, namely :-

- it is effectively an open loop material control system and it makes no attempt to reassess the high level plan (i.e. MPS) in response to changes in manufacturing status ;
- MPS calculation is generally based on regenerative mode and the resulting work load and purchase orders are established without any due consideration of the available resources ;
- MPS is established without any means of assessing the practicality of the production plan and
- MRP is only concerned with generating the material requirements plan but lacks the ability to plan other important resources, such as labour ; neither does pure MRP provide the tools needed to execute and control the plan, even for materials.

Manufacturing Resources Planning (MRP II) is an enhanced version of MRP and it includes 'downstream' activities such as capacity planning, work-in-progress ,purchasing, etc. By adding the capability mentioned above, has become known as 'closing' the loop. An overview of MRP II mechanism is shown in Figure 7.

The Rough Cut Capacity Planning (RCCP) incorporated within the MPS module, is designed to provide a quick and rough check on the viability of the MPS prior to a full MRP and CRP run. However it does not attempt to produce precise load analysis, since it only considers product families (not individual items), key production areas (not individual machines) and long time frames. In addition, it is based on simplistic assumptions since it ignores work-in-progress by assuming the plant is empty; it does not take into account lead times of sub-components, that is, anything below MPS demands; it assumes that all assemblies can be completed in the period they are demanded; it ignores any MRP or shop control policies and batch or lot sizing. In the light of these assumptions, it is difficult to generate an accurate and realistic MPS.

A key element in the MRP II process is the Capacity Requirements Planning (CRP) module which calculates time phased work loads for all the work centres in the factory. It is generally based on infinite capacity planning to highlight the amount of capacity which will be required to meet the plan and this action is used by local planner to determine what actions need to be taken. However in the event of capacity shortages, MRP II mechanism provides a number options to revise the MPS and rerun MRP.

Normally the time taken to complete MPS-MRP-CRP cycle can be significant and this depends on the complexity of the product and the commonality of components in the BOM across the range of products. Time constraints render such process impractical and therefore in practice MRP II is operated very much like a standard MRP system.

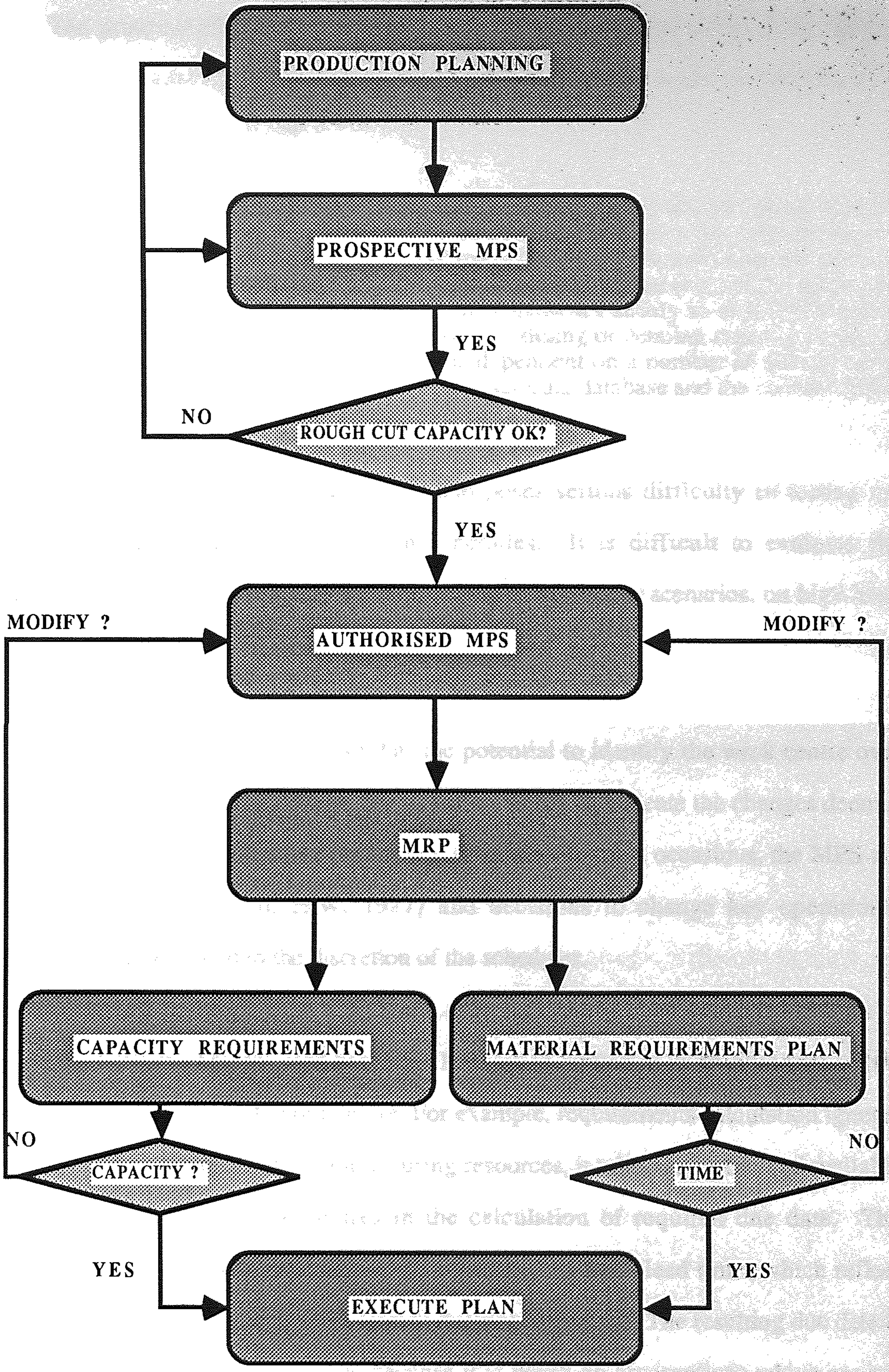


FIGURE 7 AN OVERVIEW OF MRP II MECHANISM

The prospect of undertaking 'what if' analysis to master production scheduling and detailed capacity analysis is equally difficult under such an environment. Love.D.M.et. al [1988c] wrote:-

> "The number and complexity of the transactions involved in calculating material requirements may limit the frequency of calculation to once per week or month. Each regenerative calculation may take many hours of dedicated computer time and have to be performed when all other activities have ceased (e.g., at the weekend). This constraint may seriously impair management's ability to support "what if" analysis in relation to master production scheduling or detailed capacity planning. The length of the MRP recalculation is dependent on a number of factors but is particularly related to the size of the manufacturing database and the number of live inventory items held in the system".

The lack of ' what if ' capability also poses serious difficulty in testing the reliability and viability of production schedules. It is difficult to evaluate the implications of various manufacturing policies and shop floor scenarios, on high level plan (i.e. MPS).

In reality, MRP II mechanism has the potential to identify the work centre over and underloads in each time period but lacks the ability to indicate the changes deemed necessary to generate a feasible production schedule. In most occasions, the MPS are adjusted manually [Oden, H.W. 1987] and decisions to change key operational parameters are delegated to the discretion of the scheduler.

The CRP mechanism used in the MRP II is also limited in its ability to reflect the true capacity status at each work centre. For example, requirements calculation ignores the capacity constraints of the manufacturing resources, it takes no account of available capacity at dependent work centres in the calculation of required due date. The manufacturing lead times are calculated on the basis of fixed lead times which reflect only the total processing time and a (fixed) queuing allowance. The resulting due date is therefore inaccurate and unrealistic because it is based on assumptions which are too simplistic and impractical. This contributes to the deterioration in the quality of the resulting MPS.

The complexity of the multi-level BOM coupled with the effects of commonality in the end product structure and lot sizing policy, renders MRP II process, a difficult task to achieve. Therefore this limits the prospect of closing the feedback loop since it is difficult to identify which entries in the MPS are responsible for a work centre overload which is evident from the CRP analysis of suggested work orders.

MRP II adopts a centralised and top-down approach to planning and control and hence it is difficult to institute the concept of autonomy and ownership. This removes much of the key decision making functions from the shop floor and hence, it is difficult to implement local manufacturing policies and to exercise complete control over the manufacturing activities under such an environment. The application of a single processor or computer to undertake all the manufacturing activities, limits the system's ability to process all data simultaneously and as the data size increases, the control mechanism becomes increasingly inefficient and ineffective to operate. The failure of the central processor (computer), could halt the entire operation of the system and paralyse all the manufacturing activities.

The centralised approach to planning and control operates on a centralised database system [Weber,D.M et.al 1989]. This does not always guarantee an adequate solution for a large, flexible and highly integrated manufacturing system because, when the system is heavily loaded, the users have to queue in front of the database ; in the case of a crash in the database the entire manufacturing activities are blocked. This leads to a negative trade off between efficiency and volume of data that can be stored (e.g. the performance of the system worsens as the volume of data increases). A schematic view of the centralised database concept is illustrated in Figure 8A.

The centralised database concept used in MRP II system implies that all the data required to support the conversion of raw materials to finished product need to be

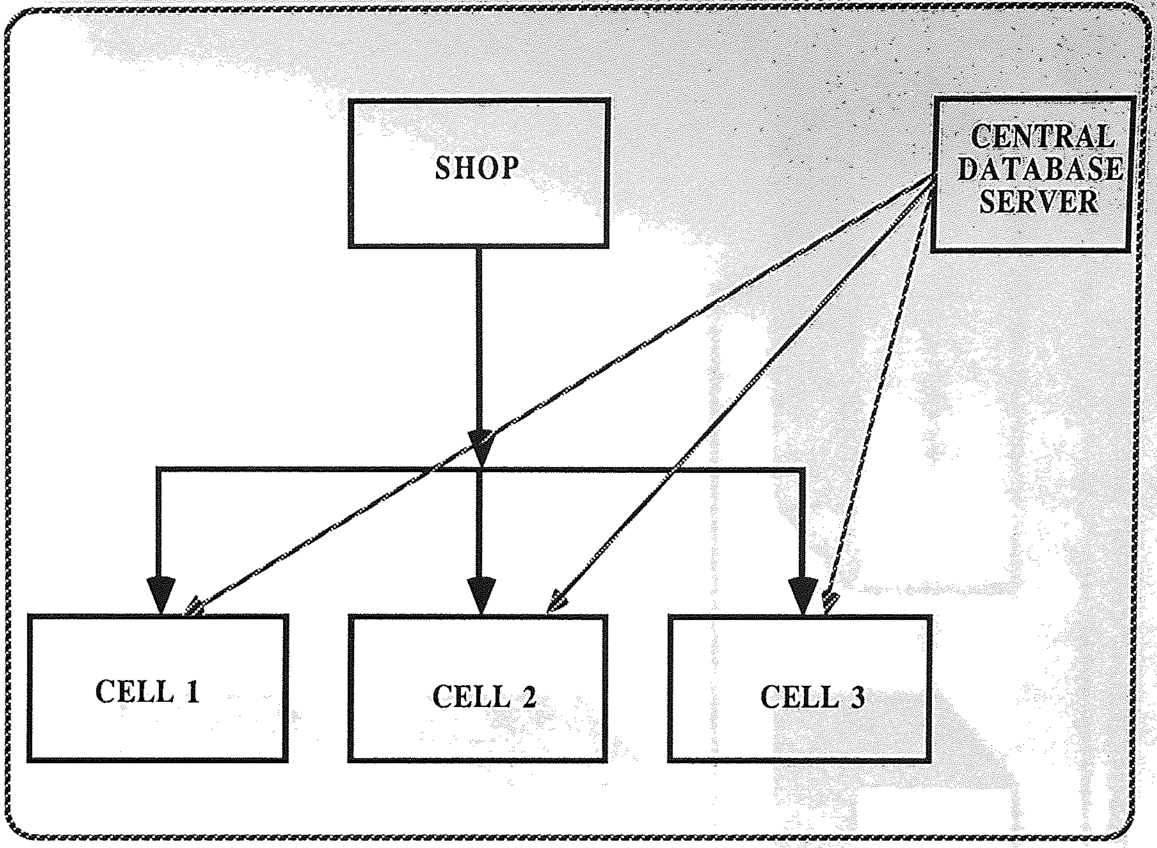


FIGURE 8A CENTRALISED DATABASE CONCEPT [AFTER WEBER, D.M. (1989)]

maintained in a single and massive database system. Maintaining adequate levels of accuracy in the BOM, routing and inventory data poses a major database management problem. For example, modification of data can be tedious and labourious and use of such a system requires high level of competence from system managers. The prospective end users require extensive training to gain an adequate operational knowledge of the system. The problem becomes more critical as the number of products to be processed increases since this leads to a further increase in the amount of data to be processed and maintaining data accuracy and integrity can be problematic. The prospect of achieving an accurate and realistic due date under such an environment is also extremely remote. An overview of the centralised approach to planning and control is shown in Figure 8B. All the work cells in such an environment are driven from a centralised MPS and MRP modules respectively. It utilises a central (global) database which holds all the operational data required to support manufacturing activities within the system.

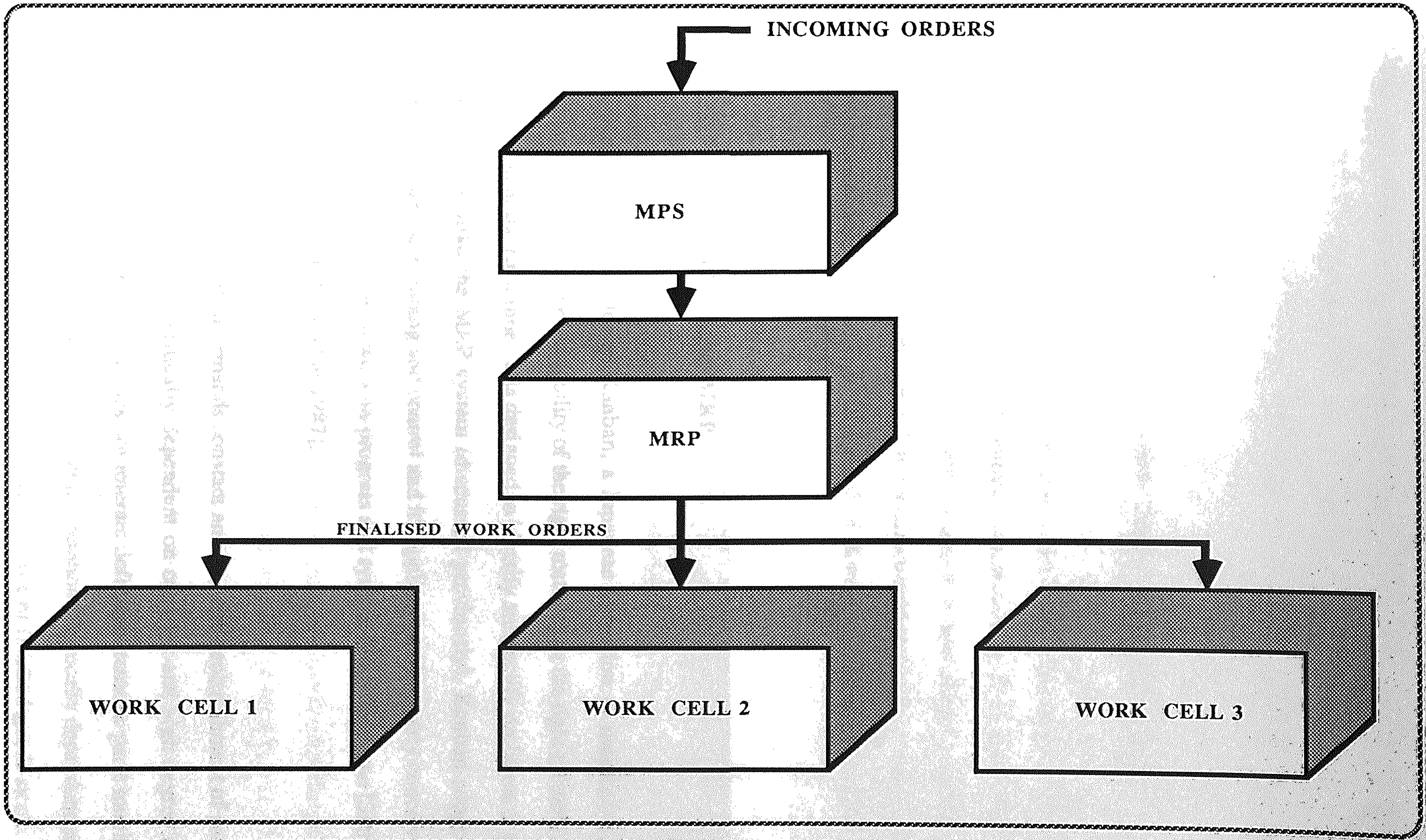


FIGURE 8B AN OVERVIEW OF THE CENTRALISED APPROACH TO PLANNING AND CONTROL

The inherent limitations of MRP II system, poses serious difficulty in achieving automation of MPS. A comprehensive review of Master Production Scheduling (MPS) principles and practices are illustrated by [Berry, W. L et. al 1983] and their limitations are discussed in Chapter 5.

3.5 Hybrid System's Approach to Cellular Manufacturing Control

The hybrid approach to cellular manufacturing control referred to in the following discussions is based on a combination of centralised and distributed control systems (concepts). The application of such a concept is aimed at providing an integrated manufacturing control system. The approach to manufacturing control referred to in the subsequent discussions are based on a hybrid of Kanban/MRP and GT/MRP II systems.

3.5.1 A Hybrid of Kanban and MRP

The underlying principles of Kanban, a Japanese invention to material flow control problems, stresses on the availability of the right material, in the right quantity, at the right place and at the right time. It is designed to identify and rectify problems at the shop floor level. Unlike the MRP system (discussed previously), Kanban adopts a decentralised approach to planning and control and it's application if properly conceived can lead to significant reduction in work-in-progress and system throughput time [Sinha, R.K.et. al 1984] and [Parnaby, J. et.al 1987].

The application of Kanban demands constant and frequent replenishment of parts and its successful operation is critically dependent on constant and high degree of repetition in demand. Furthermore it does not tolerate defective items or parts moving forward between production processes and its implementation is critically dependent on a smooth MPS which may lead to comparatively large holding of finished goods stock. It is predicated on the assumption that set-up and order costs are negligible and it stresses great emphasis on priority control [Rice, J.W. et. al 1982]. In reality, the fulfilment of these requirements could pose serious difficulty, especially, in a dynamic manufacturing environment.

Kanban is designed specifically to deal with internal material flow control and makes no attempt to reschedule parts or components in response to shop floor problems. Since these activities are carried out by outside suppliers, it is difficult to anticipate part or component shortages and the application of Kanban under such an environment can therefore be problematic. The prospect of automating MPS under a hybrid of Kanban and MRP (limitations discussed earlier) systems is difficult due to practical limitations inherent in them.

3.5.2 A Hybrid of GT and MRP II

A hybrid of Group Technology (GT) and Manufacturing Resources Planning (MRP II) systems was mooted by Hill, J.F. et. al [1986] and was applied in the coordination of production activities and simplification of production control functions. The integration and potential benefits of a hybrid of GT and MRP II systems, namely reduction in queuing, setup times and decrease in transfer time have been reported by Hyer, N.L. et. al [1982].

Despite these claims, the application of such a concept in a real manufacturing environment are constrained by differences in philosophies used in each system. For example, MRP II is critically capacity insensitive because it does not consider the shop floor manufacturing planning and control policies in the generation of planned order releases. On the contrary, GT is critically concerned with broader aspects of shop floor activities and it uses horizontal relationships as opposed to vertical relationship of parts applied in MRP II [Hsu, J.P 1978].

In a hybrid of GT and MRP II system, the potential advantages offered by GT, such as shop floor autonomy, concept of ownership, involvement in manufacturing planning and control decision making are severely eroded by the concept of centralisation applied in the MRP II planning and control methodology. For example, potential benefits, namely, the prospect of instituting local decision making functions ; management of production processes through simplification of routing ; reduction in the number of data elements present in GT systems, the application of simple MPS-MRP-CRP modules are severely impaired by limitations inherent in a centralised MRP II system. Practical limitations inherent in MRP II system pose a major obstacle towards the automation of MPS in a hybrid system based on GT and MRP II.

3.6 The Flexible Manufacturing System's Control Approach

Flexible Manufacturing Systems (FMS) represent a technically more advanced version of cellular manufacturing systems. It is a typical example of GT concept blended in an automated form of manufacturing under the control of a supervisory computer or stand alone computer control system [Hartley, J 1986]. It incorporates automatic material handling system under the supervision of the main computer.

FMS adopts a distributed approach to planning and control, in which each system is complete with its own local database and control mechanism. This enables the system to exercise complete autonomy and ownership over all manufacturing activities within its operating environment. The control algorithm applied in the system is generally complicated but it offers considerable degree of flexibility in decision making. The control mechanism used in a typical FMS has the capability to respond to dynamic changes arising from 'bottom level' inputs (i.e. machine breakdown). But, it provides no response to 'top level' inputs arising from new incoming orders or enquiries. Normally, the status of manufacturing resources in a FMS is not fedback to high level plan (i.e. MPS) and hence it is not possible to automate MPS under such an environment and furthermore, standard FMS do not incorporate a built-in MPS.

3.7 Concluding Remarks

The above review has demonstrated that existing manufacturing control systems are limited in their ability to provide automatic replanning. In this context, replanning is referred to the control system's ability to respond to changes arising from the top (i.e. incoming orders or enquiries) and bottom (i.e. machine breakdown) level inputs respectively. This hinders the prospect of undertaking dynamic evaluation of capacity and due date constraints under such an environment. This also limits the system's ability to provide automation of MPS.

In view of these shortcomings, there is a need to explore an alternative manufacturing control system architecture, that has the potential to resolve the key manufacturing control problems discussed above. It is anticipated that decentralisation of key control functions provides a better prospect of minimising existing control problems and hence, this warrants a review of decentralised control concept.

CHAPTER 4

The Distributed Manufacturing Resources Planning Approach

In view of the fact that the concept of decentralisation appears to be a prominent and key element to any potential control solution to existing manufacturing control problems, it is therefore necessary to review research work related to such a concept and in particular its practical implications for cellular manufacturing control.

4.1 The Distributed Planning and Control Approach

4.1.1 The Distributed Data Processing Concept

The concept of distributed data processing was first mooted in the field of computer science, where it was widely used in data distribution and processing. It is based on the distribution and processing of data across a number of computers. It can be perceived as a number of processing centres sharing a common Central Processing Unit (CPU) [Hawkes, B 1988] linked together via local area network. This enables communication between different processing units and facilitates data sharing and distribution. The main advantage of the distributed data processing concept is its ability to provide various functions within an organisation with its own computer processing and data sharing facilities, thus reducing the dependence on a centralised data processing department. In this connection, Hares, H [1980] wrote:-

> "The facilities offered by the distributed database software mean changes are occurring in the way that information is handled and business is conducted. The days of monolithic, all powerful, centralised data processing department are over. The growing user-friendliness of data software is increasing the independence and power of managers and users in using and developing information systems. Because of the long lead time and back log in the data processing (DP) department for developing application systems, many have gone their own way and created their own personal systems on PC's".

The advantages of distributed processing have been elaborated in a number of literatures. Weston, J.A [1982] described the use of distributed processing in the context of distributed manufacturing systems whereas Shaw, M.J [1987] enlightened the concept in the context of distributed scheduling method for computer integrated manufacturing. Briefly, the main advantages of distributed data processing in the context of decentralised management can be classified as follows :-

- faster and efficient data processing ;
- better data accountability and integrity ;
- small and simpler database ;
- better management over local activities, and
- improved response to incoming enquiries.

4.1.2 The Decentralised (Distributed) Planning and Control Concept

The distributed planning and control concept referred to in this thesis has a much broader definition than just ordinary data distribution. In the context of manufacturing control, not only all the relevant data are down loaded into smaller processing units or computers but some of the key central functions are also distributed to smaller cells in the system.

The application of such a concept in manufacturing systems permits manufacturing functions, namely, planning and control to be distributed across the computers in individual manufacturing cell. This method of managing manufacturing activities is commonly known as distributed planning and control system. A schematic view of the distributed planning and control system is shown in Figure 9A. Each work cell operates on its own, local (micro) Manufacturing Resources Planning (MRP II) system and it is driven by a local database, which provides all the operational data required to support manufacturing activities within the system.

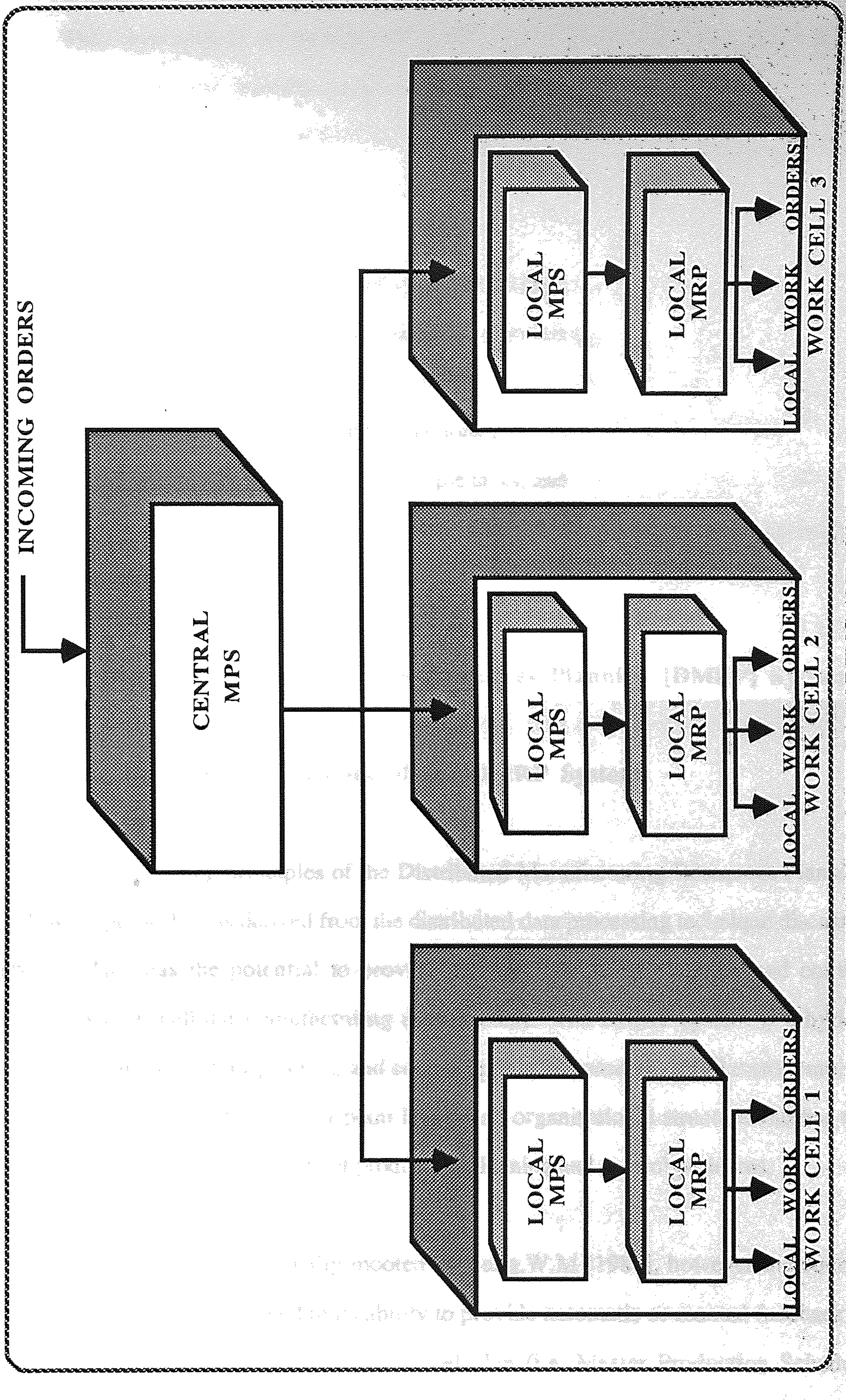


FIGURE 9A THE DISTRIBUTED PLANNING AND CONTROL SYSTEM

The development of distributed planning and control concept represents a significant milestone towards simplification and rationalisation of manufacturing activities. Briefly, the potential benefits that can be derived from the implementation of such a concept in a typical manufacturing environment can be classified as follows :-

- simplification of planning and control functions ;
- simplification of database and database processing ;
- refined control of the overall system ;
- ownership of data and control functions ;
- rationalisation of complex into simple tasks, and
- provides rapid and better quality response to changes in the operating environment.

4.2 The Distributed Manufacturing Resources Planning [DMRP] System

4.2.1 The Underlying Principles of the DMRP System

The underlying principles of the Distributed Manufacturing Resources Planning (DMRP) approach, was derived from the distributed data processing technique discussed above. This has the potential to provide decentralisation of planning and control functions in a cellular manufacturing environment. The DMRP system is a hybrid production and inventory planning and control approach, based on cellular structure. It is designed to exploit the cellular plant layout and organisational structure and has the potential to minimise complexity of production planning and control problems.

The concept was originally mooted by Lung.W.M [1988], however the control system developed was limited in its ability to provide automatic or manual feedback of manufacturing resource status to high level plan (i.e. Master Production Schedule (MPS)). This is due to lack of a truly closed loop feedback control system [Burcher, P.G. 1985]. However, the current DMRP system was mooted by Baraket, M. [1989] and it is an improved or enhanced version of previous system and the major difference is that it incorporates a manual feedback mechanism which provides management with the relevant shop floor information.

4.2.2 The Operational Aspect of the DMRP System

An overview of DMRP system is illustrated in Figure 9B. It entails that major planning and control functions such as Master Production Scheduling (MPS), Rough Cut Capacity Planning (RCCP), Material Requirements Planning (MRP), Capacity Requirements Planning (CRP) are local to the environment in which it operates. Each manufacturing cell therefore maintains its own micro MRP II (MPS, RCCP, MRP, CRP) system and is totally responsible for the management of all manufacturing and control activities within individual cell. This has the potential to minimise the complexity of manufacturing control problems, as compared with an equivalent manufacturing system, based on a centralised planning and control architecture.

The DMRP system is based upon the distribution of planning and control functions across the computers located in each of the manufacturing cells and hence, the database in each cell, maintains Bills-Of-Material (BOM), route data, inventory records and other information which are relevant to the product family of individual cell. This enables the implementation of smaller and simpler database within each cell and therefore all cell activities (i.e. operational planning and control) can be driven with accurate and realistic data. This also provides a better prospect of achieving accurate and realistic action reports which are essential for the overall operation of the cell.

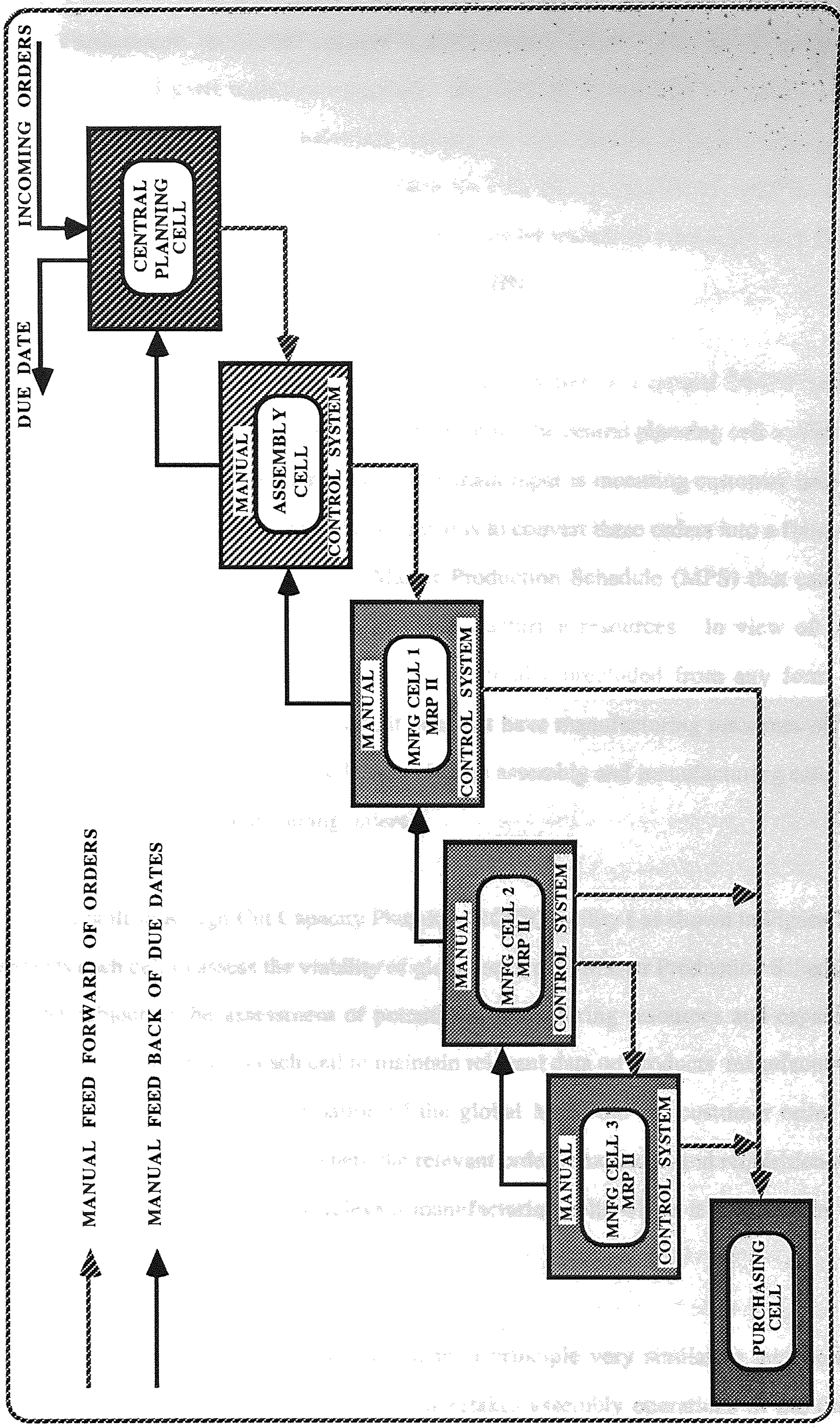


FIGURE 9B AN OVERVIEW OF THE TRADITIONAL CELLULAR MNFG. CONTROL SYSTEM BASED ON DMRP CONCEPT

Furthermore, the DMRP concept is also based on a single level BOM structure, linking finished parts with raw materials. The bill of inventories holds only parts manufactured or procured by individual cell and the same applies to all the routing data for parts or components manufactured within the cell. This simplifies the complexity of BOM and enhances the prospect of establishing better traceability between shop level scheduling activities and the high level plan (i.e. MPS).

An overview of the planning and control activities in a typical DMRP based manufacturing environment is shown in Figure 9B. The central planning cell resides at the top level of the control hierarchy and its main input is incoming customer orders. The main function of the central planning cell is to convert these orders into a finished product plan and generate a viable Master Production Schedule (MPS) that can be achieved within the scope of available manufacturing resources. In view of its supervisory role, the central planning cell is totally precluded from any form of manufacturing activities. In addition, it does not have manufacturing resources of its own but relies mainly on other cells, namely, the assembly and manufacturing cells to fulfil the requirements of incoming orders.

A built-in Rough Cut Capacity Planning (RCCP) facility (as shown in Figure 7), enables each cell to assess the viability of global or overall Master Production Schedule (MPS) subject to the assessment of potential manufacturing resources and capacity constraints. This requires each cell to maintain relevant data on products manufactured within the system. On confirmation of the global MPS, the net customer order is dispatched to the assembly cell where the relevant order is exploded and requisition for parts manufacture are issued to relevant manufacturing cells where it is treated as an incoming customer order.

The operation of the assembly cell is in principle very similar to the central planning cell with the exception that it undertakes assembly operations of the final product based on components supplied by various manufacturing cells. It maintains its own local database and control algorithm that governs the activities within each cell and it communicates interactively with the central planning and manufacturing cells respectively. The validated MPS from the assembly cell is then cascaded down to the manufacturing cell which undertakes the actual manufacture of components required by the assembly cell. Under the existing DMRP system, the feed forward and feedback of information between cells is undertaken with the aid of the human scheduler and this is shown by the dotted and solid lines in Figure 9B.

The main input to the local MPS in each manufacturing cell is derived from the assembly cell or orders generated by other cells. Using the local RCCP process and stored bills of resources, each cell assesses the viability of MPS and potential manufacturing resources and capacity constraints. The RCCP process enables each cell to undertake 'what if' analysis to master production scheduling prior to detail MRP and CRP run.

In the next hierarchical level within individual cell control system, is the MRP module and its input is derived from the MPS module. Using locally held BOM and inventory records, the local MRP system generates three main orders, namely, work orders for batches of parts to be made in time to support the local MPS ; orders for parts to be processed by dependent cells and purchased orders for parts which are handled by an independent purchasing cell.

Using the work orders generated by the MRP system, the local CRP process examines the short-term capacity problems using techniques which vary from simple infinite capacity planning to complex finite scheduling. If the CRP process highlights problems (e.g. insufficient capacity available to fulfil the orders), this results in subcontracting part of the orders to other manufacturing cells or alternatively it may also lead to the modification of local MPS. In the event of the failure to meet the customer cell specified due dates, the relevant information is fedback to the customer cell. Under the current DMRP system, the feedback process within and between cells is undertaken with the aid of a human scheduler. On receipt of this information, the customer cell reschedules all its operations and generates a viable production schedule that reflects the current status of manufacturing resources. In this context, the shop level scheduling activities, namely, the evaluation of capacity and due date constraints are undertaken with the aid of a human scheduler and this implies that the system is potentially slow.

As shown in Figure 9B, the actual calculation of requirements, cascades from the top level (i.e. central planning) cell to final assembly cell. This is then cascaded down to the dependent manufacturing cell where the arrival of this order triggers the local scheduling process. The purchase orders generated by each cell is passed on to the central purchasing cell whereas parts which could not be processed within individual cell is subcontracted to other manufacturing cells. The supplier cell schedules all its operations and generate a due date that can be achieved under the current manufacturing status. If it fails to meet the due date required by the customer cell, then this requires the latter to reschedule all its operations and the tentative due date generated by the cell is then fedback to the immediate customer cell, higher up the hierarchy and the communication of information between cells are handled by the human scheduler. Changes in the due date within a supplier or customer cell has two major effects, namely, it triggers the local scheduling process and it also leads to a chain reaction where other dependent cells are required to reassess their MPS to accommodate changes reflected by the bottom level cell (s).

The process of determining the required due date initially starts from the top level (i.e. central planning) cell and then cascades upwards from the bottom level cell which performs manufacturing operations, through intermediate cells to that concerned with final assembly. Under the current DMRP system, the modification of due date or MPS is undertaken manually and therefore it is potentially slow.

4.2.3 The Major Benefits of the DMRP System

The DMRP strategy offers significant advantages in many aspects, namely, operational planning and control as compared with equivalent conventional manufacturing control systems discussed in the previous chapter. The major benefits of the DMRP approach are described in the subsequent discussions.

The concept of decentralisation enables key manufacturing functions, namely, planning and control to be distributed across each cell. This enables the simplification and rationalisation of complex manufacturing activities [Gallagher, C.C. et. al 1986] into simple and well defined functions. This offers each cell with a greater degree of responsibility and accountability over its activities and hence, improve the efficiency and performance of the system. It provides a better prospect of simplifying the nature of control problems present within such a system.

The DMRP concept offers a better prospect of instituting cell ownership and autonomy. Each cell is therefore completely autonomous and are totally accountable over all the activities within its operating environment. It permits local management to plan or replan their activities to suit local operating conditions and environment. It also enables local control policies to be implemented without the need to extensively update other parts of the system.

The DMRP system permits the cell manager within individual cell to make full use of local MRP II system. The delegation of responsibility to allow shop floor controllers to manage various functions within each cell is therefore equally matched with providing them with the tools they need to carry out their tasks professionally and efficiently. This offers a better prospect of simplifying the key production control activities into a set of visible and easily definable tasks and hence, this permits the delegation of total responsibility to individual cell manager.

Since each cell has its own distributed MRP II system hosted on a local computer, this provides the opportunity of using local MPS, which is driven by orders for parts which may originate from other cells (that is, for components or sub assembly) or central planning cell (finished products). The localisation of cell activities, namely, local MPS, RCCP, MRP, CRP provides the cell management with greater degree of freedom, flexibility and a powerful tool to undertake the viability of local production programme and MPS. This can be taken to strengthen local management structure in which manufacturing activities, namely planning and control functions are much more simplified and refined to suit local needs and policies.

Similarly, the local CRP is much simpler in design and functions, since it is only required to undertake requirements planning of parts built within each cell. Since the DMRP system is supported by a manual feedback mechanism, it is therefore potentially capacity sensitive. This provides the system with the ability to feedback relevant information on manufacturing status to the scheduler and enables the local cell manager who is responsible for making key decisions to evaluate the effect of such action on capacity and due date constraints. This provides the cell management with a potentially powerful tool to generate an accurate and realistic due date.

The DMRP system entails that product BOM are distributed across all the relevant cells. Each cell is only required to hold bills of data that are relevant to products or parts manufactured within the system and since it is based on a single level BOM structure, each bill contains only the levels between the input and output stages of the item manufactured by the cell, that is, a bill linking finished parts with raw materials. This simplifies the complexity of BOM (e.g. resolves the problem of commonality) as compared with an equivalent multi-level BOM system.

The database is designed primarily to support local activities and hence, it is only required to maintain inventory records, BOM, routing data, etc., for parts manufactured by the cell. This provides high data integrity, accountability and improves the database management system. Data accountability is also significantly improved since the amount of information to be processed in a distributed environment is much lesser as compared with an equivalent centralised system. The smaller and simpler BOM together with extensive local knowledge of cell entities improves the linkage between MPS entries and the shop level scheduling activities (i.e. work centre overloads evident from the CRP run). This helps to minimise the overall manufacturing control problems within individual cell. A schematic view of the distributed (local) database concept is illustrated in Figure 9C.

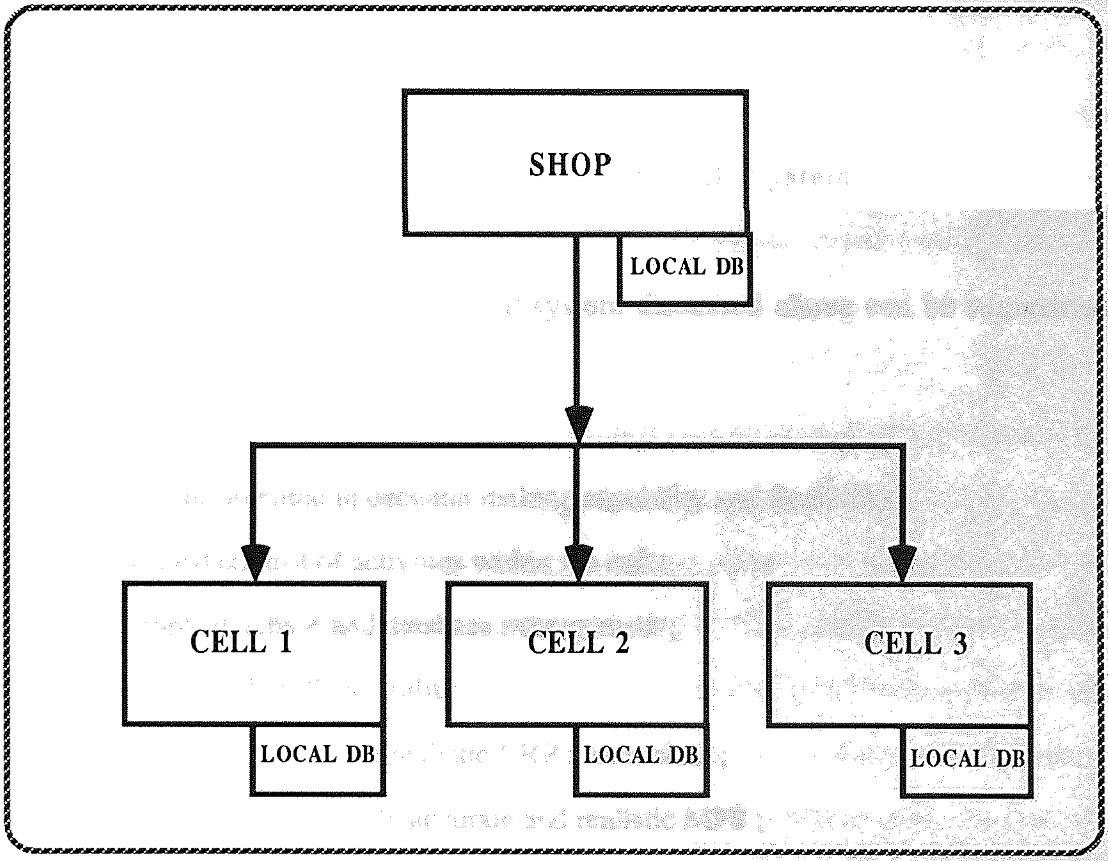


FIGURE 9C LOCAL (DISTRIBUTED) DATABASE CONCEPT [AFTER WEBER, D.M. (1989)]

By distributing the control functions across a number of computers, each cell is only required to deal with the inventory items related to the product range manufactured within the system. This provides the local computer faster localised data processing capability, improved processing time and greater flexibility than a computer in an equivalent centralised planning and control system. The simpler requirements planning within individual cell implies that it is relatively faster to execute the MPS-MRP-CRP cycle and this enhances the management's ability to undertake extensive 'what if' analysis to master production scheduling and detailed capacity analysis.

The cellular based DMRP system provides an improved plant layout with relatively small numbers of processing centres and well defined product or part families. This simplifies material flow within the system as compared with an equivalent centralised cellular manufacturing system. It also enhances the prospect of minimising the complexity of local manufacturing activities and provides improved manufacturing performance within such a system.

4.2.4 Summary of the Major Benefits of DMRP System

The major benefits of the DMRP system discussed above can be summarised briefly as follows:-

- greater potential in decision making capability and flexibility ;
- refined control of activities within the cell ;
- simple database and database management ;
- greater 'what if' capability ;
- simple, accurate and realistic CRP mechanism ;
- simple and potentially accurate and realistic MPS ;
- greater ownership and autonomy, and
- improved response to changes in the status of manufacturing resources.

4.3 Problems and Limitations of DMRP System

A review of above discussions suggest that the DMRP system offers significant advantages from the prospective of cell planning and control. However, despite these advantages, it suffers from a number of critical problems which limits the system's ability to provide effective and dynamic control functions. The main limitations of existing DMRP system are described in the subsequent discussions.

A distinct difference between the existing and previous DMRP systems, lies in the feedback mode applied within each system. Existing DMRP system is based on a manual feedback technique and so this implies that it is potentially slow and limited in its ability to provide rapid response to changes arising from top and bottom level inputs. In this context, top level inputs are referred to incoming orders or enquiries whereas, bottom level inputs imply changes in manufacturing status (i.e. machine breakdown). This offers the potential to limit the management's ability to respond with accurate and realistic data to changes in the manufacturing environment.

In a DMRP system, the shop level scheduling (e.g. evaluation of capacity and due date constraints) activities are performed by a human scheduler and this implies that the prospective solution or corrective action to a particular problem is potentially slow and hence the quality of solution is also likely to deteriorate. This could produce a negative effect in a dynamic manufacturing environment where the speed of response is very critical. The prospect of achieving an accurate and realistic due date, under a dynamic manufacturing environment is therefore severely impaired. Furthermore, this limits the prospect of undertaking dynamic 'what if' analysis or evaluation in response to changes in the status of manufacturing environment and hence it is difficult to evaluate the impact of various manufacturing policies on due date performance and MPS.

4.4 The Need for a Realistic Cellular Manufacturing Control System

In view of the above shortcomings in existing manufacturing control systems, there is a need for an alternative manufacturing control architecture that can provide a more pragmatic and realistic control functions as described below :-

- undertake automatic evaluation of capacity and due date constraints ;
- provide rapid response to changes in the status of manufacturing resources arising from inside (e.g. machine breakdown, operator absenteeism) and outside (e.g., incoming orders or enquiries) the cell, and
- undertake automatic evaluation and modification of MPS.

4.5 Concluding Remarks

Existing cellular based manufacturing control system (i.e. DMRP) has demonstrated that it has the potential to offer significant advantages (described in section 4.2.4) compared with equivalent traditional control systems based on centralised approach to planning and control. This helps to minimise some of the key control problems present in an equivalent traditional manufacturing environment. Despite these claims, it is still critically limited in its ability to provide automatic replanning in response to changes arising from top and bottom level inputs. This is largely attributed to manual scheduling and information feedback technique applied in such a system which weakens the link between downstream activities (i.e. shop level scheduling) and high level plan (i.e. MPS). It is therefore difficult to provide automatic (rapid) feedback key manufacturing status information to MPS.

However, automating the MPS and shop level scheduling activities will provide a better prospect of resolving the core control problems present in existing manufacturing control systems. In the light of these findings, there is a need to review the existing

MPS regulation methodology and to pursue the search for an alternative manufacturing control architecture that is capable of resolving the key control problems discussed above.

CHAPTER 5

Review of Master Production Scheduling and Manufacturing Resources Planning

In view of the fact that automation of all aspects of the manufacturing control system and in particular high level planning is the key to the development of a coherent and cohesive control system architecture, there is a need to review Master Production Scheduling (MPS) and Manufacturing Resources Planning (MRP II).

5.1 The Need for Master Production Scheduling

The Master Production Schedule (MPS) is a statement of the anticipated build schedule for selected items produced by a manufacturing facility. The development of an effective MPS system is frequently cited as a critical element in obtaining the full benefits of Material Requirements Planning (MRP). The need for MPS has been elaborated by Proud, J. F [1981] who wrote:-

> "The Master Production Schedule is defined by APICS as a statement of what the company expects to manufacture. It is the anticipated build schedule for selected items assigned to the Master Scheduler. The Master Scheduler maintains this schedule and in turn it becomes a set of planning numbers which "drives" MRP. By nature of its definition, the MPS is the tool that is used to plan the company's material and capacity requirements in the right priority sequence. Since the MPS is usually the highest level of planning done in most Production and Inventory Control systems, it is vital that good, credible plans be established and maintained. Besides being a plan, the MPS must facilitate order processing and establish ....".

Although numerous articles (see section 5.4) have been published during the last decade on the development and implementation of manufacturing control systems, there is hardly any evidence to suggest that any research work being directed towards the automation of high level plan (i.e.MPS).

5.2 Existing MPS Evaluation Methodology

5.2.1 An Overview of the MRP II Approach to MPS Evaluation

5.2.1.1 The Rough Cut Capacity Planning (RCCP) Process

The main goal of the MRP II process is to produce a practical and realistic MPS within the framework of available manufacturing resources. A conceptual overview of the MRP II iterative process is shown in Figure 10A. The MRP II mechanism recognises the needs of the scheduling system to consider the customers requirements and the capability of manufacturing resources to meet such demands. In a typical MRP II system (shown in Figure 10A), the practicality of the MPS is checked at two different stages, each resulting in different levels of accuracy in the MPS. The first stage of the check (RCCP) is carried out within the MPS module prior to a MRP process whereas the second stage involves a more detailed evaluation of post MRP using the Capacity Requirements Planning (CRP) module.

The RCCP process involves an analysis of MPS to identify the existence of critical manufacturing resources that are potential bottlenecks in the flow of production. It translates the market requirements for products into load profiles for various key manufacturing resources. Failure to generate a satisfactory production schedule, leads to manual modification of MPS or production schedule and this is generally used to compensate for under or overload conditions in the plant and to satisfy both the customer (market) requirements and existing capacity constraints. The MPS or production schedule generated by the RCCP process is generally unrealistic because it does not always reflect the current status of manufacturing resources. Furthermore, the RCCP process adopts a gross view (e.g. it only considers production areas, not individual work station ; product families not individual items) which makes the application of such technique feasible.

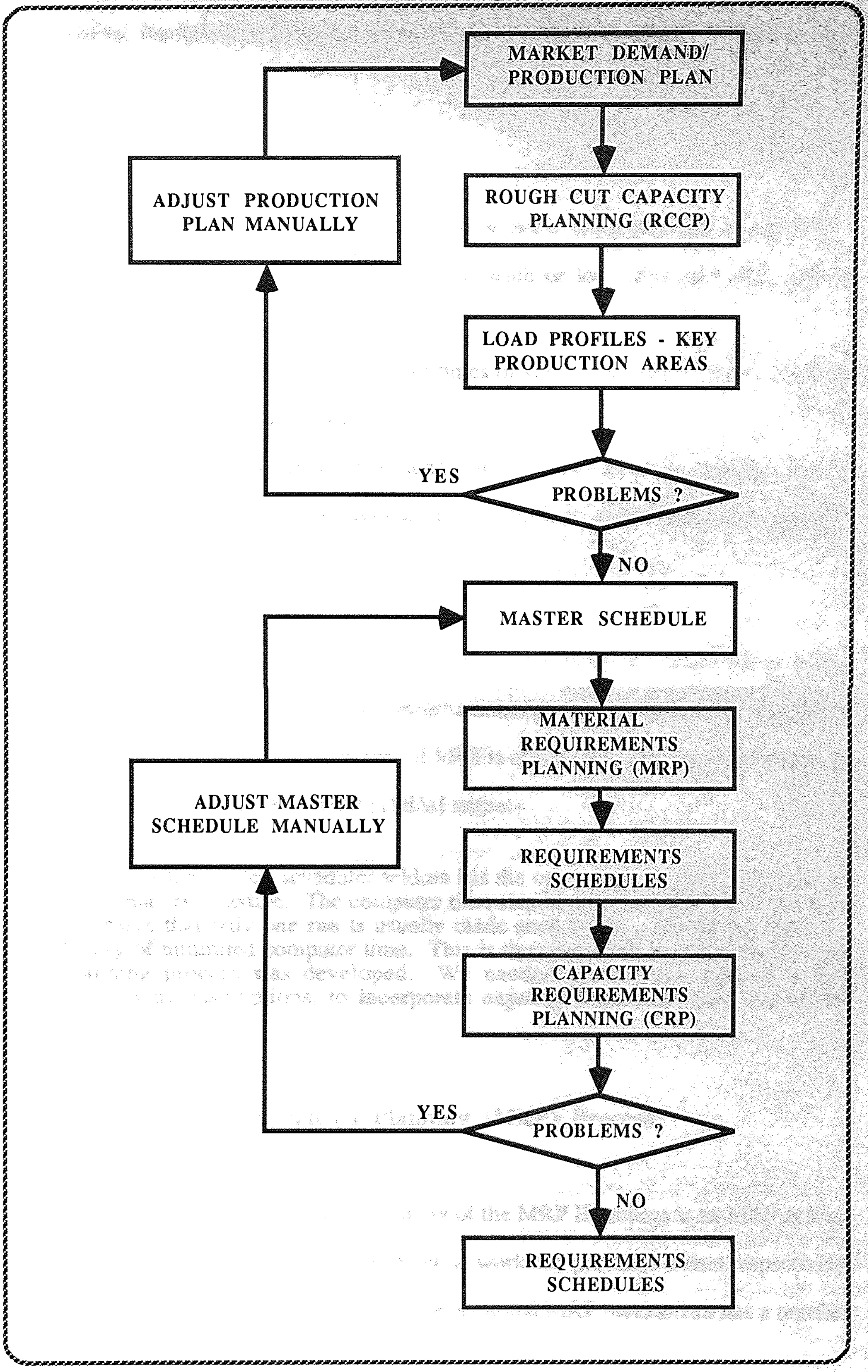


FIGURE 10A A CONCEPTUAL VIEW OF THE MRP II ITERATIVE PROCESS

For example, the RCCP mechanism is based on a number of simplistic assumptions, namely :-

- it assumes no work-in-progress ;
- the plant is empty ;
- sub-assembly and final assemblies can be made in the required time period ;
- production is not governed by any batch or lot sizing and shop control policies;
- it does not take into account lead times of sub-components, that is, anything below MPS demands, and
- it only considers production areas (not individual work station), part or product families (not individual items) and long time frames (not minutes, hours or days).

The production schedule is normally based on simplistic capacity planning technique, which uses far less detailed information than the standard CRP technique. Benefits of rapid analysis and generation of MPS is offset by lesser degree of accuracy. In connection with this issue, Fox, B [1983a] wrote:-

> "In reality the master scheduler seldom has the opportunity to make adjustments in the master schedule. The computer time required for an MRP-CRP run is so extensive that only one run is usually made each week.... we do not have the luxury of unlimited computer time. This is the reason the Rough Cut Capacity Planning process was developed. We needed a short cut, even if it had simplifying assumptions, to incorporate capacity limitations into our master schedule".

5.2.1.2 Material Requirements Planning (MRP) Process

The subsequent process in the hierarchy of the MRP II process is an MRP system (shown in Figure 10A) which is used to generate work and purchase orders respectively. As discussed in Chapter 3 (section 3.4.2), conventional MRP mechanism has a number of serious limitations, namely : -

- critically capacity insensitive ;
- ignores shop floor (manufacturing) policies ;
- not responsive to changes in the manufacturing environment ;
- lacks " what-if " capability, etc.

It adopts a centralised approach to planning and control and this removes much of the key decision making functions from the shopfloor. It is therefore difficult to use the system in the evaluation capacity and due date constraints. Furthermore, it does not provide any direct links between shop level scheduling activities and high level plan and it is therefore difficult to automate MPS under such an environment.

5.2.1.3 The Capacity Requirements Planning (CRP) Process

CRP is a technique designed to 'fine tune' the master schedule produced by the RCCP process. In the MRP process, the nett part requirements are generated by netting off the gross requirements from the planned order receipt and on-hand inventories. These requirements are then backward scheduled from their due dates by the CRP module so that work centre load profiles can be generated for individual processing centre to satisfy the required production schedule. The role of CRP mechanism has traditionally been used in the comparison of alternative schedules. Where the load generated by a proposed MPS proves unsatisfactory due to significant overload in the planning periods, the schedule is then modified on a trial-and-error basis and the process is repeated until a feasible schedule is achieved.

As shown in Figure 10A, the master schedule is adjusted manually to resolve any over or underload conditions that may exist in the MPS planning horizon. The fact that MPS is modified manually implies that conventional CRP is used to highlight the potential capacity problems but limited in its ability to provide automation of MPS. In this context, CRP process cannot be considered as a dynamic and interactive method for undertaking evaluation of various control policies due to practical limitations. For example, it requires a substantial computer (processing) time to produce a viable MPS and this renders the technique impractical and undesirable. This also limits the prospect of operating the system under 'simulation' or 'what if' mode to view the practical implications of various manufacturing policies on the MPS.

The complexity of multi-level Bills-Of-Material (BOM) (as shown in Figure 10B) coupled with the effects of commonality and lot sizing, makes the conventional MRP II process difficult to achieve without load pegging facilities. For example, it is difficult to identify the parts which cause work centre overload problems with the relevant entries in the MPS. This impairs the prospect of closing the feedback loop between shop level scheduling activities and high level plan (i.e. MPS).

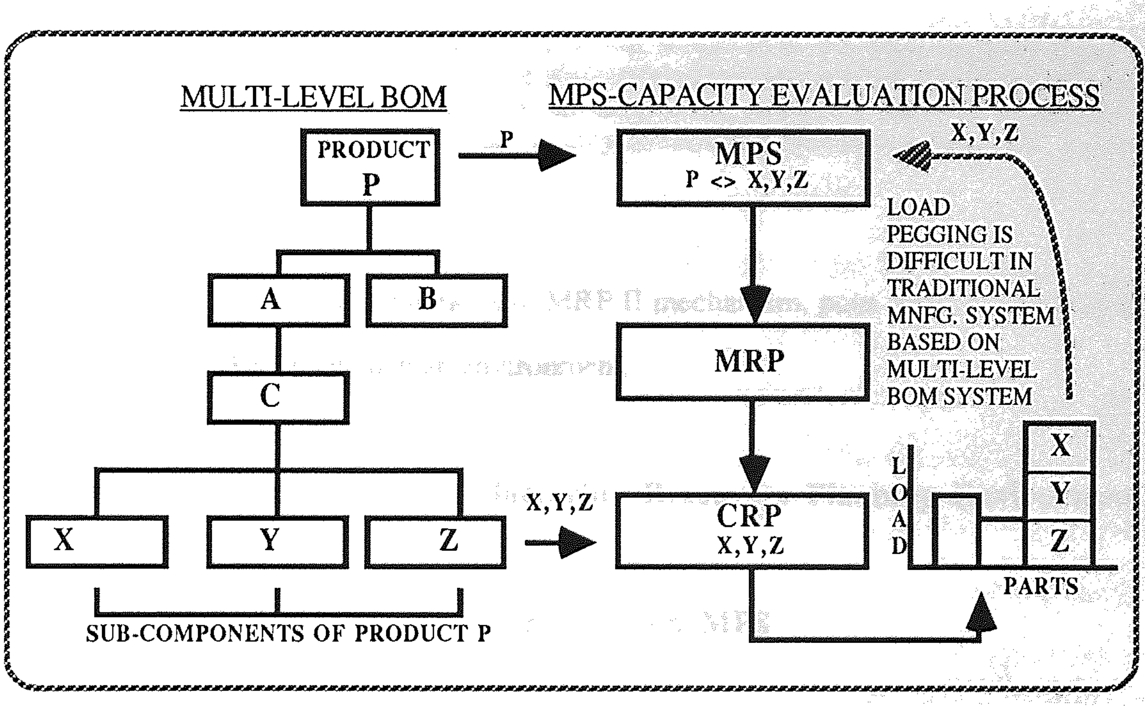


FIGURE 10B LOAD PEGGING IN A TRADITIONAL MANUFACTURING SYSTEM

As shown in Figure 10B, load pegging referred to in this context, is analogous to requirements pegging illustrated by Orlicky, J [1975] but here it is perceived in the context of CRP process through which the load generated on a particular work centre can be traced back to the relevant entries in the MPS or vice versa. As shown in Figure 10B, it is difficult to establish a common link between the parts or sub-components X ,Y, Z which cause the overload problems with the relevant entries in the MPS (i.e.product P). Other techniques such as manual load pegging is virtually impossible to perform under such an environment due to time constrains posed by such an exercise. The common technique used is therefore based on RCCP [Fox, B 1983a] at the MPS level, followed by conventional CRP process and overtime to adjust the MPS. Existing technique used to resolve such a problem stresses great emphasis on key work centres and popular items and thus, it ignores the effects of other items and hence renders the system potentially inaccurate and unrealistic. Practical limitations such as complexity of the shop floor, high product range or variety and complex material flow structure makes this process difficult to achieve. In connection with this issue Kruse, G [1990] wrote : -

> "The problem with most master schedules is that they are frequently developed without sufficient knowledge of a plant's products and processes. For example, they ignore the limiting factors on the shop floor, such as wandering bottlenecks and no amount of sophisticated factory scheduling can compensate for a poor master schedule ".

In brief, the inherent limitations in MRP II mechanism, pose serious difficulty in automating the MPS under such an environment.

5.3 MPS in a Distributed Manufacturing Resources Planning Environment

5.3.1 The Influence of Cellular Structure on MPS

The potential benefits offered by the cellular concept in simplifying the complexity of traditional manufacturing systems and associated control problems were discussed extensively (Chapter 4) in the context of cellular based, Distributed Manufacturing Resources Planning (DMRP) system. The following discussions highlight the major roles of cellular manufacturing concept in the context of Master Production Scheduling (MPS).

The use of single level BOM structure in a DMRP system, simplifies the complexity of such a feature because only the cell ' products ' appear in it . This improves the management of database, since the amount of data maintained in each cell is relatively small compared with an equivalent centralised database system. This provides improved data accountability and integrity and offers a better prospect of using simple process routes and smooth material and information flow within the cell. A major contribution of such a concept is its ability to simplify the complexity of manufacturing control problems by providing a direct path (link) between downstream activities (i.e. CRP) and high level plan (i.e.MPS). The requirements planning is also relatively simple, since only the cell ' products ' should be ordered. There is therefore a better prospect of executing the MPS-MRP-CRP cycle and this enhances the prospect of undertaking ' what-if ' analysis to Master Production Scheduling and detailed capacity analysis.

As illustrated in Figure 10C, the prospect of undertaking the process of load pegging in a cellular manufacturing environment is much easier compared with an equivalent traditional manufacturing system, based on multi-level BOM structure. For example, the overload conditions created by either parts X, Y, Z at the shop floor level, can be easily traced back to the relevant entries in the MPS due to the similarity of the items at both ends. It is therefore relatively easy to institute the concept of traceability between MPS entries and those parts which cause overload problems. This provides a better prospect of establishing a truly closed loop feedback control system that enhances the automation of MPS and implementation of an "automated DMRP" system. However this also requires automation of low level scheduling activities and manufacturing status feedback mechanism.

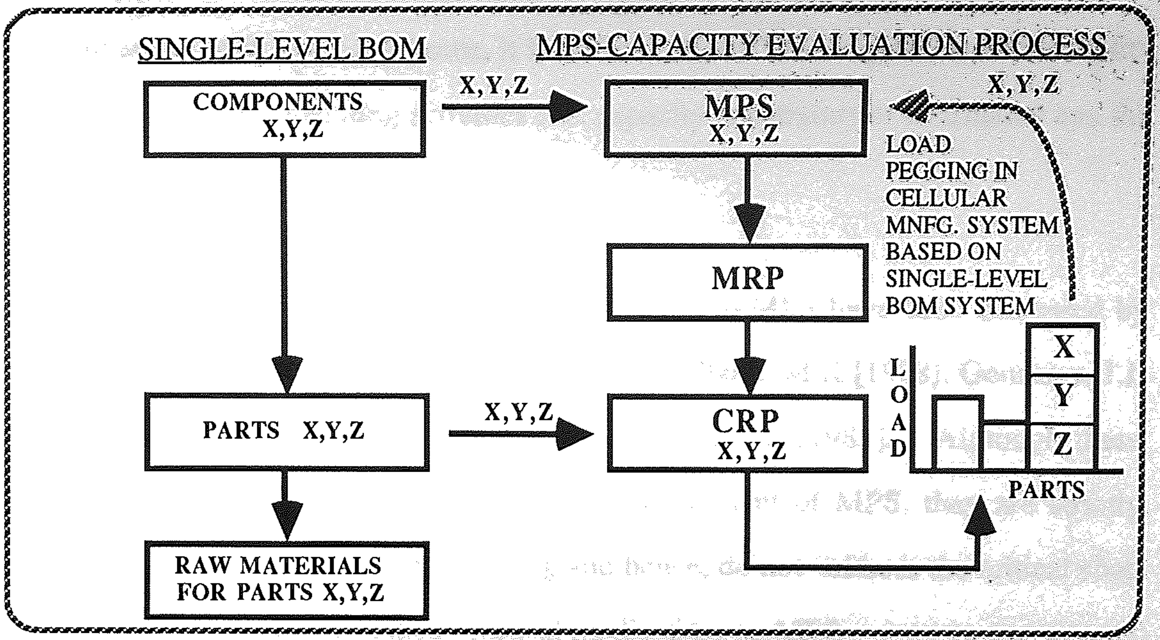


FIGURE 10C LOAD PEGGING IN A CELLULAR MANUFACTURING SYSTEM BASED ON DMRP CONCEPT

5.4 Existing Research on Master Production Scheduling

A review of relevant literatures, suggest that a significant number of Master Production Scheduling related research work are focussed on the automation of shop level scheduling activities, using a wide range of techniques, ranging from hierarchical, expert system, operational research, simulation, to simple analytical techniques. An extensive coverage of research work related to general shop level scheduling has been highlighted by Savell, D.V. et. al [1989], Kerr, R.M. et. al [1988], Ragahavan, V. [1988], Hulaiga, M.I.B. et. al [1988], Kanai, N. et. al [1988], Fox and Smith [1984], Lepape, C [1985], Zhang and Hahns [1985], Semeco, A.C. [1986], O'Grady, P.J et. al [1988], Villa, A [1988], King, B.E. et. al [1988], McClelland, M.K [1988], Falster, P [1987], Kusiak, A. et. al [1988], Solot, P [1990], Young, R.E. et. al [1988], Kim, J. et. al [1988] and Buxey, G. [1989]. Although these represent a significant milestone in shop level scheduling and automation of manufacturing control, there is hardly any evidence to support of any credible research work, which provides dynamic (i.e. automatic) link between shop level scheduling activities and high level planning (i.e.MPS) and vice versa. The shop floor activities are therefore not immediately apparent at the MPS level and hence, it is difficult to establish any form of traceability between shop floor scheduling activities (i.e. capacity constraints or overloads) and the relevant entries in the MPS.

Similarly, a number of research works related to MPS have been discussed by Wilson, E.L [1987], King, B.E. et. al [1988], McClelland, M.K [1988], Gonzalez, J.J. et. al [1983], Sridharan, V. et. al [1990] and Proud, J.F [1985]. Although these represent a major contribution towards the development of MPS, they are strictly confined to Master Production Scheduling and hence, do not address the critical shop level scheduling activities and their practical implications on MPS.

In addition, a number of relevant literatures, namely, by Browne, J [1988] and Morton,T. et. al [1984] represent examples of MPS related work which provide a link between MPS and shop level scheduling activities. The Production Activity Control (PAC) technique advanced by Browne, J. and PATRIARCH mooted by Morton are examples of multi-level (hierarchical) planning and control systems that integrate key manufacturing activities, namely, strategic and capacity planning, scheduling, dispatching. For example, the system mooted by Browne, J. is capable of providing automatic response to changes in the manufacturing status (i.e. bottom level inputs) and to generate a viable due date, that reflects the current status of manufacturing resources. However, it does not provide automatic cascading of due date upwards to the high level plan (i.e. MPS). Although such systems have the potential to provide automation of MPS, there is hardly any evidence to support the development of a control system, based on a truly closed loop feedback mechanism, which provides a "two way" link between the MPS and shop level scheduling activities and vice versa. It is therefore difficult to undertake automation of MPS under such an environment.

5.5 Concluding Remarks

A review of relevant literatures suggest that existing MPS methodology is limited in its ability to provide automation of MPS. This is attributed to a number of factors, namely, the manual scheduling technique (applicable to DMRP system) and the lack of a formal feedback mechanism and truly closed loop control system. The problem is compounded by the lack of a truly flexible, intelligent reasoning and decision making mechanism. However, the difficulty posed in establishing a dynamic, closed loop feedback between the MPS and shop level scheduling activities is also attributed to the complexity of multi-level BOM structure (applicable to traditional manufacturing systems). This limits the prospect of undertaking effective and dynamic load pegging and automation of MPS.

Furthermore, there is simply no credible research work that has been undertaken towards this direction, particularly in a DMRP environment (based on single level BOM) where the problem of load pegging (which is a critical factor in this context) could be easily resolved. In addition, the above findings has also underlined that an effective and dynamic linkage between shop level scheduling and MPS is a crucial factor in the automation of the prospective control system. This will provide significant advantages from the prospective of better traceability between ' downstream ' activities and the high level plan (i.e. MPS).

Broadly defining, what is required to resolve the existing control problems, is a control system architecture that can provide automation of all aspects of operation of the manufacturing control system. Briefly, the criteria for the selection of an alternative, cellular based, manufacturing control methodology can be classified as follows :-

- provide traceability between MPS and shop level scheduling activities and vice versa ;

- provide automation of Master Production Schedule (MPS) without human intervention ;

- undertake automatic evaluation of capacity and due date constraints;

- capacity sensitive ;

- responsive to changes in the status of manufacturing resources and new incoming enquiries ;

- provide dynamic feedback of shopfloor scenarios ;

- provide flexible and dynamic reasoning and decision making capability, and

- provide dynamic 'what if' capability.

CHAPTER 6

Development of New Manufacturing Control Methodology

This chapter discusses the development of a new manufacturing control methodology as an alternative to existing control systems. It underlines the key control system characteristics which form the basis for the development and implementation of a new control system architecture.

6.1 Control System Characteristics

The prospective manufacturing control methodology should be characterised by features which are practical and realistic since these have major influence on the operational aspect of such a system. Broadly defining, the methodology should exhibit the following characteristics :-

- Cellular design ;
- Decentralisation of planning and control functions ;
- Automatic replanning ;
- Bottom-up planning ;
- Inherent flexibility in the means of decision making ;
- Broader applicability ;
- Simplistic design and operation etc.

As discussed in Chapter 3, the cellular concept to manufacturing has the potential to minimise the complexity of manufacturing systems and related control problems as compared with an equivalent traditional manufacturing system. For example, the reorganisation of the manufacturing facility has a significant effect on the simplification and rationalisation of manufacturing activities and the nature of control problems. This would allow production targets to be set based on individual cell requirements without significant changes to other modules. Breaking the manufacturing systems down into small and tightly controlled units, simplifies the nature of material and information flow within and between cells. Furthermore, it has the potential to improve manufacturing performance even in circumstances unsuited to other material flow control system. In connection with this characteristic, major benefits have been claimed for the application of cellular concept, specifically in relation to reduced throughput time and work-in-progress [Burner, L et. al 1980]. In view of the potential advantages that can be accrued from the implementation of such concept, the adoption of cellular design in the development of an alternative manufacturing control methodology would be of paramount importance.

Most of the existing manufacturing control systems (e.g. Manufacturing Resources Planning (MRP II), Optimised Production Techniques (OPT)) adopt a centralised, top-down approach to planning and control. " Centralisation " of computer facilities normally implies centralisation of responsibility for system operation and policies. Therefore local management lacks ownership of the system and this removes much of the key decision making functions from the shop floor. The top-down concept is normally based on the assumption that the same control practices are applicable in many different applications. This makes the system more complex than is required by one module. On the converse, the decentralised approach to planning and control enables the simplification and rationalisation of complex manufacturing functions into simple and well defined tasks. This permits the institution of cell ownership and autonomy and enables the cell management (i.e. cell manager) to exercise greater control over the operational planning and control aspects of each cell. For example, cell management can select or design policies and control rules to suit local needs or requirements. This also provides a better chance of instituting the concept of local database within individual cell. Each cell is only required to maintain bills of data that are relevant to the product or part families manufactured within the system. This provides a better prospect of implementing simple and improved database system designed to support local functions. Since the control functions are clearly defined and the amount of data to be processed is relatively small, this enables the application of small processor (i.e. computer) to control individual manufacturing system (cell) and thus, provides improved material and information flow within the cell. In this context, the Distributed Manufacturing Resources Planning (DMRP) methodology would enhance the realisation of the above functions, since it is based on a cellular concept.

The adoption of DMRP concept would permit the delegation of responsibility for operational planning and control to individual cell manager, who could operate the cell from a micro version of MRP II, installed on a local micro computer. From a managerial point of view, this would simplify the high level planning and downstream activities into a set of well defined tasks, since the cell manager is only required to deal with a smaller and predefined product range and manufacturing resources.

By instituting the concept of decentralised control, there is a better opportunity of implementing local Master Production Schedule (MPS) within the cell. This improves the identification and processing of MPS entries, since the control mechanism is only required to process small MPS entries relevant to the product range manufactured within each cell and hence, the problems inherent in the system are relatively simple to resolve.

This also permits the implementation of local Material Requirements Planning (MRP) which enables each cell to maintain its own Bills-Of-Material (BOM) relevant to parts manufactured within the system. This simplifies the requirements planning and enables rapid and accurate generation of the planned order releases. The concept of distributed control simplifies the local Capacity Requirements Planning (CRP) function, since each cell is only required to deal with capacity problems within its own operating environment. The shop scheduling problems can therefore be resolved more rapidly and accurately. In addition, it provides a better potential of establishing close linkage between the shopfloor problems and the relevant entries in the MPS.

As discussed in Chapter 4, the adoption of DMRP concept would provide simpler requirements planning and thus, the finite scheduler used within the CRP module would be able to provide dynamic and effective scheduling function. In this context, it has been cited [Norton, N 1988] that the finite scheduler can be considered as the basis on which shopfloor control can be implemented and this is due to its ability to identify and quantify true bottleneck work centre.

The problems inherent in the existing manufacturing control systems are also attributed to the practices adopted in such systems. As discussed earlier, the centralised, top-down approach to planning and control is capacity insensitive because key decision making functions are not delegated to the shop floor controller. However, a bottom-up approach to manufacturing planning and control would provide a better prospect for cell management to be actively involved in the shop floor decision making functions rather than by the central organisation. For example, stock policies, batching or lot size rules are determined at the shop floor level. An intrinsically bottom-up approach to planning and control should be included as a key design feature. This would provide greater autonomy in key decision making by shop floor personnel on a wide range of planning functions.

The existing manufacturing control systems can be classified under three main categories, namely, manual (e.g Kanban), semi-automatic (e.g. MRP II) and automatic (e.g. Flexible Manufacturing Systems (FMS) controllers). Generally, automatic control systems have been used only in low level, process control applications. These may respond to low level inputs (e.g. machine breakdown) but they are limited in their ability to respond to top level inputs (e.g. incoming orders or enquiries). In addition, these systems attempt only low level replanning in response to changes in manufacturing status but they do not trigger replanning of systems higher up the control hierarchy. For example, an FMS breakdown will not affect material procurement plan since the problem is related to manufacturing processes rather than MRP. Most of the current manufacturing control systems rely on human intervention for key policy and operational decisions. For example, in a traditional MRP system the time required to calculate the requirements for complete parts range by either generative or regenerative method can be time consuming and therefore it is only calculated occasionally (i.e. once a week or month). This results in the deterioration of control actions because as time progresses these actions become less relevant. The modification or preparation of Master Production Schedule (MPS) in a MRP system is always performed manually. However, the DMRP system offers significant improvement over the conventional MRP system. For example, the MRP process implied in such a system is less time consuming since the number of products or parts manufactured are smaller and based on a single level BOM. However the modification of MPS in a DMRP system is still undertaken manually and this makes the system potentially slow. It is difficult to undertake dynamic ' what-if ' analysis in relation to master production scheduling and detailed capacity planning.

Decisions made in an automated manufacturing environment are normally good for three main reasons [O'Grady, P.J. et. al 1988] namely :-

- large volume of data can be generated to undertake decision making ;
- data generated automatically is likely to be more accurate than that produced manually, and
- this enables data to be made available to the decision making mechanism more rapidly than a manual system and thus, it improves the quality of decisions made.

The ultimate aim of the control system development is to provide complete automation of all aspects of the manufacturing systems. In this context, the downstream activities (i.e. shop level scheduling), the cascading of manufacturing status to high level plan (i.e. MPS) and the process of modification of MPS are automated. This would enable replanning of all manufacturing activities in response to changes arising top and bottom level inputs respectively. In this context, top level input is referred to incoming orders or enquiries, whereas bottom level input is related to changes in manufacturing status (e.g. machine breakdown).

One of the major limitations in existing manufacturing control systems is its inability to undertake ' what-if ' analysis in relation to master production scheduling and detailed capacity planning. Although this phenomenon is attributed to large time requirements involved in executing the MPS-MRP-CRP cycle in a typical MRP II system, it is also posed by the manual scheduling technique applied in it. For example, the shop level scheduling process in the existing DMRP system is undertaken manually and this slows down the execution of the above process. However by automating the high level planning and downstream activities within a manufacturing system, this would enable the prospective control system to undertake 'what-if' analysis to scheduling or planning more readily. It would also enhance the prospect of undertaking automatic evaluation of capacity and due date constraints and automation of MPS. The concept of automation should therefore be considered as an important feature of the new manufacturing control system.

A major deficiency in the existing DMRP system is its inability to undertake automatic replanning in response to dynamic changes in the manufacturing status or incoming enquiries and this has a major implication for the quality of decisions made. However, the automation of operational planning and control functions within the DMRP system, makes possible the development of an automated form of distributed MRP II. This can be used to strengthen (i.e. automate) the cascading concept, in particular the feed forward and feedback mechanism within the cascaded cellular manufacturing system, based on automated DMRP concept. An overview of the cascaded cellular manufacturing system based on automated DMRP concept is shown in Figure 11 and its operation is described below.

The central planning cell resides at the first level of the control hierarchy and its main inputs are incoming customer orders. Its main function is to transform the incoming customer orders into a set of finished product plan and produce a viable MPS. As discussed in Chapter 4, the central planning cell does not undertake any form of manufacturing, but distributes the relevant orders to the assembly cell (s). The local Rough Cut Capacity Planning (RCCP) mechanism (used in conventional DMRP) evaluates the viability of the MPS and if no capacity problems exist, then these orders are passed down to the assembly cell. However, in the automated DMRP system, this feature becomes redundant because the new control methodology is capable of providing rapid execution and analysis of complete MPS-MRP-CRP cycle and accurate and realistic due date.

In principle, the operation of the assembly cell, is very similar to the central planning cell, but its main function is to undertake assembly of final part/product, using components supplied by various manufacturing cells. It explodes the orders from the central planning cell and determine a viable MPS, which is cascaded down to various manufacturing cell (s) which performs the actual manufacturing of components requested by the assembly cell.

Each manufacturing cell maintains its own (local) MRP II system and manufacturing resources and hence is responsible for all its activities. As explained above, the RCCP process becomes redundant under the automated DMRP system. Using the local BOM and inventory status file, the local MRP generate purchase orders handled by specialist purchasing cell and work orders for parts to be manufactured within the cell or sub-contracted to other cells.

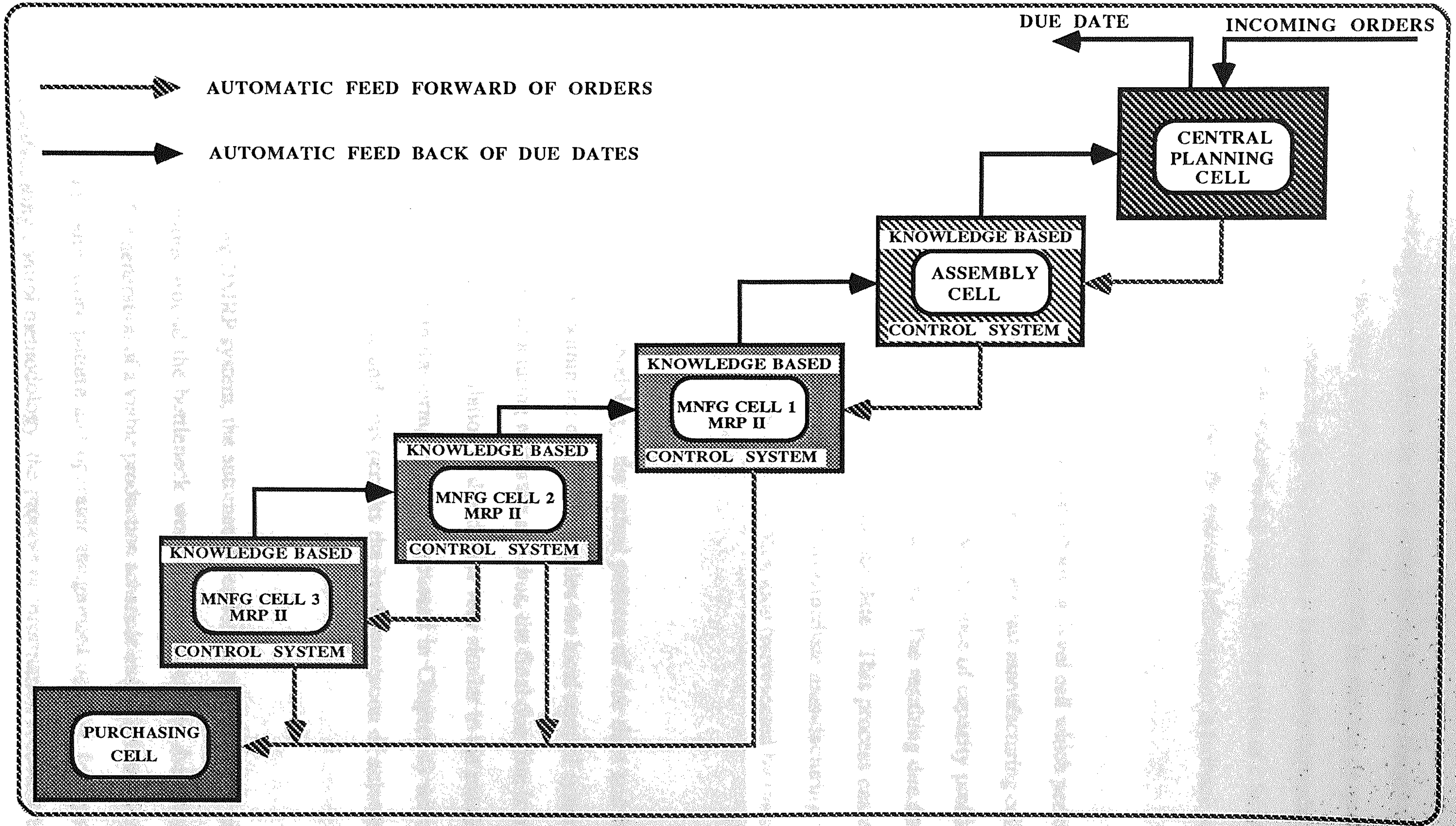


FIGURE 11 AN OVERVIEW OF CASCADED CELLULAR MANUFACTURING SYSTEM BASED ON AUTOMATED DMRP CONCEPT

In the next hierarchical level (within the cell) is the local Capacity Requirements Planning (CRP) mechanism and this checks the viability of the production programme by using both infinite and finite scheduling techniques but it is critically dependent on the finite scheduler to generate a feasible production schedule. In the event of a failure to meet the customer cell specified due date, then the relevant information is fedback to the relevant cell.

The actual calculation of requirements cascades from top level cell which performs final assembly through intermediate manufacturing cells to the last manufacturing cell via the feed forward path indicated by the dotted line. The presence of capacity problems within the supplier cell triggers the local scheduling process. The resulting due date is reflected at the customer cell which also readjusts its due date. This process cascades upwards from the relevant manufacturing cell, through intermediate manufacturing cells and to the actual assembly cell via the automated feedback loop (represented by the solid line).

Under the new control methodology, the actual process of due date and MPS modification is fully automated within the cell. This enables the local control system to reflect the current status of manufacturing resources and thus, the final due date is more accurate and realistic. The actual calculation of due date is very similar to the manually controlled cascaded cellular manufacturing system (discussed in Chapter 4) with the exception that it is fully automatic and this permits the implementation of automated DMRP system.

Unlike the existing DMRP system, the automated version uses a variety of route and work pattern options around the bottleneck work centre to resolve the existing capacity problems. The generation of a viable production schedule and due date involves the use of different route, work pattern and operator assignment options. In the new cellular manufacturing control methodology, the process of information feedback both within and between the cells is undertaken automatically. This enables the control system to provide rapid response to changes in the manufacturing status and incoming orders or enquiries. Furthermore the quality of due date or MPS generated is better because it reflects the current status of manufacturing resources.

A major problem with existing manufacturing control systems (e.g. MRP II, FMS controllers, DMRP) is their inability to provide dynamic response to changes arising from top and bottom level inputs respectively. As a result, it is difficult to automate the MPS under such an environment. However, by automating the feedback, reasoning and decision making mechanisms, would enable the development of a responsive and capacity sensitive control mechanism. For example, an automatic feedback mechanism would be able to reflect the current manufacturing status, whereas the reasoning and decision making mechanism would be able handle conflict resolution and provide an accurate and realistic due date. In this context, it is also important that the control mechanism has the potential to provide the following functions :-

- able to quantify bottlenecks, where, when and how much ;
- inherently flexible, so that the critical resource failures and dynamic rescheduling can be undertaken immediately without waiting for a full factory reschedule ;
- able to provide close control of those bottlenecks to ensure maximum throughput and delivery of required jobs, and
- able to provide 'what-if' capability around the bottleneck work station such that the various options, namely, route, work pattern and operator assignment can be easily facilitated.

Although some of the existing control systems, have some of the capabilities required to fulfil the above requirements, none can offer the potential to fulfil all of them and this is attributed to the limitations inherent in existing manufacturing control system architecture. For example, Optimised Production Techniques (OPT), resolves capacity problems at a predefined bottleneck by using a large overtime option but limited in its ability to handle transient overloads. This normally occurs when a work station, which on average has ample capacity, is unable to make the programme demanded in the required time frame. Since, OPT finite schedules only the bottleneck operation, it cannot spot capacity problems which may occur at a bottleneck operation, located at the ' downstream ' level, which cause serious loss in throughput. Although OPT is responsive and capacity sensitive and has the ability to generate a practical due date, it provides no means of automating the MPS. On the other hand, Micross (i.e. a control system software based on finite scheduling) uses the infinite CRP run followed by manual adjustment of overloads using overtime option at the bottleneck work centre and this process is performed prior to the creation of the finite schedule. However, the application of route and work pattern options as an alternative to existing techniques of resolving capacity problems would refine the resolution of such a problem since this selects options on a gradual and incremental basis as opposed to a single (i.e. overtime) option discussed above. This would also provide a better potential to match the capability of existing control systems (e.g. OPT) in resolving the dynamic (i.e. travelling bottleneck) capacity problems. Unlike OPT such a system could cope with transient bottleneck thus providing a more effective capacity sensitive planning and control system.

One of the main problems with existing manufacturing control systems is attributed to the complexity of the control structure used in them. For example, the centralised, top-down approach to planning and control entails centralisation of responsibility for system operation and policies. It is therefore difficult to institute the concept of ownership and autonomy. Furthermore the adoption of a centralised database system, entails that all the manufacturing data are maintained in a single, massive and complex database (e.g. multi-level Bill-Of-Materials (BOM)) and therefore, the system becomes increasingly difficult to maintain and operate.

A simplistic design based on distributed, bottom-up concept would minimise the complexity of planning and control aspects discussed above. For example, a distributed database built on a single level BOM, as implied in a DMRP system, is only required to maintain information on the product range manufactured within its individual cell and this permits the implementation of simple database system. Ideally, the simplest BOM is one that is based on a single level structure. As discussed in Chapter 5, this would enhance the prospect of establishing better traceability between shop level scheduling activities and the relevant entries in the MPS. This simplifies the closing of the feedback loop between downstream activities and high level plan and thus, provides a better opportunity of automating the MPS. There is a better prospect of achieving an accurate and realistic due date under such circumstances. The implementation of a practical manufacturing control system requires the main logic of the control algorithm to be simple and precise so that the logical steps through the algorithm can be easily traced. Modification of the operational logic of control program can be undertaken without significant changes to the core control algorithm. Broadly defining, simplicity in the design and operation of the prospective manufacturing control system, should form one of the characteristics of the new manufacturing control methodology.

Automation is the key to successful operation of a dynamic manufacturing control system since this has the potential to provide automatic reasoning and decision making capability. In this context, a knowledge based manufacturing control system architecture would enable human intelligence required to make decisions be emulated and transfered to the computer hardware. The application of such a concept could be used primarily to perform logic manipulation for conflict resolution, sequencing and resource allocation. Therefore many of the key decisions will be made automatically without human intervention. It has been acknowledged [Bullers, W.I et. al 1980] that knowledge based concept is indeed useful in representing the control knowledge in a control system. The incorporation of such a concept in the new manufacturing control methodology would therefore enhance its application.

Most of the existing manufacturing control systems do not offer inherent flexibility in the means of decision making, so that the control mechanism can match a variety of manufacturing environments. For example, MRP II or DMRP offers no routing flexibility in the event of manufacturing status change (i.e. machine breakdown) although it has the potential to offer alternate routes within the cell.

The concept of routing flexibility would enable the use of alternate routes within the cell. Routing flexibility is of particular interest in connection with cellular manufacturing due to the fact that it is relatively easy to implement it in such an environment. Its application is critical in resolving capacity problems (e.g. transient overload) at the bottleneck work centre. With regard to part processing, the concept of flexibility would accommodate a variety of product or part families to be processed in the cell to meet demands of customer cell, without significant change overs. Inherent flexibility in decision making in response to internal and external changes is one of the characteristics that needs to be adopted in the new manufacturing control methodology.

The application of most of the existing manufacturing control systems are either limited to automated or manually operated manufacturing environment. However, the application of these systems in a hybrid manufacturing environment can be problematic due to the incompatibility of the core control mechanism with the manufacturing environment. In this context, a hybrid manufacturing environment is referred to a cellular based manufacturing system, made up of a combination of automated cell(s) operating next to a non automated cell(s). A control system architecture with broader applicability would be able to meet the demands of cells with different nature or mode of operation. In this context, an non automated manufacturing cell could derive the same benefits as an automated cell. The incorporation of such a feature in the development of a new manufacturing methodology would be of paramount importance. In this context, it is important that the prospective control mechanism is able to provide dynamic control functions under the following manufacturing environment :-

- Automated manufacturing environment (i.e. Flexible Manufacturing Systems) which depends heavily on automatic reasoning and decision making functions ;

- Non automated manufacturing environment (i.e. manually operated cellular manufacturing systems). If, the system could be operated under the environments discussed above, there is a better prospect of implementing the same control mechanism in a hybrid manufacturing system based on a automated and non automated manufacturing cells, and

- Local cell environment (i.e. within the cell) where the control mechanism (rules, policies, database, etc.) reflects the local needs and functions.

6.2 Concluding Remarks

A major review of above discussions demonstrate that the successful development and implementation of a dynamic control system are dependent on a number of critical factors as highlighted above. It is extremely important that the development of new cellular manufacturing control methodology is envisaged within the framework of the functional characteristics prescribed above.

In summary, the potential advantages of the new manufacturing control methodology, postulated in this thesis can be classified as follows :-

- provide automatic evaluation and modification of MPS and hence facilitate the institution of a cohesive and coherent control function ;

- cope with dynamic bottleneck problems so that shopfloor problems can be easily identified and reflected to the scheduler ;

- applicable in product and component cells, that is, the control concept can be extended to both types of cells ;

- cope with dynamic cascading problem which is a critical feature of the DMRP concept and this is achieved by strengthening the feed forward and feedback mechanism within the cascaded cellular manufacturing system, and

- cope with automated (FMS), non automated and semi-automated (hybrid) cellular manufacturing systems.

CHAPTER 7

Design Considerations for the New Control Methodology

This chapter highlights the major design features that were considered in the development and implementation of the control algorithm which governs the operation of the new (proposed) cellular manufacturing control model and this includes hardware and software requirements.

7.1 A General Overview of the New Control Algorithm

A schematic view of the new cellular based manufacturing control model is shown in Figure 12. The standard logical steps stipulated in the control algorithm are described in the subsequent discussions. The development of the above algorithm was envisaged in an enhanced (i.e. automated) version of Distributed Manufacturing Resources Planning (DMRP) system. The planning and control functions, namely, Master Production Schedule (MPS), Rough Cut Capacity Planning (RCCP), Material Requirements Planning (MRP), Capacity Requirements Planning (CRP) are local to individual work cell.

Complete automation of cell operations would allow DMRP system to replan all its activities automatically, thus a new order enquiry could trigger automatic evaluation by all the cell systems to yield the earliest feasible due date. Breakdowns or other shop failures would trigger not only local replanning within the cell but force rescheduling of any cells which are directly or indirectly related to the one in which the breakdown occurred.

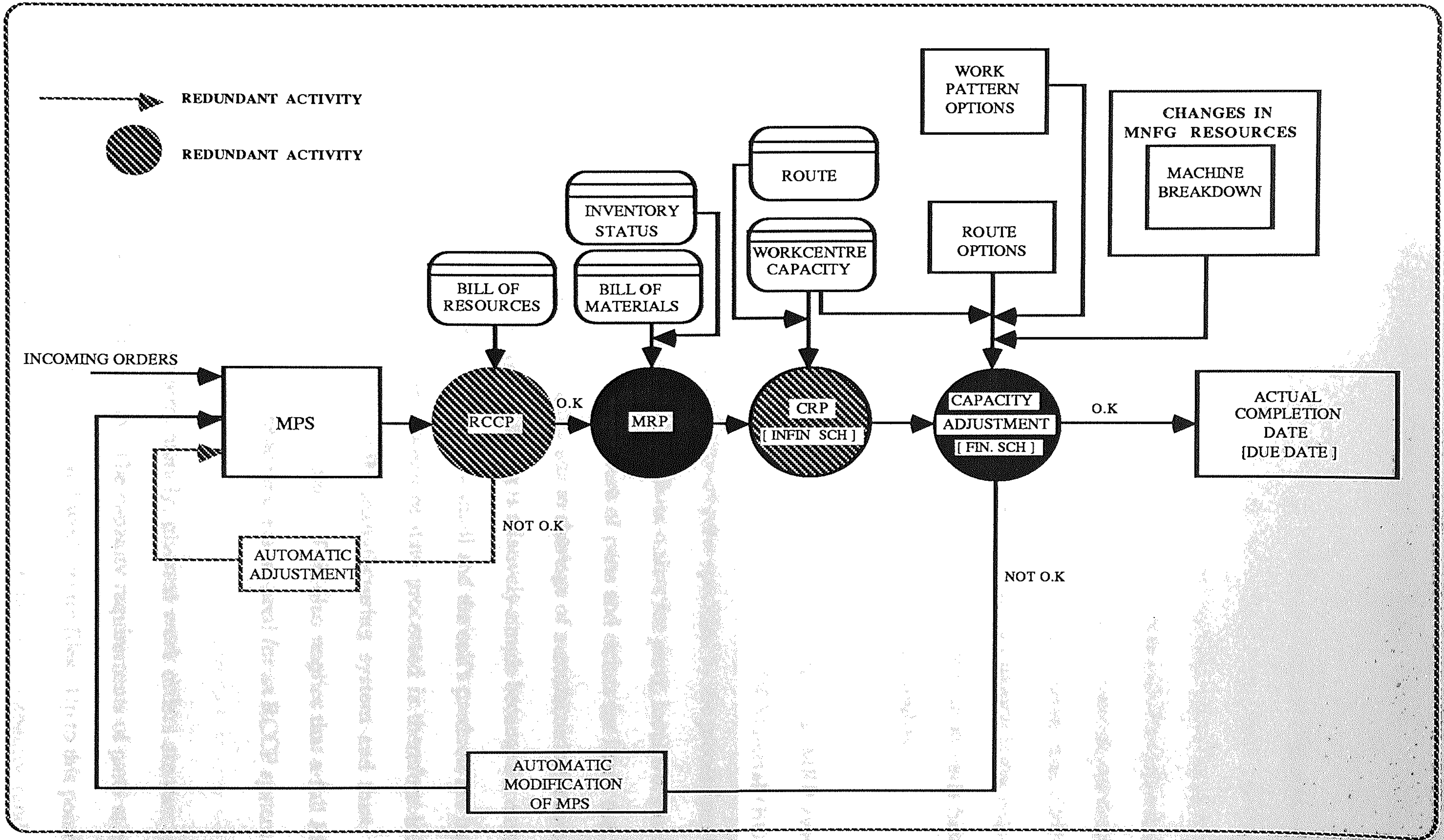


FIGURE 12 SCHEMATIC VIEW OF CELLULAR MANUFACTURING CONTROL SYSTEM BASED ON AUTOMATED MPS CONCEPT

7.2 Detail Description of the Cell Control Algorithm

The key input to the high level plan (i.e. local MPS) module is derived from the incoming customer orders originating either from the assembly or other work cells. These orders are pooled and processed together with the existing list of work orders awaiting to be processed. In a standard MRP II system, the local RCCP process is used to provide a quick check on the viability of the MPS without going through the detailed MRP and CRP processes. The RCCP process is generally less accurate than CRP but this is offset by the processing speed it offers. However, such a function is not required (i.e. redundant) at least in the new control methodology other than in cells having 'product' bills of material of great complexity or very large product families.

The output from the local MPS module is used to drive the local MRP system which undertakes requirements planning by utilising local Bills-Of-Material (BOM), inventory and standard manufacturing lead time of parts specified by the process plan. It generates three main output files, namely, purchase orders for parts, local work orders which are used for authorising local manufacture of parts and orders for items that are sub-contracted to other manufacturing cells, due to shortage of manufacturing resources to manufacture them. The requirements planning is relatively simple because the number of components manufactured within each cell is small and the cell's products are based on a single level BOM structure. The amount of data processed is therefore lesser compared to an equivalent multi-level BOM manufacturing system and thus, the requirements calculation can be performed rapidly. This also implies that a full MRP calculation can be performed quickly and hence there is no need for an RCCP system.

The output from the MRP system, namely, planned work orders are cascaded downwards to drive the local CRP system. The capacity requirements of parts at each work centre are generated by using local route and work centre files. Up to this point the system uses conventional DMRP processing. The evaluation of capacity (and any necessary revision of the MPS) is handled by the ' new ' elements of the system and these are described below.

7.2.1 Infinite Scheduling

Normally infinite capacity planning is used prior to finite scheduling, to drive capacity adjustment procedures, such as sub-contracting or overtime working. Since the new finite scheduler has the ability to adjust resource availability to suit capacity requirements, infinite capacity planning are no longer required.

7.2.2 Finite Scheduling

7.2.2.1 Backward Scheduling

The Finite Scheduling Algorithm (FSA) applies both backward and forward scheduling to determine the actual start and completion date of a job. The algorithm starts with the backward scheduling process which is based on a attribute (i.e. criteria) within the due date (i.e. earliest due date which provides basis of initial allocation). The purpose of backward scheduling is to determine the actual issue date of a particular job and this is undertaken against the background of current work centre load status. A job is backward scheduled from its due date by subtracting the process times (accumulated in reverse order) from the due date. Precedence constraints are applied to control the start and end time of each and every operation. Backward scheduling process highlights whether a job is either ahead, on or behind schedule and such a phenomenon is influenced by the current work load status of each work centre and, in this way it determines the actual start date of a particular job. This process identifies those jobs which could be made early, on-time or will be late. These conditions are considered by the next stage of the scheduling process.

If the launch date generated by the backward scheduling process is prior to the current date, then it follows that the job cannot be completed on time. It is therefore forward scheduled from the current date in order to find the earliest completion date that can be achieved. The segregation of jobs in this second phase of scheduling process is based on the job ' float '. The float is calculated as follows :-

(i) Total Float Time = Order due date - Total production time ---------------------- (7.1)

(ii) Total Production Time = Sum of all the process times as calculated ----------- (7.2)
when an order is added to the system

7.2.2.2 Forward Scheduling

This is designed to provide the earliest date a job can be completed and in this context, it provides the earliest due date that can be attained under the current work load status at each work centre. The jobs are loaded according to the sequence based on float or slack technique as described above. The magnitude of float determines whether the job is early or late and it is used as the basis for sorting the job priority. The first step in the process of determining the priority of jobs is to arrange the orders in the order of minimum float sequence. The sorting process starts with a job that has the most negative float and this is given the highest priority in the forward scheduling process.

(i) Scheduling the Activities at the Work Centre (with Negative Total Float)

The jobs with the most negative float are considered late and hence will not meet the delivery date, even if no other orders are taken into consideration. These orders take priority over all the other orders which are either deemed to be early (positive float) or just in time (zero float). The order with the most negative float is planned first by forward scheduling from the current date (i.e. issue date) so that it can be completed in the minimum makespan and days late.

The start times at each operation are calculated by accumulating the process times to the current day and on completion of this, the system plans the activities for the order with the second most negative float. It's start time on the first operation (if it is the same as the previous orders first operation), is the time that the previous order vacates the machine. The rest of the activities are forward scheduled the same way as the previous orders but the start times for any of its operations cannot precede the completion time of the previous order. Precedence constraints applied in the algorithm ensure that the start and end times of operations are not violated.

(ii) Scheduling the Activities at the Work Centre (with Zero Total Float)

The orders that have zero total float are assumed to be going according to plan and the start times for the activities are calculated by reverse scheduling to find the latest time that a job can begin being processed on a particular machine without it resulting in the order not meeting its due date. In reality, reverse scheduling means subtracting the process times (accumulated in reverse order) from the due date. The order is then scheduled by looking at the plan for the first operation at the latest start time. If the machine is free for the duration of the process time then the activity is scheduled and the process is repeated for all the other relevant operations. However, if the machine is unavailable for the order to be processed then the system must look backwards through the machines schedule to see if there is a gap large enough for the order. This is to ensure that the job is completed before the latest start time for the next operation but however if no gap is available then whatever lateness is accrued must be accepted and the system must look forward to fit in the order. The reverse scheduling process helps to determine the precise time when a machine should be scheduled at an operation assuming that the machine is available to process the job.

When the first operation has been scheduled, the completion time is compared with the latest start time for the next operation. If, for instance, the operation float is negative, then the rest of the activities are scheduled in the same way as the negative total float as discussed in (i).

(iii) Scheduling the Activities at the Work Centre (with Positive Total Float)

The orders with positive float are considered early and in theory it can be completed before its due date. These orders are selected in the order of minimum float and are scheduled very much the same way as the zero total float (ii).

7.2.3 Bottleneck Resolution

The FSA highlights the actual completion date of an item and the over and underloads at each work centre, which are evident from the CRP analysis of committed work orders. The failure to achieve the targeted due date is generally attributed to capacity problems posed by the bottleneck work centre. The capacity constraints may be due to transient overloads or a permanent condition.

The process of bottleneck identification is not as simple as defining an acceptable utilisation figure and checking the projected utilisation figure against it [Copas, C. et. al 1990]. In the context of the new manufacturing control methodology, the identification of bottleneck is undertaken by netting off the total available capacity from that required, at each work centre over the scheduling horizon. The work centre with the least free available capacity represents the potential bottleneck.

The capacity problems at the bottleneck work centre are resolved by using a combination of route and work pattern options. As discussed in Chapter 6, most of the existing manufacturing control systems (e.g. Optimised Production Techniques (OPT), MRP II, Micross) cannot handle transient bottlenecks. For example, OPT is focussed towards the resolution of capacity constraints at predefined bottleneck and whereas Micross is based on manual adjustment of bottleneck capacity using overtime or other options. A unique and important feature of the control algorithm is the refined adjustment of capacity at the bottleneck work centre using a combination of different route and work pattern options. The route options allow the selection of a number of alternate process routes through the manufacturing facility. In this way, the bottleneck machine may be avoided, perhaps at the expense of greater machining elsewhere. The alternate routes would be specified in advance by the system administrator.

It is common for line management to resolve simple capacity problems by altering the work organisation in the cell. They may move operations, arrange overtime, alter shift patterns, work more days or recruit more people. The proposed algorithm includes a series of work patterns which are selected incrementally by the system. Each pattern will typically increase the working time available at the bottleneck machine. For example, in most cases, the working days and hours differ from one work pattern to the other. As the work pattern number increases, the working days and hours also increase gradually.

The resolution of capacity constraints at the bottleneck work centre using work pattern option requires a readjustment of work force (operators) at this centre because successful implementation of a production schedule also depends on the availability of sufficient work force (operator) to execute the plan. In this context, the new control algorithm uses the operator assignment module to determine the actual number of operators needed to fulfil a feasible production schedule. The control model incorporates two different operator assignment methods, namely, manhours and operators techniques and each has its own merit. The main technique applied in sorting operator assignment is based on manhour technique and this is discussed extensively in Chapter 9. The system may detect that insufficient operators are available to meet the required work pattern and will inform the user of the number (manhours) that should be brought in from other cells.

7.2.4 Due Date Evaluation

The resolution of capacity problems using the above options are undertaken in conjunction with the evaluation of due date. The actual completion (due) date, is apparent at the end of the forward scheduling process and this is compared against the required due date to determine the final status of the job. If the actual due date is greater than the required, then the next route option is selected and applied in conjunction with the current work pattern on the bottleneck work centre. The forward scheduling process is repeated and at the end of each run (cycle), the actual due date is checked against the required date. If all the route options have been attempted but the actual due date is still greater than the required date, then the next work pattern is selected and the route options reinitialised (i.e. it is reset to original route). This process or cycle is repeated until a satisfactory due date, that is, the actual due date is either equal to or less than the required due date situation is achieved.

However, in circumstances where all the route and work pattern options have been attempted and the final (actual) due date is still greater than the required, the latter is then modified automatically and made equal to the actual due date. This becomes the legitimate due date that can be envisaged within the framework of current status of manufacturing resources. The information is cascaded upwards to the high level plan (i.e. MPS) via the closed loop feedback path which provides the vital automatic link between the finite scheduling (shop level scheduling) module and the MPS. This mechanism is simple where a single level BOM is used, since the MPS can contain a record of related works order number which is used to access and modify the requirement date.

7.2.5 Response to Changes to Top and Bottom Level Inputs

In addition, status changes lower in the system may upset assumptions or plans made at higher levels. In connection with such a phenomenon the control algorithm design ensures that sufficient link exists between levels to guarantee proper response to a status change occurring in any of the control levels (hierarchy). For example, changes in the status of manufacturing resources (e.g. machine breakdown) detected during the scheduling process, leads to automatic termination of scheduling process, freezes the capacity of the affected work centre over the breakdown period and triggers forward scheduling and the subsequent processes. On the other hand, the arrival of new incoming orders (i.e. top level inputs) lead to automatic termination of existing activities and invalidation of previously established schedule. New orders are pooled with the existing list of orders awaiting to be processed and the total capacity requirements are recomputed.

7.3 Hardware Requirements and Selection Criteria

The design and development aspects of the new control methodology also need to be considered from the prospective of hardware and software requirements, suitable for the implementation of the new cellular manufacturing control methodology. The following discussions highlight the basic hardware and software requirements.

The development and implementation of the new control methodology discussed above requires a number of basic hardware systems (computers, printers) as described below.

A 16 bit microprocessor, namely, any IBM XT or AT compatible computers (e.g. Apricot 286/386) preferably with colour monitor, either EGA or VGA system are adequate for the development of the system. Although, an IBM XT compatible computer could be used for the development and demonstration of the algorithm however, computers with a 386 processor and 25 MHz clock speed would provide a significant advantage in terms of processing speed.

A Random Access Memory (RAM) of 640 kilobytes is adequate to run the program, however, larger RAM would be an advantage because this would provide sufficient memory space to undertake program loading, execution, creation of dynamic database and the maintenance (storage) of data in the memory during program execution mode. In addition, large memory space would permit more data to be added into the memory during the execution of the program. It would also facilitate the development or expansion of the program (source code) and execution of functional modules which involve massive computation. Large memory space would be an advantage because this permits the addition of new functional modules and data files to existing program.

A 5 MB (Mega Byte) hard disk space is more than adequate to instal and run the program. The hard disk storage system enables files to be stored permanently for use during program execution and provides a practical database management system because the disk space is much larger than memory space and therefore more data can be stored in the disk than in the memory. Disk based databases are also extremely useful for almost all large database applications. This facilitates database expansion, especially as this grows larger and becomes more complex to operate. Although programs can be run in a stand-alone mode under the Disk Operating System (DOS) and without the application program, this requires executable files which are normally larger in size compared with the source codes. This often requires a much larger disk storage space and the use of hard disk will therefore be an ideal choice under such circumstances.

A simple dot matrix printer would enable the listing of programs (source codes) however, quality of print-out depends very much on the type of printers used. For example, a laser or liquid crystal printer will provide better quality program listing as compared with an equivalent dot matrix printer. So, if quality and speed of printing are the major criteria, then the type or nature of device used is critical.

7.4 Software (Application Program) Considerations

The software system referred to in the following discussions would incorporate computer operating system, programming language and other supporting software tools which are essential and critical for the development, implementation and demonstration of the algorithm.

7.4.1 Operating System (OS)

The common choice of operating system for many micro-computers is currently MS-DOS or PC-DOS. The Micro-Soft Disk Operating System (MS-DOS) is the registered trademark of Microsoft Corporation and it is one of the most commonly used disk operating system which can be implemented on all IBM compatible computers. A major advantage of using MS-DOS is that it supports hierarchically structured directories which are also known as 'tree' structured directories. Programming languages, such as Turbo Prolog are designed to operate under such an operating system.

In addition, the operating system based on MS-DOS supports good networking facilities and this is particularly important if the application program is to be implemented in a cascaded cellular manufacturing environment where the medium of communication is via the Local Area Network (LAN). It supports multi-user systems and provides good disk file directory handling (supports the hierarchy of directories) and enables files (programs or DOS utilities) to be stored in sub-directories that is related to the file (function) and provides easy access to all the files and directories.

7.4.2 Programming Language Requirements

Successful development and implementation of the application program to demonstrate the concept postulated in this thesis is to a large extent dependent on the efficiency of the programming language. The selection of a suitable language is of paramount importance in the development of the prototype model. The basic requirements of such a language are described below.

A good programming language is one that is highly flexible in terms of program development for different applications, so that the development, modification and expansion of the program can be undertaken easily. This would permit different features or functions to be incorporated or embedded into the application program without much difficulty. A programming language which is portable would provide better advantage, because it can be run on a wide range of (IBM) compatible computers, provided they meet the relevant hardware requirements.

It is also important that the programming language is able to provide good data handling facilities so that information can be processed faster and with great accuracy. This would provide an improved information processing mechanism, thus enhancing the prospect of providing fast response to input data. This would also enable large data processing with less computer time and lower cost.

It is essential that the programming language supports different data formats in order that files can be read in and out of individual module with great ease and the matching of the common denominator within the file or record can be easily facilitated. It is also important that the prospective programming language permits easy editing so that program modification, editing and expansion can be undertaken within the source code mode; this would make the application program more transparent to the user or programmer.

A programming language which supports good database system would be essential so that data can be processed or retrieved more rapidly and effectively. Similarly, this would also assure high data accuracy and integrity. Incorporation of good window facilities would be essential in order that various aspects of the main program could be run in different windows. This would also enable specific aspect of the application program to be viewed in isolation and in each window, thus permitting fast analysis and diagnosis of program structure.

The incorporation of good tracing facility would be an advantage since this would allow programs to be debugged more easily and every logical steps of the program or software execution could be easily traced. This would also allow programs to be diagnosed in isolation from the main part of the core program. Provision of a good inference mechanism is important because this would permit the development of simple program structure. In the context of manufacturing control, this would improve handling of conflict resolution and permits consistent conclusions (inferences) to be drawn in response to changes in manufacturing status.

Modularity is an important aspect of program development and therefore a programming language that supports modular structure would be an advantage since this would permit programs to be broken down into simple functional modules. This would also allow programs to be edited, compiled and linked together to create a single executable program. Modular programming would allow different modules to use the same predicate and domain names in different ways and hence, enhance the overall structure and operation of the program.

7.4.3 Popular Programming Languages

A number of different programming languages, namely, Turbo Basic (TBASIC), Turbo Pascal (TPASCAL) and Fortran were evaluated and most of them were not particularly suitable for the development of the manufacturing control application program due to the limitations inherent in such languages.

Traditional procedural languages such as Basic, Fortran, Pascal etc., have been commonly used to implement application programs. While the efficiency of such implementations is largely acknowledged, they cannot adequately satisfy many of the other essential requirements, namely, transparency, modularity and flexibility [Giorgio Bruno, et. al 1986]. For example, in procedural languages, the knowledge representation is normally embedded in the program's control flow and therefore, the process of updating programs in order to account for modifications in the control policy could be a very tedious task [Bel,G. et.al 1986]. Similarly, adding, deleting and updating the knowledge (i.e. control knowledge) is time consuming even for a skilled programmer [Giorgio, Bruno].

7.4.4 Turbo Prolog as a Programming Language

The application program used to demonstrate the new manufacturing control concept was developed with Turbo Prolog as the implementing language. This is due to its ability to provide significant advantages from the prospective of program development and implementation of the prototype manufacturing control methodology. The main reasons for selecting Turbo Prolog as the programming language are described in the subsequent discussions.

Turbo Prolog is a logical programming language suitable for general problem solving applications, handling dynamic databases, natural language processing and general problem solving using the structured representation scheme. It is suitable for the implementation of knowledge (rule) based manufacturing control system which has been strongly advocated in the development of the application program.

It provides good facilities for producing powerful application programs with multiple windows, interactive input and output facilities and colourful graphics. These features are useful for the development and implementation of interactive and user friendly programs.

Turbo Prolog is a compiled language and therefore it provides fast compilation of source codes (fastest among all the Prolog implementations available for the IBM personal computers). It supports stand-alone executable program which can be run under MS-DOS environment without the main application language. The execution of program under this mode requires less memory space and this improves the speed and efficiency of the application program.

In addition, Turbo Prolog provides a good user interface which is useful for the development and implementation of the application program. Its declarative aspect (feature) enables the user to analyse the effects and outcomes of certain logic and improves the efficiency of softwares. Its powerful internal unification routines enable relentless search through all possible combinations of the relevant rules in attempting to satisfy the goal set by the programmer. This simplifies the programming task and enables the programmer to spend more time/effort on developing the algorithm.

It offers the advantages of modularity and flexibility since the data, knowledge and control elements are segregated. This encourages structured development by step wise refinement that incrementally adds and verifies new features and constraints. This also enhances the prospect of broadening the scope of the control system and permits rapid prototyping. Furthermore, it permits heuristic knowledge to be easily incorporated in the form of behavioural rules that encompass the quantitative and qualitative aspects of decision making. In addition, it allows each program module to be operated on a stand-alone basis and in executable form. This also enables individual program to be debugged and diagnosed independent of other program modules.

Turbo Prolog also provides good graphical facilities which permit program inputs and outputs to be presented in graphical form. This is particularly useful in the graphical representation of work centre load profile over the planning horizon, capacity requirements at different processing centres, work pattern distribution etc.

It provides good tracing facility, where every logical step of program flow can be easily followed and debugged. The short trace facility incorporated in Turbo Prolog enables the programmer to run and debug smaller sections of the main program, whereas the built-in interactive editor enhances the development of powerful software system or program. This enables fast editing of programs and data files in interactive mode. It supports a wide range of powerful routines which are available in the form of toolbox options and this provides the programmer or user with a wide range of facilities, namely, pull down menus, screen layout control, graphical routines, interfacing with other languages, natural language processing etc.

The inference mechanism embedded in Turbo Prolog supports powerful reasoning and program control functions. This allows control knowledge to be represented in the form of rules and facts and thus, programs can be configured easily by only modifying the rules of the particular module without affecting the main and other programs. The built-in inference mechanism frees the programmer from the control aspect of programming and allows more effort to be concentrated almost entirely on the logic design of the application program [Weber, D.M. et.al 1989]. Turbo Prolog supports knowledge representation using production rules technique and this is useful for the development of application programs based on rule-based concept. It allows control rules to be more easily stored, removed and modified during the design process [Bel,G. et. al 1986].

For these reasons Turbo Prolog was used in the development of the prototype system which is described in the subsequent chapter.

CHAPTER 8

Description of the Cellular Manufacturing Control Model

This chapter discusses the basic architecture of the cellular manufacturing control model and provides a detailed overview of the operational aspect of the relevant application program and its implications on cellular manufacturing control.

8.1 Objective of the Application Program [cocMacs]

The main objective of developing the application program, entitled COmputerised Cellular MAnufacturing Control System (cocMacs) is two fold in nature, namely :-

- to develop a prototype model of the cellular manufacturing control system based on the concept postulated in this thesis, and

- to demonstrate the operational logic of the cellular manufacturing control methodology.

8.2 The Architecture of the Cellular Manufacturing Control Model

As shown in Figure 13, the prototype cellular manufacturing control model is composed of four main elements, namely :-

- the user interface ;
- the data acquisition module ;
- the knowledge base, and
- the control module.

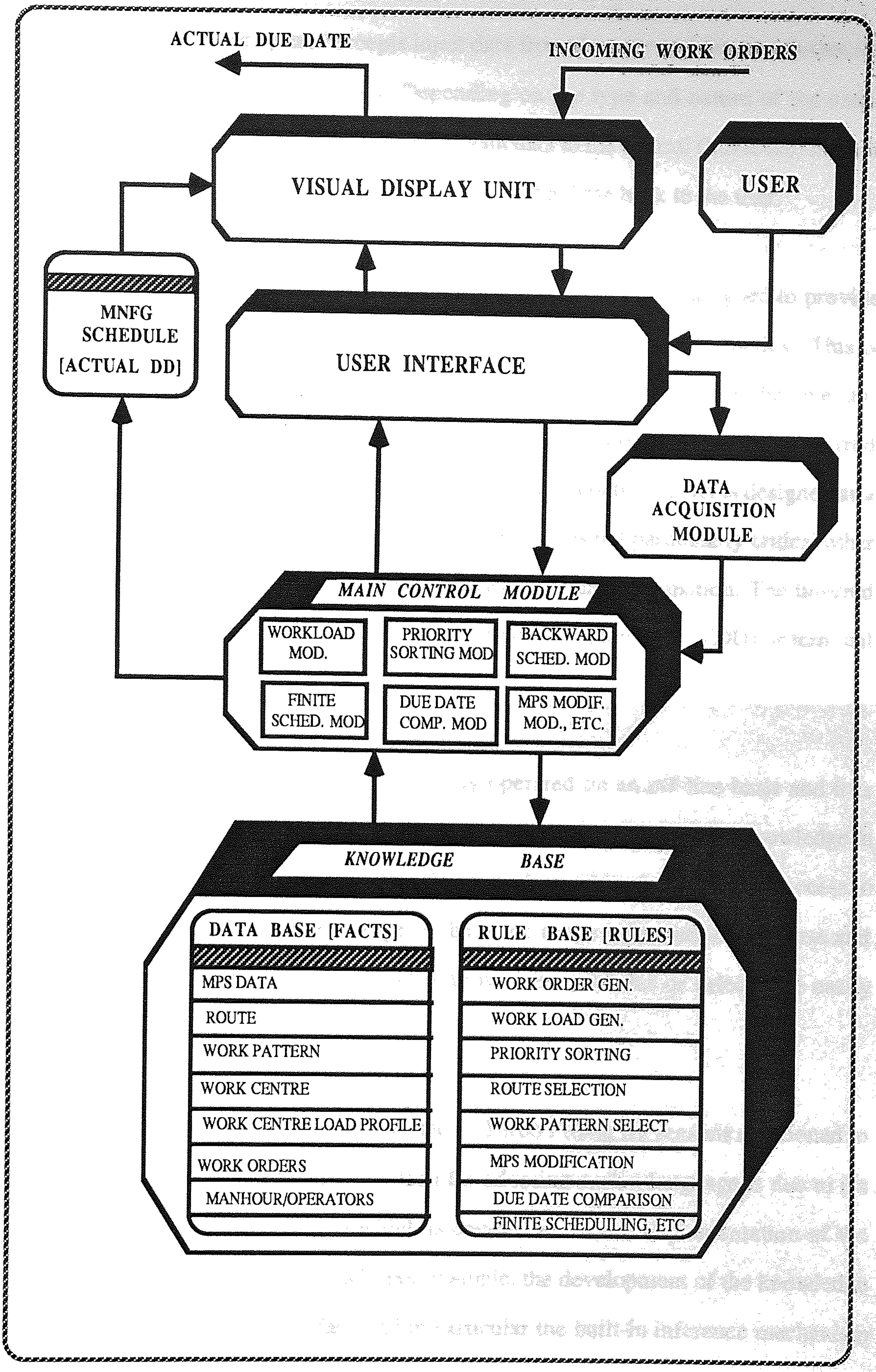


FIGURE 13 ARCHITECTURE OF THE [K.B] CELLULAR MANUFACTURING CONTROL SYSTEM

The user-interface system accepts input data from the user and communicates the inferred information back to the user. Depending on the type and nature of the user's input , the user interface communicates the relevant data to the control (inference) module and passes the inferred information from the knowledge base back to the user.

In the context of manufacturing control, the user interface is designed to provide features such as menu system for the selection of different work order modes. This is then communicated to the control module which selects and applies the relevant production rules to generate a practical solution and communicates the inferred information (or solution) back to the user. Since the cell control model is designed as a fully automated system, the function of the user interface is not particularly critical other than for the incorporation of new control knowledge or data acquisition. The inferred information is communicated to the user via the Visual Display Unit (VDU) or terminal or by means of an on-line printer.

The data acquisition module is generally operated on an off-line basis and it is mainly used for editing, appending or displaying the files of the declarative knowledge in the form of facts on specific domain of application. It provides the user direct access to the knowledge base and permits changes to be made to the information (database and rules) held in the knowledge base. It also allows new modules or rules to be easily accommodated into the system.

The prototype model was implemented in Turbo Prolog for reasons mentioned in the previous chapter, however, a key reason for adopting such a language is due to it's ability to provide an environment which is conducive for the implementation of the cellular manufacturing control model. For example, the development of the knowledge base (facts and rules), user interface and in particular the built-in inference mechanism can be easily accommodated in Turbo Prolog.

The knowledge based control system is the heart of the cellular manufacturing control model and its application enables the cell control system to manage situations that would normally require the worker's or scheduler's experience. In this context, the cell control model was built to include scheduler's experience and problem handling ability, monitoring, intervening and decision making capability. This enhances the control models ability to undertake automatic decision making and handle abnormalities (e.g. work station breakdown) of cell's operations using computer control.

As shown in Figure 13, the knowledge base is the central part of the cellular manufacturing control model and it consists of two main elements, namely, the factual knowledge and the procedural rules (control knowledge) which govern the scheduling and control tasks within the cell. The facts are represented in Turbo Prolog in the form of first order predicate logic and these reflect all the essential information on parts and the manufacturing resources needed to manufacture them. This part of the control model is made up of a two-parts data base, namely :-

- static data base, and
- dynamic data base.

The key facts or information held in the static data base can be classified as follows :-

- part routing ;
- work patterns;
- work centre data ;
- work orders ;
- work centre load profile ;
- operator data, and
- Master Production Schedule data etc.

The facts stored in this part of the data base are easily accessible to the control structure or module and the relevant information extracted from it, is used by the control structure (built-in inference mechanism) and other interface programs. The dynamic data base is generated while a session (i.e. execution) is being run by a user. This maintains data acquired from the user or deduced by the application program (cocMacs) during a consultation (program execution). This information is either maintained in the memory during program execution or it is stored in a disk file. Examples of the facts (static data base) relevant to some aspects of the cellular manufacturing control model are described below.

work order(Wo_no,P_name,P_no,Qty,O_date,I_date,D_date) ;
route(R,P_no,Id,Seq,Op_code,Wc_no,Lab,Set,Opt), and
work pattern(Wp_no,D,Wh_hr).

The first fact " work order " stores all the information related to a particular work order and the arguments represent the key information related to the work order. For example, the first argument describes the work order number followed by the part name, part number, quantity, ordered date, issued date, required due date. The second fact "route" maintains all the relevant information associated with the parts routing; the first argument specifies the route number followed by the part number etc. The third fact "work pattern" prescribes work pattern number, working day and working hours. Some of these information are used in the calculation of the capacity required by each part at different work centres.

The second major component of the knowledge base is the domain specific problem solving strategy which are represented in the form of rules which provide the required control function. It is designed to solve the problems that occur in a typical manufacturing cell. It contains the knowledge about scheduling and control aspects in the form of production rules. A production-rule base scheme has been used to represent the knowledge groups in the application program (cocMacs). The knowledge groups can be classified as work centre knowledge, part knowledge, cell status knowledge etc.

Examples of these rules are as follows :-

- capacity requirement generation ;
- process time-summation ;
- minutes-hours-days conversion ;
- latest start date sorting ;
- slack computation ;
- just-on-time job sorting ;
- work centre freezing ;
- priority sorting ;
- route selection ;
- work pattern selection ;
- backward scheduling (based on finite scheduling) ;
- forward scheduling (base on finite scheduling) ;
- operator assignment ;
- bottleneck sorting/resolution ;
- work centre breakdown ;
- incoming customer order ;
- work centre configuration ;
- due date comparison, and
- MPS modification rules etc.

A detailed overview of the factual knowledge (database) and (control knowledge) key control rules applied in the knowledge based cellular manufacturing control model are discussed in the later part of this chapter.

As shown in Figure 13, the control module is the 'brain' of the cellular manufacturing control model. The process of inferencing was performed by means of searching and pattern matching. In Turbo Prolog, which is the implementing language of the cell control model, these tasks are performed by the internal unification routines and this is therefore implicit within the programming language and hence the programmer or user is only required to describe the relevant information to Turbo Prolog so that it can carry out all the other related tasks.

In the prototype cellular manufacturing control model, the control module or also commonly known as the control structure or rule interpreter or inference engine, contains the rules to control the steps required to solve the problem by consulting the knowledge base and in this context, it uses the 'IF<condition>THEN<action>' rules to form a line of reasoning. It decides the type of rule to be applied to arrive at an appropriate solution in solving a particular problem arising as a result of the changes in the status of the manufacturing resources (cell status), namely, work centre breakdown or new incoming orders. However, in most cases the searching process is regulated by means of appropriate heuristics which govern the searching process.

8.3 Discussion of Program Design Objectives and Features

The following discussions highlight the basic guidelines on critical aspects of the application program, namely, the basic specifications and requirements of the manufacturing control model, database, rule base, etc., which are critical for the execution of each and every functional module.

8.3.1 General Requirements of the Cellular Manufacturing Control Model

The application program is designed to provide key operational and control functions of the prototype control model. The fundamental requirements of the cellular manufacturing control model can be described as follows:-

- to provide effective interaction with the local database, rule base and other control modules so that data accessing and retrieval process can be easily facilitated; thus enabling smooth execution of specific scheduling and control functions; this enhances the prospect of instituting better interaction or communication of information between various modules ;

- to provide rapid response to changes in the status of manufacturing resources or new incoming orders so that these can be easily accommodated and reflected in the prospective production schedule ;

- to reschedule all jobs on detection of changes in the status of manufacturing resources; this encompasses the automatic invalidation of previously established production schedule and the generation of a new schedule which reflects the current status of manufacturing resources ;

- to represent each work centre individually so that capacity constraints can be easily identified and investigated in isolation from the other work centres; this facilitates the application of an appropriate policy (e.g. application of different route, work pattern options) that is required to resolve the particular bottleneck work centre problem ;

- to determine the dynamic capacity at each work centre, thus the resulting due date would therefore be based on the current status of manufacturing resources ; this enhances the prospect of establishing an accurate and realistic due date and MPS ;

- to undertake automatic evaluation of labour/operator constrains and resolve problems associated with operator assignment at a given work centre ;

- to provide effective database management system so that the control model can be supported by a simple, small and easily manageable database, which is local to the individual functional module and based on a single level Bills-Of-Material (BOM) structure; this permits easy and effective data accessing and retrieval and hence improves the data accuracy and integrity ; all functional modules within the system can therefore be driven with accurate and realistic data, and

- the control rules which govern the operation of the control model are designed to reflect the needs of individual module, hence providing greater flexibility in the modification and implementation of local policies and control functions to suit local needs; in reality this enhances the prospect of establishing a greater degree of accountability both at the individual module and cell level.

8.3.2 General Specifications for the Database

The database is one of the key elements of the cellular manufacturing control model because it provides the essential data required to drive the entire manufacturing system and its role is therefore significant in the development and implementation of the cell control model. The major factors that need to be considered in the design of the database include:-

- the size of the actual database ;
- the organisation of the data elements, and
- the methods used in manipulating the database etc.

In addition, the database must be able to provide the following functions :-

- add data to the database ;
- delete data from the database, and
- retrieve and output data from the database etc.

The structure of the database system should facilitate effective transfer of data so that these can be analysed and processed rapidly and accurately. This improves the prospect of providing rapid response to changes in the status of manufacturing resources and decision making. Similarly , the standardisation of the input and output data formats enables effective retrieval and storage of data. As a result, it improves the communication between functional modules by providing better interactions between them.

The database is also designed to provide logical interaction with the main module so that execution of control functions can be undertaken in the most desirable sequence. This enables the manufacturing resource status or shopfloor scenario to be readily available to the scheduler and hence improve the opportunity of undertaking critical control functions, namely, the invalidation of previously established schedule or generation of new schedules.

As part of a broader manufacturing control objective, the database is designed to provide good logical interaction with the rule base , which is an independent entity of the knowledge base. This is designed to facilitate the application of relevant control rules to resolve the arising control problems and hence provides smooth handling of conflict resolutions. This improves the prospect of attaining an accurate and realistic control solutions for all the likely problem scenarios, either on a retrieval or generative mode.

8.3.3 General Specifications for the Rule Base

The main reason for using a rule based control technique is due to its ability to permit control and scheduling functions to be represented by a set of event driven activities which cooperate to solve the complex, ill structured problem of cellular manufacturing control. In addition, it is also suitable for scheduling purposes because this is one of the manufacturing functions which require a great deal of reasoning capabilities and expert knowledge.

Furthermore, a number of other factors were also considered in the design of the control rules, namely, the rules were developed to provide the best possible logical steps or procedures of executing a goal so that precise execution of each control function in response to an input data can be easily accommodated. In addition, these rules are also designed to reflect the needs of individual module and hence this facilitates the modification of these rules to suit local requirements. In essence, this provides greater flexibility in the design and implementation of local policies and to strengthen the implementation of modular concept which is a critical design feature of the application program.

8.4 A Detail Overview of Database System

The implementation of the application program (cocMacs) requires the preparation of essential input data files. Examples of key input files used in the application program are as follows :-

[i] Work Order File

The work order file contains static data on the specific work order, namely :-

- work order number ;
- part name ;
- part number ;
- quantity ordered;
- ordered date (i.e. the date on which the customer placed an order);
- issued date(i.e. the date on which the items were issued to the shopfloor),and
- required due date (i.e the customer specified due date).

[ii] Route File

The route file contains static data on the alternative process routes that may be used by each part number and these are specified in a standard format of one record per operation. The route file contains the following key information :-

- route number ;
- part number ;
- identification number ;
- sequence number ;
- operation code ;
- work centre number ;
- set-up time , and
- operation time.

[iii] Work Pattern File

The work pattern file contains static data on alternative patterns and it incorporates information related to working days and hours (shifts). Each record in the file contains the following information :-

- work pattern number arranged in ascending order ;
- working day (e.g. Monday, Tuesday, etc.), and
- working hours (e.g. 8, 9, 10, 11, 12 hours).

[iv] Master Production Schedule File

The Master Production Schedule (MPS) file contains static data on specific work orders, namely :-

- work order number ;

- customer's name ;
- part number ;
- required due date ;
- ordered date, and
- quantity ordered.

[v] Operator File

The operator file contains static data on the operator requirement, namely :-

- work centre number ;
- work pattern number , and
- number of operators allocated to the work centre.

8.5 A Detail Overview of the Rule-Base

Among the various knowledge representation methods, the rule-based concept is one of the most commonly used techniques in the field of manufacturing systems for reasons explained above. In the context of cellular manufacturing control, the rule base technique contains a set of rules local to individual program module which is designed to emulate the logical sequence applied in solving a particular problem scenario. It uses static and dynamic data to provide an appropriate solution to a particular problem. The relevant rules are invoked by 'forward chaining' technique in which the occurrence of an event, arising as a result of changes in the status of manufacturing resources (e.g. machine breakdown) or new incoming enquiries, triggers a search of relevant subset of the rule base (which is defined by the nature of event) to gather those rules whose conditional parts are satisfied.

The rules used in the application program are classified according to individual function. Examples of rules, paraphrased in structured English are described below :-

[i] Order Priority Sorting Rule

This rule serves to establish a priority to each and every work order (part) that is fed into the work order sorting module. The criteria used in the job ordering or prioritisation process is based on slack technique (discussed in Chapter 7) where the job with the most negative slack is given the first priority in the forward scheduling process. On the other hand, the criteria used for selecting jobs in the backward scheduling process is based on the earliest due date, which implies that the job with the earliest due date is scheduled first, unless it is specified otherwise.

Example of job priority sorting rule is presented below:-
Rule<name>
IF the slack (lateness) of part A100 is X ,
    and the slack of A100 is greater than the slack of part A200,
    and the slack of A100 is greater than the slack of part A300,
THEN set first priority to part A100.

[ii] Route Sorting Rule

The route sorting rule is designed to provide a variety route options which are used to achieve the required due date target as specified by the MPS. The implementation of different route options are specifically designed for resolving the capacity constraints at the bottleneck work centre. In circumstances, where all the route options have been attempted to achieve the required due date but still unable to achieve the targeted due date, then a new work pattern option is selected and the whole process is repeated.

Example of route selection rule:-
Rule<name>
IF the existing route number is X,

and the existing route number (X) is less than the maximum route number (M),

and the existing work pattern number(W) is less than the maximum work pattern number (K),

and the actual due date of part A100 is greater than its required due date,

THEN select the next route number option.

[iii] Work Pattern Sorting Rule

The work pattern sorting rule increments the work pattern from an initial number of one to a maximum of ten. This incorporates a wide range of shift and working day options. The process of incrementing the work pattern is carried out in an incremental and systematically controlled manner. The implementation of different work patterns are designed to resolve capacity problems at the bottleneck work centre. In situations, where all the route and work pattern options have been attempted but still unable to achieve the required due date, then the latter is set equal to the actual due date. The completion date (due date) is normally apparent at the end of the forward scheduling process.

Example of work pattern selection rule:-

Rule<name>

IF the route number option is at its maximum,

and the work pattern number is less than the maximum number of work patterns,

and the actual due date is greater than required due date,

THEN select the next work pattern number.

[iv] Operator Assignment Rule

The operator assignment rule is designed to assign operators to individual work centre so that a practical production schedule can be achieved. There are two distinct techniques (options) of operator assignment used in the application program, namely :-

[a] Total available against required manhours technique - in this option the failure to meet the required manhours target provides an option to recruit an equivalent number of manhours from other manufacturing cells.

[b] Total available against required operators technique - in this option, the failure to meet the required number of operators provides an option to recruit an equivalent number of operators from other manufacturing cells. The merits and demerits of these techniques are explained in Chapter 9.

Example of operator assignment and sorting rule, based on method 1:-

Rule<name>
IF the total available manhours are X,
    and the total required manhours are Z,
    and the total available manhours (X) are less than total required manhours (Z),
THEN net manhours requirement (W) is equal to X minus Z.

Rule<name>
IF the net manhours requirement are W,
    and net manhours requirement (W) are less than zero,
    and new net manhours requirement (Wnew)=W*(-1),
THEN recruit Wnew amount of manhours from other cell.

Example of operator assignment rule, based on method 2:-

Rule<name>
IF the total number of available operators are X,
    and the total number of required operators are Z,
    and the total number of available operators (X) is less than total number of

required operators (Z),

THEN net operator requirement (W) is equal to X minus Z.

Rule<name>

IF the net operator requirement is W,

and net operator requirement (W) is less than zero,

and new operator requirement (Wnew)=W*(-1),

THEN recruit (import) Wnew number of operators from other cell.

[v] Due Date Comparison Rule

The due date comparison rule compares the actual against required due date, at the end of each cycle (run) and this is performed in conjunction with a number of route and work pattern options used to resolve capacity problems at the bottleneck work centre. These options are designed to relieve the overload situation at the problematic work centre and this process therefore incorporates a number of iterations involving various combinations of above parameters.

Example of due date comparison rule:-

Rule1<name>

IF the actual due date of part A100 is greater than its required due date,

and the route number is less than the maximum available route option,

and the work pattern number is less than the maximum available work pattern option,

THEN select and apply the next route option on the bottleneck work centre and repeat the process.

Rule2<name>

IF the actual due date of part A100 is greater than its required due date, and the route number is greater than the maximum available route option,

and the work pattern number is less than the maximum work pattern option,

THEN select the next work pattern option at the bottleneck work centre, reinitialise route and repeat the process.

[vi] MPS Modification Rule

The MPS modification rule is designed to modify the due date and MPS when all the route, work pattern and other options have been attempted but failed to achieve the required due date specified by the MPS. Under such circumstances, the required due date is made equal to actual due date.

Example of due date or MPS modification rule:-

Rule1<name>
IF the work pattern number is greater than the maximum available work pattern options,
and the route number is greater than the maximum available route options,
and the actual due date is greater than required due date,
THEN set the new (required) due date equals actual due date.

Rule2<name>
IF the work pattern number is less than X,
and the route number is less than Z,
and the actual due date is less than required due date,
THEN make the new due date equals the required due date.

[vii] Work Centre Breakdown Sorting Rule

This rule specifies the nature of the breakdown which includes the relevant work centre number, time of breakdown, etc. Under such circumstances, the capacity of the affected work centre is frozen automatically over the breakdown period and this also invalidates the previously established production schedule. The breakdown of a work centre also triggers a chain reaction which eventually leads to rescheduling of all the relevant program modules (as discussed in the later part of this chapter).

Example of machine breakdown sorting rule:-

Rule<name>

IF a machine or work centre breakdown is detected,

and the work centre number is WCz,

and the day or time of breakdown is Td,

THEN terminate all scheduling activities and freeze capacity of the affected work centre over the breakdown period.

[viii]Bottleneck Sorting Rule

This rule serves to identify the bottleneck work centre and its capacity status at the end of each cycle (run). The capacity constrains at the bottleneck work centre is resolved by applying a number of route and work pattern options. The identification of the bottleneck work centre involves a number of calculations, that is, netting off the total available from total required capacity over the scheduling horizon. The work centre with the least capacity represents the potential bottleneck work centre.

Example of bottleneck sorting rule:-

Rule<name>

IF the total available capacity of work centre WC1 over the scheduling horizon (S) is X,

and the total capacity requirement at WC1 over the scheduling horizon (S) is Z,

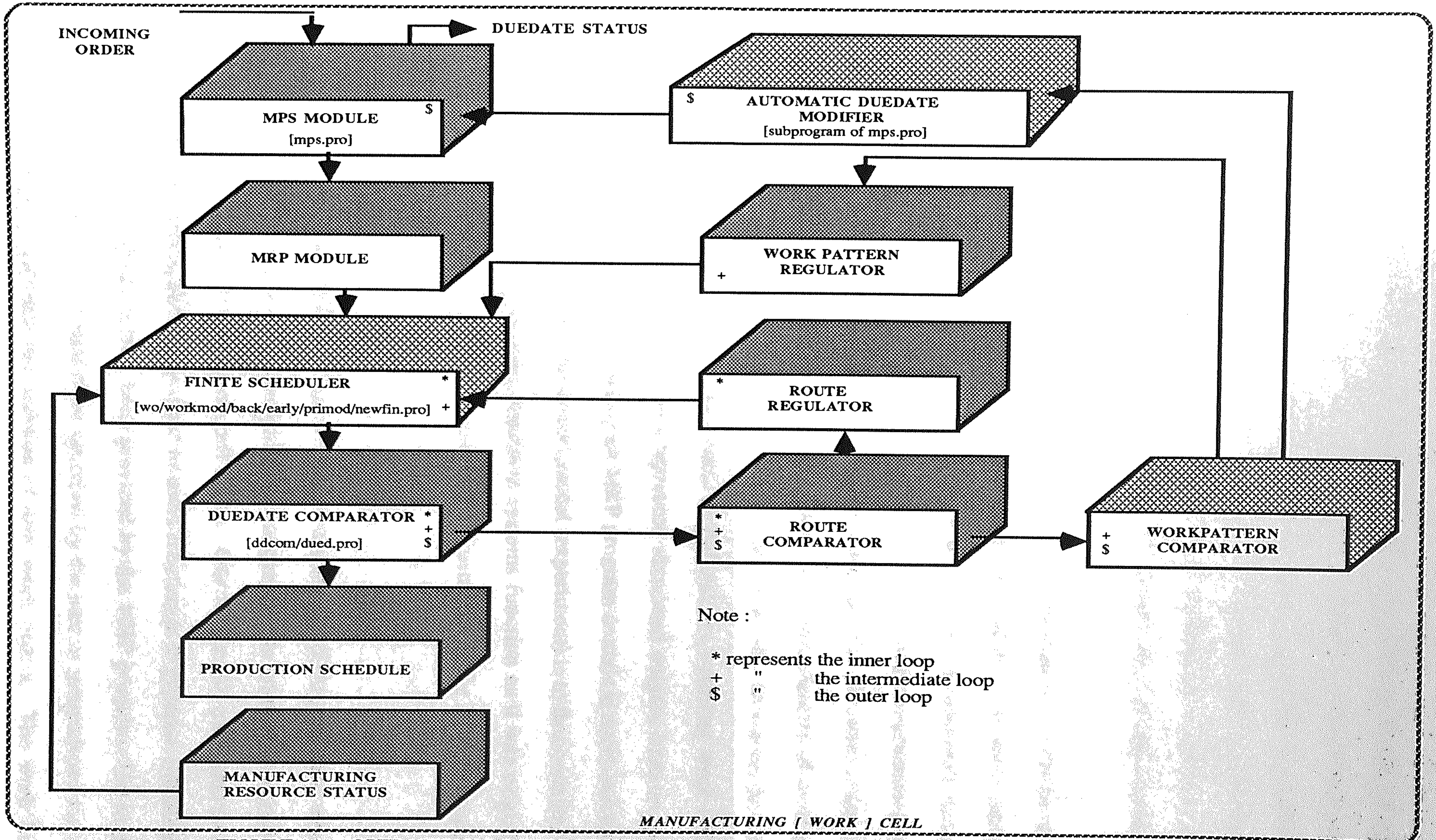
and the net (free) capacity at WC1 over the scheduling horizon is J (i.e.J=X-Z), and the net (free) capacity at WC1 is the least capacity compared with other work centres,

THEN WC1 is the potential bottleneck work centre.

8.6 Operational Aspect of the Control Methodology [Aspect of Application Program]

The prospect of implementing a dynamic manufacturing control system depends very much on the ability of each and every module to provide cohesive and coherent control functions. In this context, each module is designed to perform a specific function which is unique in its own right but it also interacts with other modules in order to achieve the main or global objective. A schematic view of the cellular manufacturing control methodology is illustrated in Figure 14A. The operational logic of the cellular manufacturing control application program is described below.

The first program module in the hierarchy of the control program modules is represented by the Master Production Schedule (mps.pro) and it is driven by incoming orders originating from the assembly or other manufacturing cell. It maintains a list of customer orders which describes the details of the particular order and this includes the customer specified due date. The program is designed to undertake dual role, namely, to maintain a list of existing orders in its original form and a version of the same orders in the new or modified form. Its main function is to provide automatic modification of MPS based on the current status of manufacturing resources. This is last task which the cell control model performs and hence it is normally executed towards the end of all the relevant program modules. The decision to modify the MPS is made when the actual due date is greater than the required, despite having attempted all the route and work pattern options. In such circumstances, the actual due date reflected by the scheduler, which is evident at the end of the program (complete run) becomes the legitimate due date.



Note :

* represents the inner loop
\+ " the intermediate loop
$ " the outer loop

FIGURE 14A OPERATIONAL LOGIC OF THE CELLULAR MANUFACTURING CONTROL METHODOLOGY

As discussed in Chapter 7, the MRP II mechanism used in the model does not incorporate a built-in Rough Cut Capacity Planning (RCCP) process because the automated DMRP concept permits a full MRP calculation to be performed quickly and hence there is no need for such a mechanism. In addition, the cell control methodology is based on finite scheduling and current status of manufacturing resources. It is therefore capable of generating accurate and realistic production schedule and due date.

The Material Requirements Planning (MRP) program module is suppose to be the second key module in the hierarchy of control program modules. Its main input is derived from the MPS output and its main function is to undertake requirements planning by utilising local Bills-Of-Material (BOM), inventory and standard manufacturing lead time of parts, etc. It generates three main output files, namely, purchase orders for parts, local work orders which is used for authorising local manufacture of parts and orders for parts that are sub-contracted to other manufacturing cells. However, the MRP system was not incorporated in the cell control model and the incoming work orders referred to in this chapter/thesis, therefore represent simulated outputs from an MRP system. The main reason for not including an MRP program module is attributed to the fact that the main objective of the cell control model (experiment) is to demonstrate that the MPS generator and the automatic feedback systems function as it was originally intended. So the role of the MRP mechanism in the illustration of the above concept is not critical.

In the next hierarchical level is the finite scheduling (CRP) module which encompasses a number of sub-programs which are invoked in the order determined by the supervisory program and the current cell status. One of the sub-programs is the work order generation program (wo.pro) and its main function is to generate (simulated) work orders that are suppose to have been provided by the MRP program. The actual work orders used in the control model are specified by the user or programmer via the user interface, which facilitates the addition of new work orders. The work load generation program (workmod.pro) is the next sub-program and its main input is the simulated work order mentioned above. Using the route file, it generates the total capacity requirements of parts at different work centres. The capacity requirements file is then used to drive the backward scheduling program (back.pro), which is the next sub-program within the finite scheduling module. Its main function is to backward schedule all jobs from the required due date, starting with the last operation first and followed by the subsequent operations. The criteria used to select the order of jobs to be processed is based on the earliest due date rule (illustrated in chapter 7). An overview of the cell scheduling mechanism is illustrated in Figure 14B.

The backward scheduling program (back.pro) generates the actual start and finish time (date) for each part at each work centre starting from the specified due date and loads the processing time requirements against each work centre by proceeding backward in time. If the relevant work centre is not available on the specified due date, then the program scans the work centre load profile file and allocates the job to the relevant work centre on the next available date. The backward scheduling process is undertaken against the background of existing work centre load profile. In reality, it provides an indication of the true status of each job, that is, whether it is ahead, behind or on schedule.

Jobs which can be produced on-time or early are segregated from the list of backward scheduled jobs by the on-time job sorting sub-program (early.pro) which is embedded in the finite scheduling module. It generates an output file which contains the relevant information on those jobs that can be produced on time or early. These jobs are not considered in the forward scheduling process but the work centres which process these parts are frozen for a period equivalent to the processing time required by each part at each work centre, so that none of the other (late) jobs can utilise them. The remaining are the late jobs and these are processed by the priority sorting program.

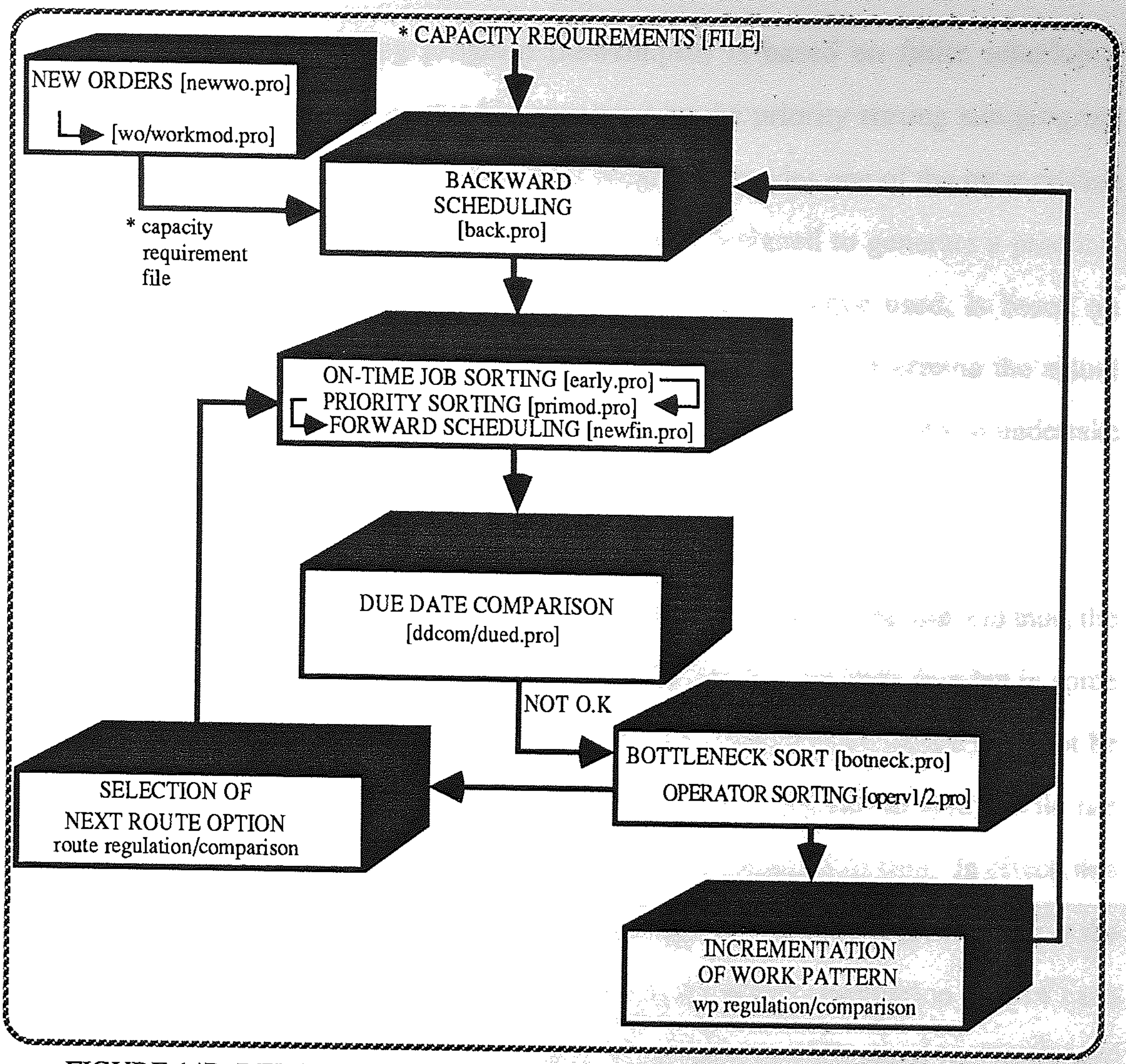


FIGURE 14B DETAIL OVERVIEW OF THE CELL SCHEDULING MECHANISM

As shown in Figure 14B, the main input to the priority sorting program (primod.pro) originates from the backward scheduling module. Its main function is to determine the priority of each job, based on the technique described in Chapter 7 and this excludes all the on-time/early jobs discarded earlier. The job with the most negative slack is given the first priority in the forward scheduling process, followed by the job with the next most negative slack and so on. This program generates an output file that specifies the priority (job loading sequence) of each job and the actual start date. These parameters are determined against the background of the existing work centre load profile and based on the current status of manufacturing resources and therefore the resulting due date is potentially accurate and realistic.

The forward scheduling program (newfin.pro) is based on finite scheduling technique and it is driven by output file generated by the priority sorting sub-program and this excludes all on-time/early jobs. This program provides one of the most critical control functions, that is, forward scheduling of jobs designed to generate a practical completion or due date and production schedule. The technique used, is based on accumulating the processing time against each work centre. To determine the actual completion date (due date) of a part, the program uses the prioritised jobs to undertake scheduling against the background of current work centre load profile.

The jobs scheduled by the above program module are considered late and thus, the effective start date of each job commences on the current (i.e. "today") date but in some cases this may not be possible to achieve because the relevant work centre may not be available on that date. So the program scans through the work centre load profile file and allocates the job to the relevant work centre on the next available date. In effect, this program determines the practical start and finish dates/time for each and every job at the relevant work centres. In addition, it also provides the actual completion date of each job, which represents the legitimate due date. Generally, it is triggered by "top level" inputs arising from incoming work orders and "bottom level" inputs resulting from changes in the status of manufacturing resources.

The outputs from the forward scheduling program module drives the initial due date comparison program (ddcom.pro). This program does the initial comparison of the required against the actual due date. Its main function is to segregate those jobs that can be produced on time or early, as a result of the changes in the route or work pattern options. If the actual due date is greater than the required due date, then this information is stored in a file allocated for late jobs, otherwise it is maintained in a file meant for on-time/early jobs which are segregated from other jobs deemed late.

The input to the due date comparison and option manipulation program (dued.pro) is derived from the above program and this comprises all the late jobs. As illustrated in Figure 14 A, this program incorporates a number of key functions, namely :-

- due date comparison ;
- route comparison ;
- route regulation ;
- work pattern comparison, and
- work pattern regulation.

The key decisions taken at this stage depend on the status of various operational parameters, namely :-

- If the actual due date is greater than the required date but there are still remaining route options to be applied on the bottleneck work centre to resolve existing capacity constrains, then the next route option is selected.

- If the actual due date is greater than the required date and all the route options have been attempted, but there are still remaining work pattern options, then the next option is selected and applied at the relevant bottleneck work centre to resolve the existing capacity constrains. In effect, the work pattern incrementation is undertaken when two conditions are met, namely, the actual due date is greater than the required date and all the available route options have already been attempted.

- If the actual due date is less than the required date, then that job is ahead of schedule and it is therefore removed from the pool of jobs to be forward scheduled. Such a situation could occur as a result of using different route and work pattern options to resolve bottleneck work centre.

As shown in Figure 14B, the bottleneck sorting program module (botneck.pro) is specifically designed to identify bottleneck work centre (i.e.work centre with the least free capacity or greatest overload) and to resolve the capacity problems at the affected work centre using different route and work pattern options discussed in Chapter 7.

The operator sorting program module (shown in Figure 14B) is an auxiliary program which is specifically designed to assign and resolve operator constrains at the bottleneck work centre. The operator assignments adopted in the control model are based on manhours (operv1.pro) and operator (operv2.pro) techniques. The first program (operv1.pro) is based on the manhours technique and it uses the total required against total available manhours to determine the free manhours status . If the required manhours are greater than what is available, then an equivalent number of manhours, based on the difference between the required and available manhours are imported from other cells.

The second program (operv2.pro) is based on the actual number of available operators and therefore it uses the total number of required operators against total number of available operators to generate a practical production schedule. If the total number of operators required are greater than what is available, then an equivalent number of operators based on the difference between what is required and available are imported from other cells.

The merits and demerits of these techniques are influenced by a number of factors, for example, the first technique (operv1.pro) is relatively complex but it is a flexible and realistic technique. Its application can be easily justified and hence, it is commonly used in most manufacturing industries. The second technique (operv2.pro) is based on a rather crude and relatively rigid method. It is simple to use but difficult to justify and therefore not very commonly used. The problem of operator constrains (i.e. operator shortages) at the bottleneck work centre is resolved by importing an equivalent number of manhours or operators from other manufacturing cells.

Apart from the normal cell operations, the cellular manufacturing control model is also designed to cope with new incoming work orders (newwo.pro) and changes in the status of manufacturing resources (e.g. workstation breakdown). For example, when a new incoming work order (newwo.pro) is detected(as shown in Figure 14B), the cell control mechanism terminates the current activities (automatically) and invalidates the previously established production schedule. The scheduling process is started all over again, commencing with the work order generation program module (wo.pro).

As illustrated in Figure 14C, when a change in the status of manufacturing resources, namely, work centre breakdown (break.pro) is detected, the cell control mechanism terminates the existing production schedule ; freezes the capacity (work load profile) of affected work centre over the breakdown period using a work centre configuration program (newfig.pro) and then proceeds with rescheduling and the subsequent operations as described above.

A supervisory program (start.pro) governs the execution of the cell control programs. It controls the overall execution of the main and sub-program modules based on the current status of manufacturing resources. For example, if all the route and work pattern options have been attempted and the actual due date is still greater than the required due date, then depending on the cell status, this triggers the MPS modification program module. This is represented by the automatic due date modifier in Figure 14A and it is effectively a sub-program built in the MPS program module.

The process of MPS modification involves a number of iterations, involving various route and work pattern options. As illustrated in Figure 14 A, the route cycle (option) represents the inner loop; the work pattern constitutes the middle or intermediate loop and the MPS modification process forms the outer loop. The MPS modification program is triggered when the inner and intermediate loops fail to achieve the required or targeted due date.

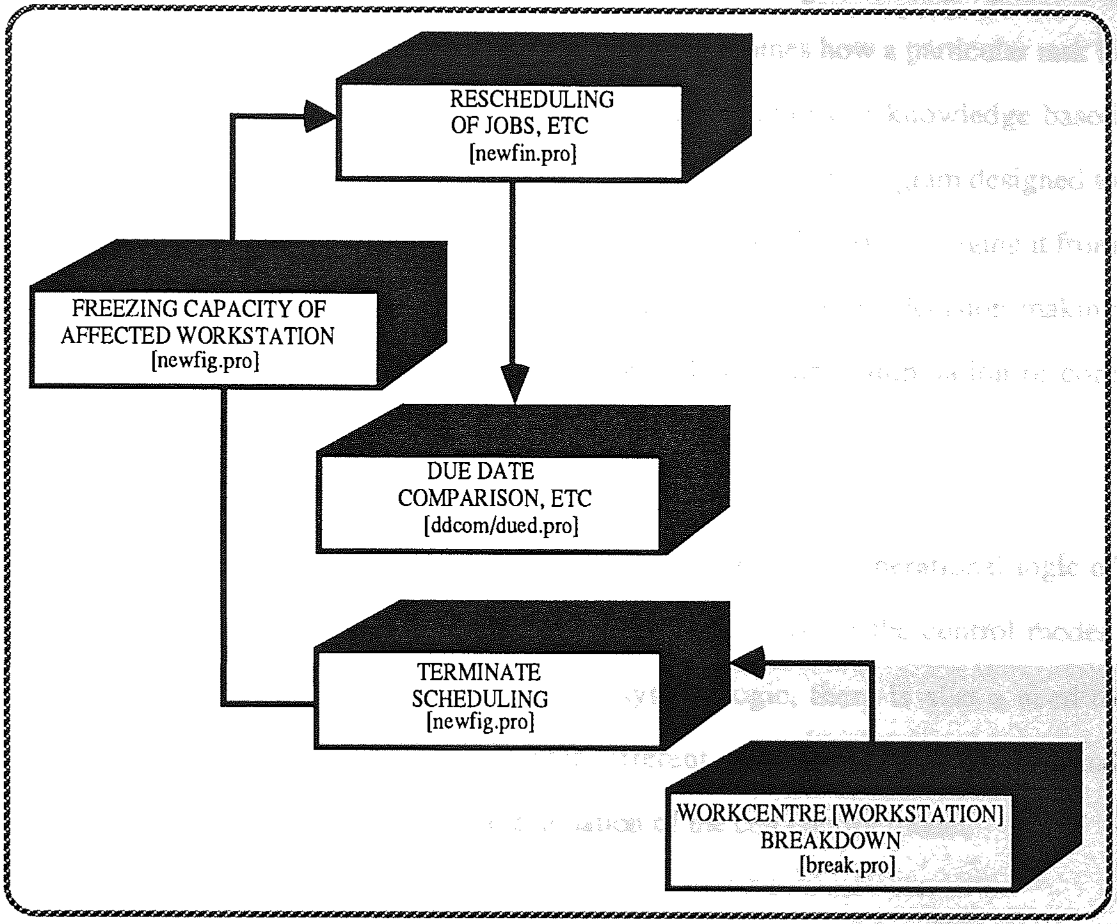


FIGURE 14C THE IMPACT OF CHANGES IN THE STATUS OF MNFG. RESOURCES

8.7 Program Output Results

The key input and output files related to the cellular manufacturing control model are illustrated in Appendices A and B respectively. These files are presented in numerical form, and are communicated to the user via the Visual Display Unit (VDU) or terminal. Although Turbo Prolog provides good graphical facilities, it was not fully utilised in the relevant application program, because it was not particularly important in the demonstration of the concept postulated in this thesis.

8.8 Concluding Remarks

A review of above discussions illustrate that the operation of the control methodology is critically dependent on how the core control algorithm is programmed, because every logical step in the application program determines how a particular task is to be executed. In addition, it also highlights the implications of knowledge based concept from a programming aspect. This enriches the application program designed to provide key control functions and enhances the cell control mechanism, changing it from operator to computer controlled but still maintaining the operator's decision making ability within the system and hence provides flexibility in the manipulation of core control algorithm.

The application program discussed so far, demonstrates the operational logic of the core control algorithm which governs the overall operation of the control model. However, in addition to the illustration of the system logic, there is also a need to evaluate the performance of the model under different manufacturing conditions and therefore this warrants further testing and evaluation of the cell control model.

CHAPTER 9

Testing and Evaluation of the New Manufacturing Control Model

9.1 Model Testing Objectives

As discussed in Chapter 1, the ultimate aim of the control system development is the automation of key operational aspects of the manufacturing control system. This would eliminate all major forms of human intervention in the management of such a system, in particular, in response to changes in the status of manufacturing environment or key inputs into the manufacturing system. In this context, changes in the status of manufacturing environment arise from disturbances on the shop floor (i.e. machine breakdown) whereas major inputs are derived from customer orders or enquiries. The ability to replan all its activities enables the system to deal with the dynamics of the manufacturing environment.

The evaluation of underlying principles of the control methodology entails testing of the model. Ideally to exhaustively test the concept postulated in this thesis, it would require an automated version of the DMRP system, preferably running in a simulated or real factory environment. This would facilitate the configuration of different shop floor scenarios and allow a very broad range of policy testing to be completed.

However, the most important aim of testing the model is to verify the key features of the control methodology, that is, automatic evaluation of capacity and due date constraints in response to changes in the status of manufacturing resources and incoming orders or enquiries. This can be achieved by concentrating on the MPS-MRP-CRP cycle which is simpler compared with the full DMRP tests mentioned above.

The DMRP mechanism (i.e. verification of core idea) has been tested previously in a simulated factory environment [Barekat, M 1989]. However, the system was based on a manual control technique and therefore, the evaluation of capacity and due date constraints and the modification of these parameters were undertaken by a human scheduler. Whereas, the testing of the model implied here is focussed on the core control algorithm within the cell. The test is therefore intended to illustrate the core control functions discussed above. In essence, the relevant tests should demonstrate the following :-

- The proposed control algorithm performs all the major functions originally intended, namely :-

    - provide automatic replanning in response to changes in the status of manufacturing resources, arising from top and bottom level inputs ;
    - provide automatic low level scheduling and high level planning ;
    - provide automation of MPS ;
    - provide dynamic load pegging and better traceability between downstream activities and high level plan , and
    - provide automatic resolution of capacity and labour constraints.

- The complete system would work successfully in automating the control loops discussed above. In this context, it is expected that the status of downstream activities (i.e. shopfloor to scheduler) can be cascaded upwards to the high level plan (i.e. MPS).

- The performance of the algorithm used in the prototype system is satisfactory and reasonable. Performance is referred to its ability to produce a reasonable due date or MPS as compared with other heuristic algorithms.

The first two objectives discussed above are served by an experimental programme which involves the development of a testbed in the form of an application program. This is used to conduct the testing and evaluation of the core control system methodology under different shopfloor scenarios. It is also used to emulate the key control functions of the control model in a DMRP environment. An extensive discussion of this aspect is presented in section 9.2. The last objective led to the need for a comparative study of the scheduling algorithm performance and this is described in great detail in section 9.4.

9.2 Experimental Programme

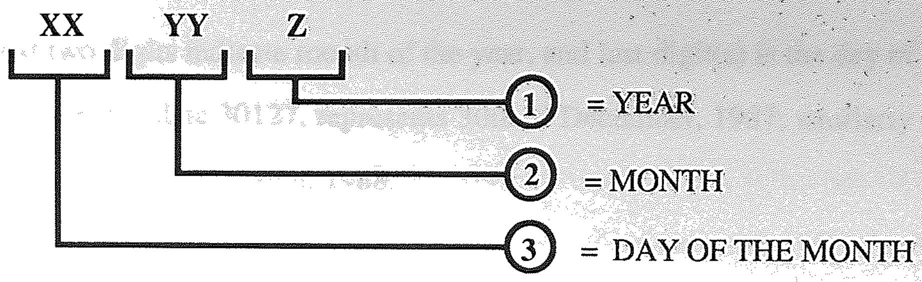
As part of the evaluation process, a comprehensive experimental programme needs to be formulated that would facilitate the relevant tests to be carried out in the most practical and realistic sequence. What is required is a set of guidelines which prescribe the basic test procedures necessary to undertake a comprehensive evaluation of the control model.

Briefly, the relevant tests were carried with two different sets of data, namely :-

- the first test involves a relatively large number of MPS data but smaller number of work patterns [refer to Appendix A, Table 1(i)], and
- the second test involves relatively smaller number of MPS data but large number of work patterns [refer to Appendix B, Table 2(i)]

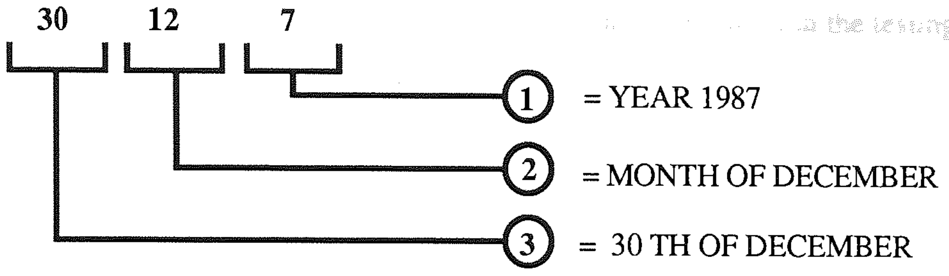
9.2.1 Basic Preparatory Procedures

The convention used in the representation of relevant dates in this experiment/thesis is illustrated in Figure 15. The first digit from extreme right represents



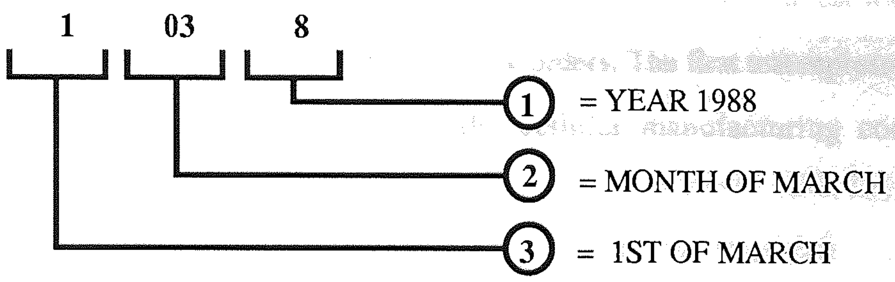
[i] Example 1

DATE =30127



[ii] Example 2

DATE = 1038



[iii] Example 3

DATE = 10039

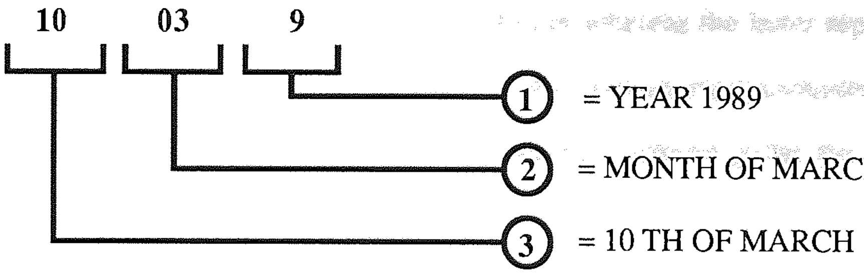


FIGURE 15 REPRESENTATION OF DATE

the year, the next two digits indicate month of the year, and last digit(s) is the day of the month. For example, the date 30127, represents 30th of December, 1987; similarly the date 1038 can be read as 1st of March, 1988.

The experimental process entails that prior to commencement of each test run, all the relevant input files are initialised and presented in the correct format so that all the functional modules can be driven more effectively. The key data files used in the testing of the prototype model are illustrated below :-

[i] Master Production Schedule

The MPS records vary according to the number of incoming customer orders. The relevant experiment was set up to incorporate a number of multiple work orders; the first test includes ten different MPS records and work orders whereas the second test was set up to accommodate four different MPS data and work orders. The first test represents a more vigourous analysis and evaluation of the cellular manufacturing control methodology.

The MPS file contains all the relevant information on incoming customer orders and in the relevant experiment , it has been classified under two main categories, namely, the original and updated MPS files. The main difference between these files is that the former is based on the due date specified by the customer whereas the latter represents the actual completion date based on the current status of manufacturing resources and it represents the practical and legitimate due date that can be achieved under the current circumstances.

The original MPS files used in Test Run 1 and 2 are illustrated in Appendix A [Table 1(i)] and Appendix B[Table 2(i)] respectively. Similarly, the updated MPS representing Test Run 1 and 2 are shown in Appendix A [Table 1(vii)] and Appendix

B[Table 2(iv)].

The number of MPS data used in the experiment has no major influence on the operational logic of the control methodology and therefore, this does not entail the use of large sets of data in the testing and evaluation of the model. As with other parameters (factors), a more extensive MPS would only serve to increase the program execution time.

[ii] Original Work Orders

A built-in user interface program allows dialog between the user and the system and permits the user to edit work orders and run the model in single or multiple work order modes. A single work order is a lot faster to process because it involves less data. The multiple work orders data file is very similar or identical in data structure to the above file with the exception that it contains more work orders. However, the actual experiment was carried out under multiple work order (and automatic) mode. The relevant work orders files are shown in Appendix A [Table 1(ii)] and Appendix B[Table 2 (ii)] respectively.

[iii] Work Centres

The work centres represent the various processing centres that undertake the actual manufacture of parts within the cell. A total of five different work centres, each representing five work stations were used in the experiment. The relevant information on each work centre used in the cell is stored in a static data file. This can be configured in editing mode and loaded into the memory whenever the need arises. The work centre file used in the cell is highlighted in Appendix A [Table 1(iii)].

[iv] Part Process Routes

The route file specifies the path through which a part starts and finishes all its operations before leaving the system. It provides essential information required to process a component, namely, set-up and operation times and other related data required to support the manufacture of a component.

A total of three different routes, representing a diverse range of sequences were used in the experiment. The decision to use only three routes is to minimise the complexity of the experiment, that is, to minimise the number of iterations, since large route options imply more iterations and hence longer execution time. Furthermore, the number of routes used are adequate to test the relevant part of the system logic although the number of options could be increased if that is deemed necessary.

The three route files used in the verification of the control methodology are illustrated in Appendix A [Table 1(iv)] and Appendix B [Table 2 (iii)]. These are static data files which are entered and maintained in the local database and loaded into the memory prior to commencement of the test run. The configuration of the route data can be undertaken off-line using the built-in editor incorporated in Turbo Prolog programming language.

[v] Work Patterns

The work patterns reflect the working days and hours, ranging from a standard eight hours (single shift) to a maximum of twenty four hours (three shifts). It incorporates a variety of overtime patterns and working days ranging from a minimum of five to a maximum of seven days. In reality, the work patterns are analogous to the shift systems used in most manufacturing industries.

A total of ten different work patterns were used in the testing of the cellular manufacturing control model. These are arranged in ascending order and are stored in a static database file which can be accessed by the user or programmer and configured in the editing mode. The number of work patterns used are adequate to test the operational logic of the control model. The relevant work pattern data which applies to both tests in the experiment is shown in Appendix A [Table 1(v)].

[vi] Operator Assignment

This file provides key information on the assignment of operators to a work centre corresponding to a particular work pattern. The actual number of operators allocated vary in accordance with the work pattern number and work centres. This information is used in the assignment of operators to various work centres, as discussed in Chapter 8. The relevant operator assignment data which applies to both tests is illustrated in Appendix A [Table 1(vi)].

[vii] Work Centre Load Profile

This represents the load profile at each work centre over the scheduling horizon and it was set up for a period of twenty weeks. This is a practical scheduling horizon for a typical cell system. However, if deemed necessary, the work centre load profile can be configured to include much longer scheduling horizon but this could result in a much larger database and a lengthy scheduling process.

The work centre load profile file is used to represent different work load scenarios at the various work centres. It offers the user or programmer greater flexibility in setting different work centre load profile and bottleneck scenarios which are essential to test the performance of the cellular manufacturing control model. It is a static file but once it is loaded into the memory during program execution, it can be considered as a dynamic file and it's status change from one run to the other.

[viii]Planning Calender

The planning calender is used primarily for configuring the working and non working days and to incorporate the initial work pattern for every work centre prior to commencement of the test run. It was set up for a planning horizon of twenty weeks with the prospect of extending it to a much longer scheduling horizon. However, the scheduling period referred above is adequate to test the performance of the cellular manufacturing control model. This does not pose serious problems on the utilisation of (RAM) memory and data storage. The calender is also used in the configuration of work centre load profile file, corresponding to a particular work pattern.

[ix] Work Centre Breakdown

The occurrence of work centre break down is a common phenomenon in any manufacturing environment and it's incorporation in the experiment is important in the evaluation of the control model. The actual experiment was designed to include a relatively small number of work centre break downs, partly to minimise the total run time required to test the model. Broadly defining the ultimate objective of the experiment is to test and verify the basic control algorithm and therefore the frequency of work centre breakdown is not particularly critical in this context.

The relevant information on work centre break down, namely, the work centre number and the day or time of occurrence of such an event is maintained in a static file which is triggered when the date and work centre prescribed in the work centre load profile file matches with those specified in the relevant break down file. It is stored in the database and loaded into the memory prior to program execution.

[x] New Incoming Work Orders

The injection of new incoming work orders are attributed to the arrival of new incoming customer orders which trigger the Material Requirements Planning (MRP) mechanism. Since the model was developed without an MRP system (discussed in Chapter 8), it is assumed that the work orders used in the experiment represent a simulated output of an MRP system. The experiment was set up to accommodate a small number of incoming work orders. Since the ultimate objective of the exercise is to test the logic of the control algorithm this does not warrant the use of large test data.

The information on incoming work orders are maintained in a file which specifies the part number, name, required quantity, due date and other related information. The format of this file is very similar to that of the original work order. It is invoked when the date in the scheduling horizon matches with that specified in the new incoming work order file.

9.2.2 Descriptions of Case Study

The actual experiment was designed to incorporate a wide range of operational scenarios, namely, multiple and new incoming work orders, work centre breakdown, operator shortages etc. The reason for incorporating these test conditions is to generate different shopfloor scenarios that would reflect the events which are predominant in a typical manufacturing environment and to highlight the practicality of the relevant tests and their implications on the cell control model.

9.3 Experimental Findings

The results of the experiment, discussed in the subsequent section can be classified under two main categories, namely :-

- the actual output of key modules which are presented in a tabular form (see section 9.3.1), and
- the run time required by individual module and the whole model (see section 9.3.2)

9.3.1 Main Output Results

9.3.1.1 Output Results of Test Run 1

All the key input and output files associated with Test Run 1 are illustrated in Appendix A [Table 1]. The first part of Table 1 indicates the key input files, whereas the subsequent part consists of key output files. All the files are accompanied by a brief explanatory note, which applies to both Test Run 1 and 2 respectively and this provides a brief description of various operational parameters used in the input and output files. The tables depicting relevant output files are listed below :-

Table 1 (vii) - Updated Master Production Schedule (MPS)
Table 1 (viii) - Capacity Requirements Data
Table 1 (ix) - Job Loading Sequence Report
Table 1 (x) - Detail Capacity Requirements Report
Table 1 (xi) - Manhours Status Report [First Technique]
Table 1 (xii) - Manhours Shortage Report [First Technique]
Table 1 (xiii) - Operator Status Report [Second Technique]
Table 1 (xiv) - Operator Shortage Report [Second Technique]
Table 1 (xv) - Total Capacity Status Over Scheduling Horizon
Table 1 (xvi) - Bottleneck Work Centre Report
Table 1 (xvii) - Backward Scheduling Results
Table 1 (xviii) - Forward Scheduling Results

A summary of the MPS results based upon Test Run 1 is illustrated in Table 3 whereas an extensive discussion of the results is elaborated in section 9.3.3.

9.3.1.2 Output Results of Test Run 2

All the key input and output files associated with Test Run 2 is illustrated in Appendix B [Table 2]. The first half of Table 2 are the main input files whereas the others represent key output files. The explanatory notes (on various operational parameters) used in Test Run 1 are also applicable to Test Run 2.

Table 2 (iv) - Updated Master Production Schedule (MPS)
Table 2 (v) - Capacity Requirements Data
Table 2 (vi) - Job Loading Sequence Report
Table 2 (vii) - Detail Capacity Requirements Report
Table 2 (viii) - Manhours Status Report [First Technique]
Table 2 (ix) - Manhours Shortage Report [First Technique]
Table 2 (x) - Operator Status Report [Second Technique]
Table 2 (xi) - Operator Shortage Report [Second Technique]
Table 2 (xii) - Total Capacity Status Over Scheduling Horizon
Table 2 (xiii) - Bottleneck Work Centre Report
Table 2 (xiv) - Backward Scheduling Report
Table 2 (xv) - Forward Scheduling Report

A summary of the results of Test Run 2 is illustrated in Table 4. An extensive discussion of these results are covered in section 9.3.3.

WORK ORDER NUMBER	CUSTOMER	PART NUMBER	QUANTITY ORDERED	ORDERED DATE	REQUIRED DUE DATE	ACTUAL DUE DATE	DAYS EARLY [+] LATE [-]
1	JOHNS	A100	100	30127	6038	12048	- 37
2	BOBBY	A200	100	30127	8038	3048	- 26
3	RINGO	A300	100	30127	10038	30038	- 20
4	ANDY	A400	100	30127	7038	3048	- 27
5	REGY	A500	50	30127	9038	31038	- 22
6	MAGIE	A600	50	30127	13038	30038	- 17
7	RIDLY	A700	50	30127	16038	29038	- 13
8	BUSH	A800	50	30127	17038	28038	- 11
9	HONDA	A900	50	30127	14038	29038	- 15
10	NICK	A999	50	30127	20038	27038	- 7

TABLE 3 SUMMARY OF MPS RESULTS OF TEST RUN 1

WORK ORDER NUMBER	CUSTOMER	PART NUMBER	QUANTITY ORDERED	ORDERED DATE	REQUIRED DUE DATE	ACTUAL DUE DATE	DAYS EARLY [+] LATE [-]
1	JOHNS	A100	100	30127	6038	5048	- 30
2	BOBBY	A200	100	30127	8038	27038	- 19
3	RINGO	A300	100	30127	10038	15038	- 5
4	ANDY	A400	100	30127	7038	28038	- 21

TABLE 4 SUMMARY OF MPS RESULTS OF TEST RUN 2

9.3.2 Supplementary Results Based on Run Time

The second category of results referred to above, is the run time of both individual and all the key program modules used in the cellular manufacturing control model. This provides a measure of the processing time required to complete an order under various shopfloor scenarios.

9.3.2.1 Run Time by Individual Module

The run time referred to in this exercise, is the approximate time required to process a given set of work orders through different modules. This varies with the number of input data, which includes all the supporting data required to drive the model. In effect, the run time is determined by a number of other factors as described in the subsequent discussion. A summary of run time by individual module related to Test Run 1 is shown in Table 5.

9.3.2.2 Total Run Time

The total run time referred to in this experiment is the actual time required to complete the test and it depends on a number of factors, namely :-

- number of work orders ;
- number of routes ;
- number of work patterns ;
- input/output files display mode (e.g. on/off-line display of files), and
- types of hardware used (e.g. IBM AT/XT).

MODULE	TIME [SECONDS]
WORK ORDER GENERATION	10
CAPACITY REQUREMENTS [WORK LOAD GENERATION]	15
BACKWARD SCHEDULING	20
ON-TIME JOB SORTING	25
PRIORITY SORTING	20
BOTTLENECK SORTING	20
OPERATOR SORTING	20
DUE DATE COMPARISON	30
NEW WORK ORDER SORTING	20
WORK PATTERN SORTING	30
WORK CENTRE LOAD PROFILE CONFIGURATION	20
FORWARD SCHEDULING	30
MASTER PRODUCTION SCHEDULING	30

TABLE 5 SUMMARY OF RUN TIME BY INDIVIDUAL MODULE

With reference to the operational logic diagram specified in Figure 14A (Chapter 8), the inner loop is represented by the three different routes whereas the outer loop comprises the ten different work patterns. Each work pattern is processed through three different routes and thus a complete test may constitute a total of thirty different loops, that is, total number of work patterns (10) multiplied by total number of routes (3).

The total run time in this experiment is also influenced by the on-line display of input and output files during program execution.

The total run time to complete each test run is as shown below :-

[i] Total Run Time of Test Run 1 = 20 minutes

[ii] Total run Time of Test Run 2 = 37 minutes

9.3.3 Discussions of Results Based on Test Run 1 and 2

The results of Test Run 1 and 2, confirm some of the critical and core aspects of the control methodology discussed in this thesis. For example, a summary of Test Run 1 and 2, illustrated in Table 3 and 4 respectively, indicate marked difference between the required and actual due dates and such a phenomenon is attributed to a number of factors, namely :-

- the initial work centre load profile ;
- the quality of the scheduler, and
- the setup and operation time used in individual route option.

The results suggest that process route is one of the major contributing factors to the presence of such a phenomenon and this is supported by the results shown in Appendix A [Table 1 (viii)] where the total capacity requirements of part A100 is 3800 minutes (i.e. summation of capacity requirements at individual work centre) is significantly higher compared with other parts. This suggests that the process route (e.g. operation time) has an influence on the work load profile and manufacturing lead time (i.e. completion or due date) since some routes could result in more parts being processed at a particular work centre than others, thus resulting in a bottleneck situation and long throughput or flow time. A practical solution to the problem is to use alternate routes which could avoid the bottleneck work centre at the expense of greater machining elsewhere but resulting in less total flow time through the system. The results demonstrate the importance of alternate routes concept and the need to advocate it in the new manufacturing control methodology.

On the other hand, the work centre load profile is also a major contributing factor that influences the final due date. Since the initial work centre load profile was setup to reflect heavy utilisation of processing centres, this resulted in jobs being completed behind schedule and this is reflected by the results shown in Appendix A [Table 1(xviii)]. For example, the start and end time/date of part A100 on WC 100 was 20038, but the start and end time/date of the subsequent operation on WC500, was 3048 and 5048 respectively, that is, it amounts to a delay of 14 days between subsequent operations. This is a clear manifestation of heavy utilisation of the particular work centre over the above period of time and as a result, the job was completed late. In this context, the control algorithm resolved the problem by using a combination of route and work pattern options on the bottleneck work centre. Results shown in Appendix A [Table 1(xviii)] and Appendix B [Table 2(xv)] prove the effect or implications of work centre load profile on completion or due date. As shown in the relevant table(s), the work pattern reflected at the bottleneck work centre is higher than others and this confirms the presence of heavy load profile (i.e. overloads) at the particular work centre.

Examination of the results shown in Tables 3 and 4 respectively, suggests that the order in which the jobs are processed is influenced by the job loading sequence. For example, in Test Run 1, Table 1(ix) confirms such a claim and the same argument can also be extended to Test Run 2. For instance, according to the job loading sequence results (Test Run 1), part A999 was loaded first and as expected, it was completed earlier than other parts. On the other hand, part A100 was started last and it was therefore completed later than all the others. The results demonstrate that the control algorithm functions as it was intended, that is, it is capable of determining job loading sequence and process all the jobs in the same order.

The effects of bottleneck work centre and the need to resolve such a problem was elaborated in Chapters 6 and 7 respectively. The control model's ability to identify transient and non transient bottleneck is manifested by the results indicated in Appendix A [Table 1 (xvi)] and Appendix B [Table 2(xiii)]. For example, in Test Run 1, the travelling bottleneck happened to be WC 600 ; this is also supported by the results highlighted in Table 1(xviii), where the work pattern used on WC 600 is higher than the others. This demonstrates the control algorithms ability to identify and resolve such problems using the route and work pattern options.

The significance and implications of the single level Bills-Of-Material (BOM) structure in enhancing the automation of MPS was discussed in Chapter 5 (Figure 10C). It was advocated that the single level BOM structure has the potential to provide better traceability between the shop level scheduling activities and relevant entries in the MPS. Results shown in Table 1(xviii) and Table 2(xv) demonstrate the control model's ability to exploit such a feature in establishing better links between top and bottom level activities. For example, Table 1(xviii) reflects the completion (due) date status of all parts at the end of the program (cycle) but these are identical to that reflected in the original MPS file shown in Table 1(i). As a result, it is much simpler to undertake load pegging and comparison of due date status under such an environment. This enhances the prospect of automating the MPS process.

As discussed in Chapter 7, it was stressed that the execution of a production schedule is dependent on the availability of adequate operators to execute such a plan. Results of Table 1(xii - xiv) and Table 2(xi - xiii) demonstrate that the cell control mechanism has the ability to undertake automatic evaluation of operator or labour constrains at the bottleneck work centre and to resolve the relevant problem using techniques discussed in Chapter 8.

The individual and total run times reflect the time duration required to process a given number of orders through various processing centres. The magnitude of run time, is influenced by a number of factors, namely :-

- the number of work orders to be processed ;
- the static and dynamic data size to be processed in order to generate the required due date, and
- the processing speed of the related computers.

The individual run time shown in Table 5 (applies to Test Run 1) whereas the total run time is illustrated above. The results reflect the effects of above parameters on the processing speed (run time). In this context, they are not attributed to the operational logic of the core cellular manufacturing control algorithm. The Total Run Time of Test Run 1 is less than Test Run 2, because the first test was carried out with small number of work patterns as compared with the second test.

The above discussions highlighted the main findings of the experimental program and it confirms the substance of earlier arguments presented in Chapters 3 till 8, which were used as the basis for the development of a new cellular manufacturing control model. Supplementary results on the performance of the model based on a comparative study is highlighted in section 9.4.

9.4 Discussion of Experimental Results Based on Comparative Studies

As part of the experimental process, there was a need to evaluate the quality of performance of the cellular manufacturing control model, in particular the effectiveness of the scheduler. A comparative study was therefore carried out involving a number of heuristic algorithms, namely :-

[i] Johnson's algorithm
[ii] Campbell's algorithm
[iii] Branch-and-Bound algorithm

It has been acknowledged that there is no single heuristic which consistently provides the best values for the performance measures over the entire range of either job or flow shop facility configuration. Articles by Baker, K.R [1974], Conway, R.W. et.al [1967], Elsayed, A.E et.al [1985] and Wild, R [1984] provide a comprehensive review of above algorithms and an insight into specific scheduling techniques. Among the variety of algorithms that have been used in job scheduling, the above represent some of the most commonly used algorithms.

9.4.1 A Comparison of Cell Scheduler (cocMacs) and Other Algorithms

Although the objective of the research is to develop a cellular manufacturing control methodology ; the quality of its performance is critically dependent on the scheduling mechanism. A comparative study was therefore initiated to evaluate the performance (quality) of the scheduler used in the cellular manufacturing control model with other algorithms, namely, Johnson's, Campbell's and Branch and Bound. The main reason for using these algorithms as the basis of comparison is due to their ability to generate an optimal load sequence. Hence, they are suitable for testing and comparing the effectiveness of the cell scheduler. The measure of performance used to evaluate these algorithms are based on the following parameters :-

- makespan (measured in terms of the due date);
- number of jobs produced late ;
- number of jobs early, and
- work centre utilisation (percentage).

The same test conditions were applied across all the algorithms and hence, the cell scheduler (algorithm) was therefore tested without its inherent capability which refers to selection of various route and work pattern options and it's ability to detect and segregate early from late jobs. These conditions impose serious restrictions on the flexibility of the core cell scheduling algorithm. Major findings and discussions of the comparative studies based on the above algorithms are highlighted in the subsequent sections.

9.4.1.1 Cell Scheduler (cocMacs) and Johnson's Algorithm

It is known that for M jobs to be processed by three work centres, Johnson's algorithm generates an optimal sequence and it's main objective is to minimise the makespan. Furthermore, there is no general solution for any problem of M jobs if the number of work centres are more than three [Lee, T 1988]. Johnson's rule works well for situations in which the same processing sequence must be maintained on both work centres and there are no over riding individual properties. This comparative study was therefore setup to reflect the constraints mentioned above. Johnson's algorithm for n jobs, two machines can be applied to n jobs, three machines and an optimal solution is obtained if either of the following conditions holds :-

$$\min t_{i1} >= \max t_{i2} \quad \text{------------} \ [9.1]$$

or

$$\min t_{i3} >= \max t_{i2} \quad \text{------------} \ [9.2]$$

where t_{ij} is defined as the processing time of job i on machine j, that is, if the minimum processing time of all jobs on either machine 1 or machine 3 is greater than or equal to the maximum processing time of all jobs on machine 2, then the three-machine, Johnson's algorithm applies.

The results of the relevant comparative study is illustrated in Table 6. A review of these results suggest that there is little difference between the performance of these algorithms. This implies that the performance of the cell scheduler is almost as good as Johnson's and thus, it has the potential to generate optimal sequence. The main reason for the early delivery of one of the jobs is due to the severe conditions (as discussed above) imposed on the cell scheduler algorithm. Similar argument can be extended to all the early jobs that were generated by the cell scheduler in the subsequent comparative studies.

9.4.1.2 Cell Scheduler (cocMacs) and Campbell's Algorithm

As discussed above, there is no general solution for any problem where the number of work centres are greater than three, but there are heuristic techniques that are capable of providing good or optimal sequence. Campbell's algorithm is one of them, which is capable of generating a good schedule but it produces the relevant schedules by actually using Johnson's algorithm as a subroutine.

The results of the comparative studies between the cell scheduler and Campbell's algorithm are presented in Table 7. These suggest that there is marginal difference between the performance of the two different algorithms. However, if the performance measure is to be based on the number of days the jobs are early or late, then Johnson's algorithm performs marginally better than the cell scheduler. In general, the performance of the cell scheduler is satisfactory.

MEASURE OF PERFORMANCE		ALGORITHMS		
PARAMETERS			[CELL SCHEDULER] COCMACS	JOHNSON
[1] MAKESPAN		REQUIRED DUE DATE	ACTUAL DUE DATE	ACTUAL DUE DATE
	A100	14039	15039	14039
	A200	15039	14039	14039
	A300	15039	15039	15039
	A400	16039	16039	16039
[2] NO OF JOBS EARLY		—	1	1
[3] NO OF JOBS LATE		—	1	—
[4] WORK CENTRE UTILISATION[%]		[CELL SCHEDULER] COCMACS		JOHNSON
	WC100	100		100
	WC200	58.7		58.7
	WC300	43.8		43.8

TABLE 6 COMPARISON BETWEEN CELL SCHEDULER AND JOHNSON'S ALGORITHM

MEASURE OF PERFORMANCE		ALGORITHMS		
PARAMETERS			[CELL SCHEDULER] COCMACS	CAMPBELL
[1] MAKESPAN		REQUIRED DUE DATE	ACTUAL DUE DATE	ACTUAL DUE DATE
	A100	14039	17039	15039
	A200	15039	16039	17039
	A300	15039	15039	16039
	A400	16039	14039	16039
[2] NO OF JOBS EARLY		—	1	—
[3] NO OF JOBS LATE		—	2	3
[4] WORK CENTRE UTILISATION[%]		[CELL SCHEDULER] COCMACS		CAMPBELL
	WC100	100		100
	WC200	53.2		55.8
	WC300	38.5		41.8
	WC400	45.3		54.4

TABLE 7 COMPARISON BETWEEN CELL SCHEDULER AND CAMPBELL'S ALGORITHM

9.4.1.3 Cell Scheduler (cocMacs) and Branch-and-Bound Algorithm

The Branch-and-Bound method is useful for solving many combinatorial problems and it is used in situations where the conditions in equations (9.1) and (9.2) are not satisfied but at the same time there is a need to determine an optimal processing sequence. A Branch-and-Bound algorithm to deal with the general three-machine flow shop problem was mooted by Ignall, E.J. [1965]. It is a relatively powerful technique and obviously has the potential to produce optimal schedule.

The results of the comparative studies between the cell scheduler and the Branch and Bound method are presented in Table 8. In brief, the results suggest that the due date achieved by the Branch-and-Bound method are a little better than the cell scheduler. On the other hand, the performance of the cell scheduler might still be considered satisfactory.

MEASURE OF PERFORMANCE		A L G O R I T H M S		
PARAMETERS			[CELL SCHEDULER] COCMACS	BRANCH AND BOUND
[1] MAKESPAN		REQUIRED DUE DATE	ACTUAL DUE DATE	ACTUAL DUE DATE
	A100	14039	15039	14039
	A200	15039	15039	14039
	A300	15039	13039	15039
	A400	16039	16039	16039
[2] NO OF JOBS EARLY		—	1	1
[3] NO OF JOBS LATE		—	1	—
[4] WORK CENTRE UTILISATION[%]		[CELL SCHEDULER] COCMACS		BRANCH AND BOUND
	WC100	100		100
	WC200	59.3		59.3
	WC300	44.2		44.2

TABLE 8 COMPARISON BETWEEN CELL SCHEDULER AND BRANCH-AND BOUND ALGORITHM

9.4.2 A General Comparison of Cell Control Model and the Heuristic Algorithms

A general comparison between the cellular manufacturing control methodology and the heuristic algorithms discussed above, suggests that the former offers significant advantages in many aspects, namely :-

- it provides a variety of route, work pattern and operator assignment options ;
- it permits the identification of dynamic (travelling) bottlenecks and provides a variety of options to resolve such problems ;
- it is a flexible system since it can accommodate a high product range based on single level Bills-Of-Material (BOM) structure; it has the potential to cope with a wide range of processing centres and hence it is not restricted to similar constraints imposed by the algorithms discussed above ;
- it is based on a relatively simple approach which is easy to understand , and
- it is an automated closed loop feedback control system, based on knowledge based concept and hence it is capable of providing flexible reasoning and decision making functions.

9.5 Concluding Remarks

A review of experimental results suggest that the core cellular manufacturing control methodology postulated in this thesis is viable. A comparative study demonstrated that the performance of the cell scheduler, is reasonable compared with other commonly used algorithms, namely, Johnson, Campbell and Branch-and-Bound. Chapter 10 discusses the broader implications of the results.

CHAPTER 10

Research Discussion and Conclusions

This chapter summarises the core research work and its main achievements in relation to the original goals and objectives as underlined in the opening chapter of this thesis.

10.1 General Discussions

The development of a cellular manufacturing control methodology and the operation of a prototype cellular manufacturing control model, to illustrate the above concept have been discussed.

The research work was undertaken in view of the need to resolve the existing manufacturing control problems, posed by the complexity of traditional manufacturing systems and the limitations inherent in traditional and current manufacturing control systems. The key solution to these problems was anticipated to lie in the complete automation of all aspects of operation of the manufacturing control system and in particular, the automation of MPS. In view of this finding, the core research work was focussed towards the automation of key processes, namely, capacity planning, due date evaluation and Master Production Schedule (MPS) regulation. The formulation of the control problem, demonstrated that the prospective solution to these problems, needs to be envisaged within the framework of a cellular manufacturing concept, based on a Distributed Manufacturing Resources Planning (DMRP) system. The main reason for adopting such course of action is the simplicity of the single level Bills-Of-Material (BOM) structure used in the DMRP system, which helps to minimise the complexity of the manufacturing system and the corresponding control problems.

A detail investigation into existing DMRP concept highlighted that it has the potential and ability to resolve the key control problems. But, despite the system's ability to provide significant improvement over the manufacturing activities in such an environment, it is limited in its ability to provide complete automatic replanning. Although, the application of the single level BOM structure provided the opportunity to establish traceability between the shop level scheduling activities and the relevant entries in the MPS, the existing system used manual intervention to close the loop between the above levels in the control system hierarchy. The manual nature of the linkage makes it difficult to evaluate and pass order status up and down the system sufficiently quickly to offer thorough evaluation of all alternate plans.

In view of the fact that the automation of key operational planning and control functions, and in particular the MPS, is the key to existing control problems, this was used as the basis for the design of an alternative manufacturing control methodology. This resulted in the development of a new control methodology based on the above concept. A prototype cell control model was developed to demonstrate the principles involved and a number of tests were carried out to evaluate the quality of performance of the model, with specific attention focussed on the automation of the cell scheduler. The overall performance of the model proved satisfactory and acceptable and it demonstrated that such a system is viable and that it is possible to automate the MPS in such an environment.

10.2 Major Conclusions

The major conclusions that can be drawn from this research are described below.

The development of an automatic control system depends on the systems ability to respond to the key dynamic inputs without human intervention. The thesis identified the receipt of new orders or equiries and changes in the status of the manufacturing resources as the key inputs to the system. The core planning function was identified as the evaluation of due dates and capacity requirements. Within a DMRP environment, this evaluation can be cell based, although the present system relies on human schedulers to determine capacity requirements and decide what resource adjustments need to be actioned.

The new system automates the due date evaluation by using a forward and backward finite scheduler and couples this with means by which the capacity available can be adjusted (through overtime, alternate routes etc) until the required due dates can be met. Failure to meet the due date, once all the adjustment options have been tried, results in modification of the local cell MPS. Thus the system achieves automation of the key aspects of the local cell-based control system. This local planning process can be triggered by either the arrival of an order enquiry or a resource status change.

Most existing systems assume that local rescheduling can cope with any problems or changes in requirements that arise. However occasions will arise when a problem, local to one cell, will mean that many other activities should be re-scheduled. In the new system, modification to the cell MPS will cause all related cells to replan their activities based on the new availability data. Thus the new system has the potential to offer a level of plan consistency and accuracy not seen in existing control systems.

The cascade process, now that it can be automated, can be used to determine potential delivery dates with a degree of confidence not currently available. This is because the date is based upon evaluation of the availability of all the component parts of the product and detailed assessment of the capacity needed for their manufacture.

The proposed method of capacity evaluation (coupled with the cascade mechanism) ensures that temporary overloads or transient bottlenecks are properly considered by the system. Unlike Optimised Production Techniques (OPT), the system does not pre-judge the location of bottleneck operations (or cells). It will therefore work effectively even in conditions where product mix changes lead to wandering bottlenecks.

The research also brought into recognition that the use of a simple single level BOM (as is feasible in cellular systems) creates conditions in which load pegging is practicable. As discussed in Chapter 5, load pegging is vital to closing the loop between capacity evaluation (i.e. shop level scheduling activities) and the local MPS (i.e. local high level planning). However, this also implies that the approach will not work in more complex (i.e. multi-level BOM) environment unless a separate Bill of Resources is created specifically for this purpose. The literature survey suggested that little work of direct relevance has been done in this area although its importance is obvious.

The scheduler's performance proved to be adequate when compared to other popular algorithms. However, during this comparison, the resource adjustment capabilities of the scheduler were disabled, that is, no alternate routes or work patterns were considered. These latter facilities offered a powerful extension to conventional approaches to the scheduling problem. In this respect, the knowledge based system reflects current operational practice whereby local management adjust work organisation so as to yield adequate levels of capacity. For example, the control methodology identifies shortages of operators that needs to be supplemented in order to successfully implement the production schedule, it assumes these shortages can be readily supplied (supplemented) by other work cells. If they are not available, it provides no means of rescheduling the work orders to take account of the resource limitations. In this context, the knowledge based concept could be extended to provide a means of rescheduling the available resources.

The scheduling system tests, demonstrated that it is capable of generating realistic and accurate due date based on the current status of manufacturing resources. The system also provides the relevant information as to when a job should commence its first and complete the last manufacturing operations and thus the actual completion or due date.

The development and operational testing of the prototype system demonstrated the validity of the principle concepts advanced by the thesis. The prototype included all the major elements required of a real system. The testing validated the operation of each of these elements and when considered in relation to testing of the DMRP logic carried out elsewhere [Barekat, M 1989] suggests that development of a fully automatic system is perfectly feasible.

CHAPTER 11

Future Research Work

The results of this research program and the current status of the prototype cellular manufacturing control model demonstrate that, there is ample opportunity for further development of the concept, in an industrial manufacturing environment. The following discussions highlight the potential research areas.

11.1 Development of the Concept

The development of the concept referred to in the subsequent discussions can be envisaged under two major aspects, namely, further development of the control model, and development/application of the concept in a traditional manufacturing environment. The subsequent discussions, will focus on these issues and the merits of each aspect will be dealt with individually.

11.1.1 Further Development of Original Concept

As discussed in Chapter 9, a comparative study between the cell scheduler and other related algorithms revealed that the quality of due date performance, utilisation of work centres etc., are satisfactory and acceptable. However, this also implies that there is potential for further improvement of the cell scheduler. Obviously, this entails further programming effort which demands more time but it is not particularly a difficult task to undertake. The alternative is to use one of the off-the-shelf finite scheduling packages which can provide good finite scheduling functions. Most of these packages are rather expensive and often difficult to modify because they do not incorporate source codes.

In addition, the existing cellular manufacturing model relies on simulated work orders to drive the whole system. However, the application of an MRP system would make the control model complete and comprehensive. In this context, there are two options available to the user, namely, to use a standard MRP package, namely, UNIPLAN or to develop a simple MRP application program. Similarly, this involves extensive programming effort and demands substantial development time. Although the MRP system is not particularly critical in the demonstration of the above concept, its incorporation would make the control model complete and comprehensive.

11.1.2 Development/Application of the Concept in a Traditional Manufacturing Environment

The development of the concept postulated in this thesis was undertaken in a DMRP environment based on single level Bills-Of-Material (BOM) structure. Its application is therefore strictly limited to such a manufacturing environment for reasons which were extensively discussed in Chapter 5. A review of relevant literatures, suggest that there is no evidence to claim of any research work which can automate MPS in a traditional manufacturing environment, based on multi-level BOM structure. It is indeed difficult to implement the concept in such an environment due to the complexity of the bill structure.

However, if the MPS can be automated in such an environment, then it is equally possible to automate the standard MRP process. This would indeed provide a significant improvement and enhancement of the planning and control functions in such an environment. Although, it is a difficult task to undertake but however, the rewards are very promising, because this would offer significant advantages, namely, it would provide better prospect of establishing dynamic links between shop level scheduling activities and relevant entries in the MPS. This would enhance the prospect of establishing a dynamic and truly closed loop feedback control system and hence permit automatic evaluation of capacity and due date constraints and automation of MPS.

11.2 Evaluation of the Concept in an Industrial Environment

The existing control model was developed and tested in a DMRP environment based on single level BOM structure ; supported by dynamic feedback of manufacturing resource status. However, the application of such a concept is also promising in an industrial manufacturing environment, based on hybrid manufacturing systems, which is made up of a combination of a fully automated Flexible Manufacturing Cell (FMC) operating next to a non automated cell. This entails the incorporation of some form of data logging device in the above cell, which reads the status of related work station and feeds the relevant information back to the cell scheduler, which then reschedules all the cell operations. This would permit the non automated cell to derive some of the benefits of an automated cell, at least in the context of automation of MPS. But, this would require some hardware modifications and installation of data logging device and probably some programming effort but it is an exercise worth pursuing because of the potential benefits mentioned above.

11.3 Testing the Model in a Simulation Environment

The investigation of shop floor decisions or policies in the implementation of the above concept can be undertaken in a stochastic factory simulator like ATOMS. The testing of the cell control model driven by a factory simulator, ATOMS [Love, D.M 1986(d)] is aimed at providing the system with greater impetus in responding to more realistic inputs generated by a more practical shop floor model. This enables the performance of the control methodology to be evaluated in a stochastic environment. The main reasons for selecting ATOMS are attributed to a number of factors, namely, it is locally available ; capable of emulating key shop floor functions and has the potential to provide rational and realistic shop floor model representation. ATOMS is a factory simulator developed at the Mechanical and Production Engineering Department of Aston University. It can be configured to create a factory model with finite number of work centres with either equal or different capacity and to represent different shop floor scenarios. In addition, ATOMS has the ability to provide the following functions :-

- represent machine or work centre breakdown ;
- change the manufacturing facility layout configuration ;
- interactively modify the available manufacturing resources ;
- implement different manufacturing policies, and
- update the model in real time to reflect the real system, etc.

The process of data communication between the cellular manufacturing control model and ATOMS can be facilitated by Desqview (developed by Quarterdeck Office Systems). Desqview is an interface program which supports multitasking operations and in this context, it can be used to support the transfer of data and as an interface between cell control model (cocMacs) and ATOMS.

A schematic view of the prototype cellular manufacturing control model based on the above concept is illustrated in Figure 16. Briefly, ATOMS is used to represent the shop floor model and the configuration of manufacturing resource status and therefore policies which are required to drive the cellular manufacturing control model can be set within ATOMS. For example, changes in status of manufacturing resources, that is, work centre breakdown, triggers the cell scheduler via the interface program, DESQVIEW. This also leads to a chain reaction which involves the automatic termination of existing activities, freezing the capacity of affected work centres and the invalidation of the previously established production schedule. Eventually, this leads to rescheduling of all the relevant activities and followed by functions as specified in the control algorithm, discussed in Chapters 7 and 8 respectively.

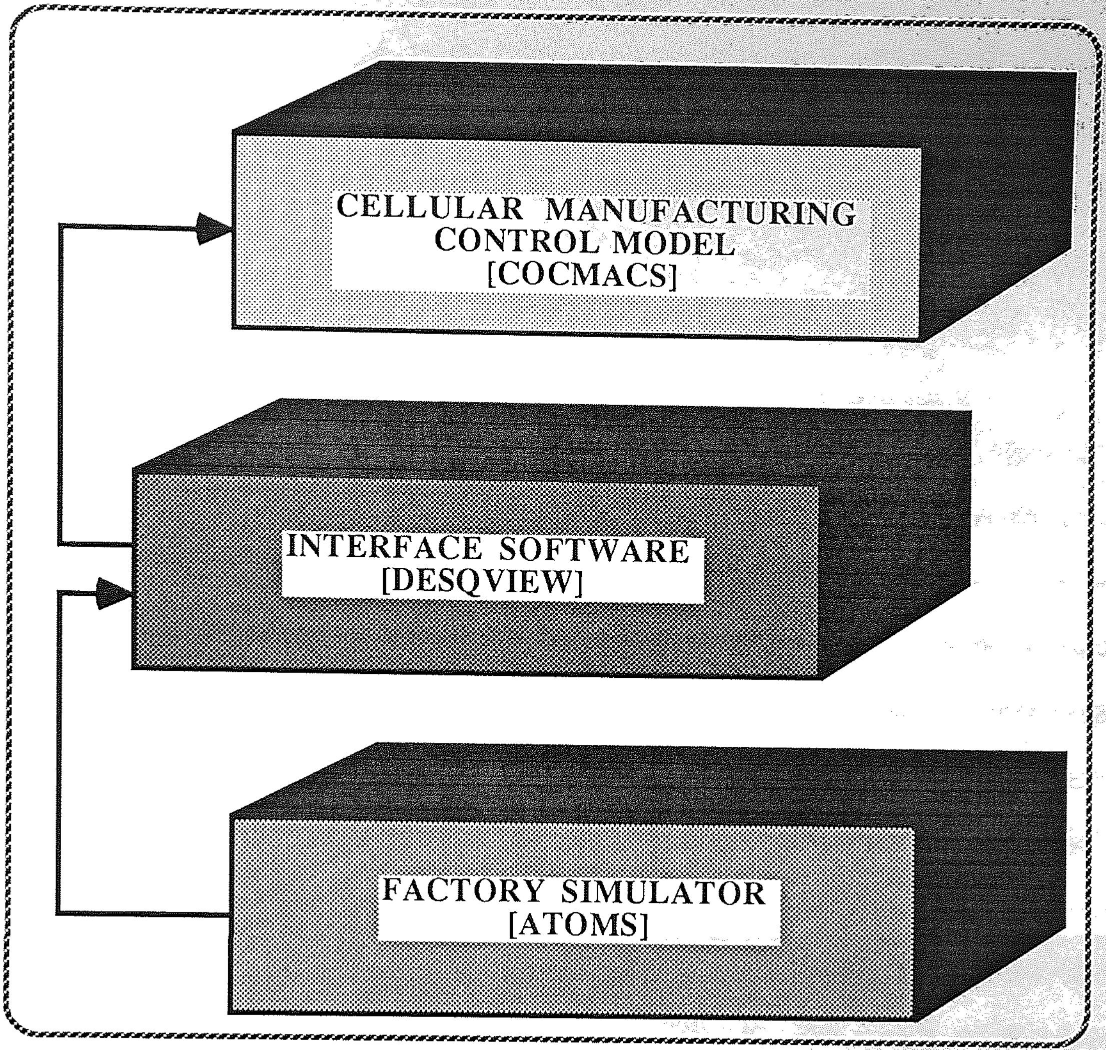


FIGURE 16 AN OVERVIEW OF ATOMS DRIVEN CM CONTROL MODEL

11.4 Testing of Model in a Totally Automated Computer Integrated Manufacturing (CIM) Environment

It is extremely important that the development and testing of the cellular manufacturing control methodology is envisaged within the framework of a Computer Integrated Manufacturing (CIM) environment because this permits the creation of a totally automated CIM system that facilitates automatic evaluation of design changes. Furthermore, there is a genuine need for a totally automated control system within the CIM system currently being developed by the Aston University's Design and Manufacturing Research Group.

Broadly defining, what is required is a totally automated CIM system that permits automatic evaluation of manufacturing resources or policies in response to changes in the manufacturing status. This would indeed represent an important advancement in the application of the above control methodology. A schematic view of the proposed prototype CIM system based on the above concept is illustrated in Figure 17.

This would permit the development of a totally automatic, integrated and autonomous manufacturing system, where all key functions, namely design, process planning, coding, simulation of machining, factory can be undertaken within the same system. The role of the cell control model is to provide key control functions, namely, to generate a practical due date or MPS in response to an incoming customer order or changes in the manufacturing status. This would be undertaken in conjunction with all the supporting facilities provided by various application programs or packages, such as, Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computer Aided Process Planning (CAPP), Computer Aided Manufacturing Classification System (CAMAC), Factory Simulator (ATOMS), etc. However, this would involve further programming effort, mainly in the development of an interface between the cell control model and the relevant application programs/packages or alternatively, the interface program, DESQVIEW, could be used to provide the interfacing.

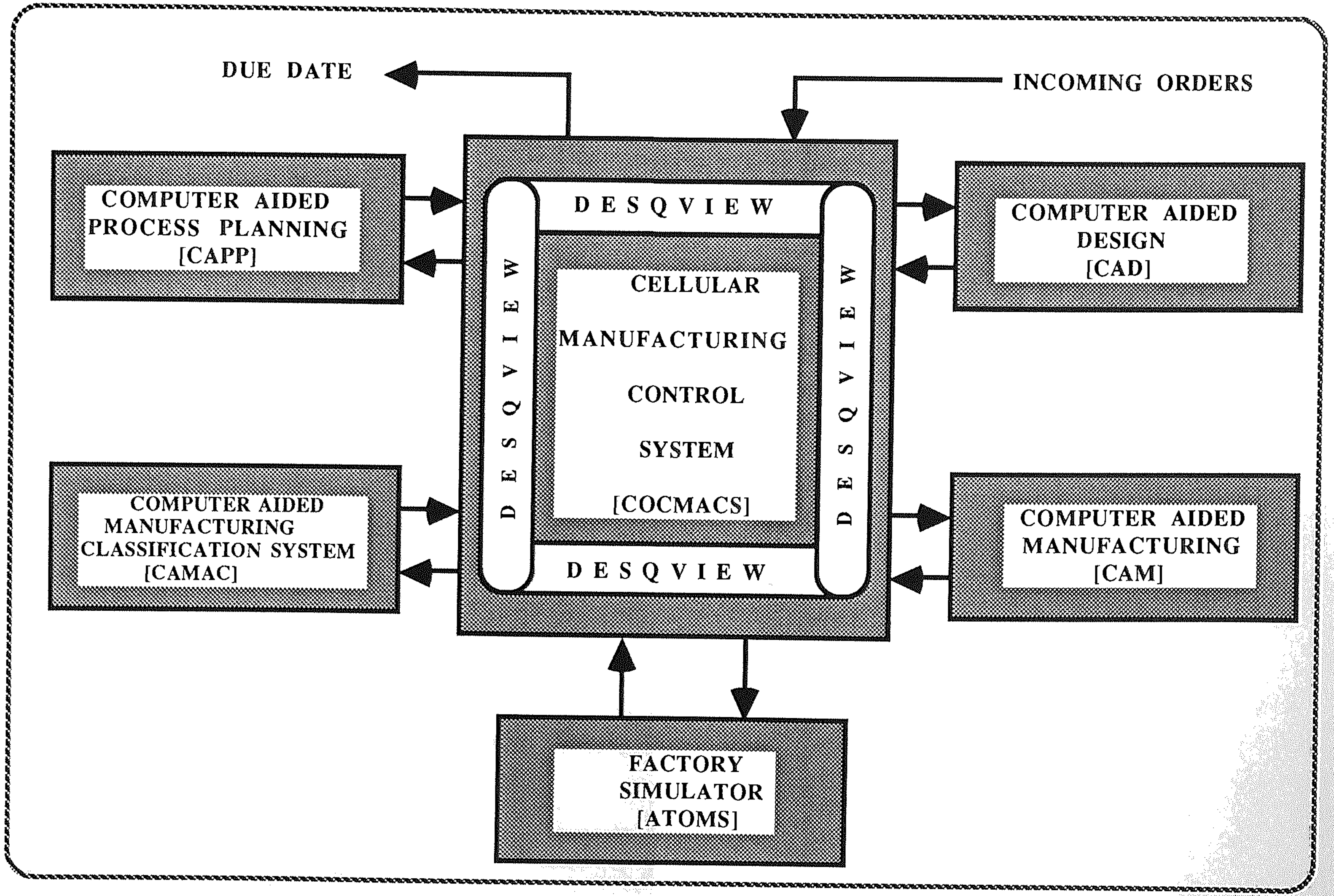


FIGURE 17 A PROPOSED TOTALLY AUTOMATED AND DISTRIBUTED CIM SYSTEM

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APPENDICES

APPENDIX A [TABLE 1]

RESULTS OF TEST RUN 1

MAIN INPUT FILES

[i] Original MPS Data

Table 1(i) is the original Master Production Schedule (MPS) data which is created based on incoming customer orders or cell specified orders. A major review of MPS was undertaken in Chapter 5 and in reality, it provides the key information which drives the rest of the manufacturing system. Most of the MPS information provided in the table are self explanatory. For example, the fifth column represents the day on which an order is/was placed for an item, whereas the sixth column indicates the day on which the item is required by a customer/customer cell.

WORK ORDER NUMBER	CUSTOMER NAME	PART NUMBER	QUANTITY ORDERED	ORDERED DATE	REQUIRED DUE DATE
1	JOHNS	A100	100	30127	6038
2	BOBBY	A200	100	30127	8038
3	RINGO	A300	100	30127	10038
4	ANDY	A400	100	30127	7038
5	REGY	A500	50	30127	9038
6	MAGIE	A600	50	30127	13038
7	RIDLY	A700	50	30127	16038
8	BUSH	A800	50	30127	17038
9	HONDA	A900	50	30127	14038
10	NICK	A999	50	30127	20038

Table 1 (i) Original MPS Data

[ii] Work Order Data

Table 1(ii) is a list of work order data used in the evaluation of the cellular manufacturing control model. The information contained in the first till the fourth columns are self-explanatory. The fifth column represents the date on which the customer placed an order for the relevant item whereas the sixth indicates the date on which the order was issued to the shopfloor and in this experiment it represents the current date. The last column represents the date on which the item is required by the customer or customer cell or in short, it is the customer specified due date.

WORK ORDER NUMBER	PART NAME	PART NUMBER	QUANTITY	ORDERED DATE	ISSUED DATE	DUE DATE
1	SMA	A100	100	30127	28028	6038
2	SMB	A200	100	30127	28028	8038
3	SMC	A300	100	30127	28028	10038
4	SMD	A400	100	30127	1038	7038
5	SME	A500	50	30127	1038	9038
6	SMF	A600	50	30127	1038	13038
7	SMG	A700	50	30127	10038	16038
8	SMH	A800	50	30127	10038	17038
9	SMJ	A900	50	30127	10038	14038
10	SMK	A999	50	30127	15038	20038

Table 1 (ii) Work Order Data

[iii] Work Centre Data

Table 1(iii) is a list of work centre data used in the evaluation of the cellular manufacturing control model. For example, the first column represents work centre name which is made up of a number of work stations (column two) and this also indicates the nature of manufacturing processes. The third contains relevant information on the number of work stations used in each work centre (e.g. 5 work stations per work centre). The fourth indicates the number of operators required to operate a particular work centre and the last column illustrates the efficiency of each work centre.

WORK CENTRE NUMBER	WORKSTATION NAME	NO. OF WORKSTATIONS	NO. OF OPERATORS	EFF. [%]
WC100	LATHE	5	2	100
WC200	MILLER	5	2	100
WC300	BORER	5	2	100
WC400	PRESS	5	2	100
WC500	WELDER	5	2	100
WC600	ASSEMBLER	5	2	100

Table 1 (iii) Work Centre Data

[iv] Process Route Data

Table 1(iv) is a summary of the process route data and it indicates the sequence of operations involved in the manufacture of a part or component. The first column represents the route number ; the third indicates the identification number attached to each part ; the fourth and fifth represent the sequence of operations which a part has to follow from start till finish; the seventh and eight indicate the set-up and operation times in minutes.

ROUTE NO	PART NO	IDENT NO	SEQ NO	OPER. CODE	WORKCENTRE NO	SET TIME	OPERATION TIME
1	A100	1	10	1	WC100	50	50
1	A100	1	20	2	WC200	25	25
1	A100	1	30	3	WC300	10	10
1	A100	1	40	4	WC500	20	10
1	A100	1	50	5	WC600	25	25
2	A100	1	10	1	WC100	50	50
2	A100	1	20	2	WC300	15	15
2	A100	1	30	3	WC500	20	20
2	A100	1	40	4	WC200	10	10
2	A100	1	50	5	WC600	15	15
3	A100	1	10	1	WC100	50	50
3	A100	1	20	2	WC500	25	25
3	A100	1	30	3	WC200	30	30
3	A100	1	40	4	WC300	20	20
3	A100	1	50	5	WC600	15	15
1	A200	2	10	1	WC100	50	50
1	A200	2	20	2	WC200	25	25
1	A200	2	30	3	WC300	10	10
1	A200	2	40	4	WC400	15	15
1	A200	2	50	5	WC500	20	10
1	A200	2	60	6	WC600	25	25

2	A200	2	10	1	WC100	50	50
2	A200	2	20	2	WC300	20	20
2	A200	2	30	3	WC200	15	10
2	A200	2	40	4	WC500	10	5
2	A200	2	50	5	WC400	15	10
2	A200	2	60	6	WC600	20	25
3	A200	2	10	1	WC100	50	50
3	A200	2	20	2	WC400	10	10
3	A200	2	30	3	WC500	15	15
3	A200	2	40	4	WC200	20	20
3	A200	2	50	5	WC500	10	10
3	A200	2	60	6	WC600	15	15
1	A300	3	10	1	WC100	20	20
1	A300	3	20	2	WC200	10	10
1	A300	3	30	3	WC300	5	5
1	A300	3	40	4	WC400	5	5
1	A300	3	50	5	WC500	10	5
1	A300	3	60	6	WC600	10	10
2	A300	3	10	1	WC100	20	20
2	A300	3	20	2	WC300	10	10
2	A300	3	30	3	WC200	5	5
2	A300	3	40	4	WC500	5	5
2	A300	3	50	5	WC400	10	5
2	A300	3	60	6	WC600	5	5
3	A300	3	10	1	WC100	10	10
3	A300	3	20	2	WC400	10	10
3	A300	3	30	3	WC300	5	5
3	A300	3	40	4	WC500	5	5
3	A300	3	50	5	WC200	10	5
3	A300	3	60	6	WC600	5	5
1	A400	4	10	1	WC100	10	5
1	A400	4	20	2	WC200	10	10
1	A400	4	30	3	WC300	5	5
1	A400	4	40	4	WC400	5	5
1	A400	4	50	5	WC500	10	5
1	A400	4	60	6	WC600	10	10
2	A400	4	10	1	WC100	5	5
2	A400	4	20	2	WC300	10	10
2	A400	4	30	3	WC200	5	5
2	A400	4	40	4	WC500	5	5
2	A400	4	50	5	WC400	10	10
2	A400	4	60	6	WC600	5	5
3	A400	4	10	1	WC100	5	5
3	A400	4	20	2	WC200	10	10
3	A400	4	30	3	WC300	5	5
3	A400	4	40	4	WC400	5	5
3	A400	4	50	5	WC500	10	5
3	A400	4	60	6	WC600	5	5
1	A500	5	10	1	WC100	5	5
1	A500	5	20	2	WC200	10	10
1	A500	5	30	3	WC300	5	5
1	A500	5	40	4	WC400	5	5
1	A500	5	50	5	WC500	10	5
1	A500	5	60	6	WC600	10	10
2	A500	5	10	1	WC100	10	5
2	A500	5	20	2	WC200	10	10
2	A500	5	30	3	WC300	5	5
2	A500	5	40	4	WC400	10	10

2	A500	5	50	5	WC500	10	10
2	A500	5	60	6	WC600	20	20
3	A500	5	10	1	WC100	5	5
3	A500	5	20	2	WC200	10	10
3	A500	5	30	3	WC300	5	5
3	A500	5	40	4	WC400	5	5
3	A500	5	50	5	WC500	10	10
3	A500	5	60	6	WC600	20	20
1	A600	6	10	1	WC100	5	5
1	A600	6	20	2	WC200	5	5
1	A600	6	30	3	WC300	5	5
1	A600	6	40	4	WC400	5	5
1	A600	6	50	5	WC500	10	10
1	A600	6	60	6	WC600	10	10
2	A600	6	10	1	WC100	5	5
2	A600	6	20	2	WC200	10	5
2	A600	6	30	3	WC300	5	5
2	A600	6	40	4	WC400	10	10
2	A600	6	50	5	WC500	5	5
2	A600	6	60	6	WC600	20	20
3	A600	6	10	1	WC100	5	5
3	A600	6	20	2	WC200	5	5
3	A600	6	30	3	WC300	5	5
3	A600	6	40	4	WC400	20	10
3	A600	6	50	5	WC500	20	5
3	A600	6	60	6	WC600	10	10
1	A700	7	10	1	WC100	5	5
1	A700	7	20	2	WC200	5	5
1	A700	7	30	3	WC300	10	5
1	A700	7	40	4	WC400	20	10
1	A700	7	50	5	WC500	10	10
1	A700	7	60	6	WC600	20	20
2	A700	7	10	1	WC100	5	5
2	A700	7	20	2	WC200	5	5
2	A700	7	30	3	WC300	10	10
2	A700	7	40	4	WC400	20	10
2	A700	7	50	5	WC500	10	10
2	A700	7	60	6	WC600	20	20
3	A700	7	10	1	WC100	5	5
3	A700	7	20	2	WC200	5	5
3	A700	7	30	3	WC300	10	10
3	A700	7	40	4	WC400	10	10
3	A700	7	50	5	WC500	10	10
3	A700	7	60	6	WC600	20	20
1	A800	8	10	1	WC100	10	10
1	A800	8	20	2	WC200	20	10
1	A800	8	30	3	WC300	10	10
1	A800	8	40	4	WC400	10	10
1	A800	8	50	5	WC500	10	10
1	A800	8	60	6	WC600	30	20
2	A800	8	10	1	WC100	10	10
2	A800	8	20	2	WC200	20	20
2	A800	8	30	3	WC300	10	10
2	A800	8	40	4	WC400	20	10
2	A800	8	50	5	WC500	10	10
2	A800	8	60	6	WC600	20	20
3	A800	8	10	1	WC100	10	10
3	A800	8	20	2	WC200	10	10

3	A800	8	30	3	WC300	10	5
3	A800	8	40	4	WC400	20	10
3	A800	8	50	5	WC500	10	10
3	A800	8	60	6	WC600	20	20
1	A900	9	10	1	WC100	10	10
1	A900	9	20	2	WC200	20	10
1	A900	9	30	3	WC300	30	10
1	A900	9	40	4	WC400	10	10
1	A900	9	50	5	WC500	20	10
1	A900	9	60	6	WC600	20	20
2	A900	9	10	1	WC100	10	10
2	A900	9	20	2	WC200	20	10
2	A900	9	30	3	WC300	10	10
2	A900	9	40	4	WC400	20	10
2	A900	9	50	5	WC500	10	10
2	A900	9	60	6	WC600	20	20
3	A900	9	10	1	WC100	10	10
3	A900	9	20	2	WC200	20	10
3	A900	9	30	3	WC300	10	10
3	A900	9	40	4	WC400	5	5
3	A900	9	50	5	WC500	20	10
3	A900	9	60	6	WC600	20	20
1	A999	10	10	1	WC100	10	10
1	A999	10	20	2	WC200	20	10
1	A999	10	30	3	WC300	20	20
1	A999	10	40	4	WC400	20	10
1	A999	10	50	5	WC500	20	20
1	A999	10	60	6	WC600	20	20
2	A999	10	10	1	WC100	10	10
2	A999	10	20	2	WC200	10	10
2	A999	10	30	3	WC300	20	20
2	A999	10	40	4	WC400	20	10
2	A999	10	50	5	WC500	10	10
2	A999	10	60	6	WC600	20	20
3	A999	10	10	1	WC100	10	10
3	A999	10	20	2	WC200	10	10
3	A999	10	30	3	WC300	10	10
3	A999	10	40	4	WC400	20	20
3	A999	10	50	5	WC500	10	10
3	A999	10	60	6	WC600	20	20

Table 1 (iv) Process Route Data

[v] Work Pattern Data

Table 1(v) is the work pattern data used in resolving capacity constraints at the bottleneck work centre. The first column represents the individual work pattern number which ranges from one till ten ; the second illustrates the day of the week, starting from Monday till Sunday and the third represents the actual working hours which changes from one day/work pattern to the other and in some respects it is analogous to shift pattern commonly used in most manufacturing industries.

WORK PATTERN NUMBER	DAY OF THE WEEK	WORKING HOURS
1	MON	8
1	TUE	8
1	WED	8
1	THU	8
1	FRI	8
1	SAT	0
1	SUN	0
2	MON	9
2	TUE	8
2	WED	9
2	THU	8
2	FRI	9
2	SAT	0
2	SUN	0
3	MON	10
3	TUE	8
3	WED	10
3	THU	8
3	FRI	10
3	SAT	0
3	SUN	0
4	MON	12
4	TUE	8
4	WED	12
4	THU	8
4	FRI	12
4	SAT	0
4	SUN	0
5	MON	12
5	TUE	8
5	WED	12
5	THU	8
5	FRI	12
5	SAT	1
5	SUN	0
6	MON	12

6	TUE	8
6	WED	12
6	THU	8
6	FRI	12
6	SAT	1
6	SUN	1
7	MON	12
7	TUE	12
7	WED	12
7	THU	12
7	FRI	12
7	SAT	2
7	SUN	0
8	MON	12
8	TUE	12
8	WED	12
8	THU	12
8	FRI	12
8	SAT	4
8	SUN	4
9	MON	16
9	TUE	16
9	WED	16
9	THU	16
9	FRI	16
9	SAT	0
9	SUN	0
10	MON	24
10	TUE	24
10	WED	24
10	THU	24
10	FRI	24
10	SAT	24
10	SUN	24

Table 1 (v) Work Pattern Data

[vi] Operator Assignment Data

Table 1(vi) represents the relevant operator assignment data and this is based on the second technique of assigning operators, as discussed in Chapters 7 and 8 respectively. The number of operators allocated vary in accordance with the number of work patterns and work centres used and these are specified in the first and second columns respectively. The number of operators allocated to the work centre is highlighted in the last column and this is determined largely by the work pattern used.

WORK CENTRE NUMBER	WORK PATTERN NUMBER	NUMBER OF OPERATORS ALLOCATED TO THE WCN
WC100	1	1
WC100	2	1
WC100	3	1
WC100	4	2
WC100	5	2
WC100	6	2
WC100	7	2
WC100	8	2
WC100	9	2
WC100	10	3
WC200	1	1
WC200	2	1
WC200	3	1
WC200	4	2
WC200	5	2
WC200	6	2
WC200	7	2
WC200	8	2
WC200	9	2
WC200	10	3
WC300	1	1
WC300	2	1
WC300	3	1
WC300	4	2
WC300	5	2
WC300	6	2
WC300	7	2
WC300	8	2
WC300	9	2
WC300	10	3
WC400	1	1
WC400	2	1
WC400	3	1
WC400	4	2
WC400	5	2
WC400	6	2
WC400	7	2
WC400	8	2
WC400	9	2
WC400	10	3
WC500	1	1
WC500	2	1
WC500	3	1
WC500	4	2
WC500	5	2
WC500	6	2
WC500	7	2
WC500	8	2
WC500	9	2
WC500	10	3
WC600	1	1
WC600	2	1
WC600	3	1
WC600	4	2
WC600	5	2
WC600	6	2
WC600	7	2
WC600	8	2
WC600	9	2
WC600	10	3

Table 1 (vi) Operator Assignment Data

MAIN OUTPUT FILES

[vii] New (Updated) MPS Data

Table 1(vii) is the new or updated Master Production Schedule (MPS) data and in reality, it is very similar to the original MPS (Table 1(i)) with the exception that the actual due date reflects the date that can be achieved under the current status of manufacturing resources. For example, the last column indicates the actual due date that can be achieved under the current status of manufacturing resources.

WORK ORDER NUMBER	CUSTOMER NAME	PART NUMBER	QUANTITY ORDERED	ORDERED DATE	REQUIRED DUE DATE
1	JOHNS	A100	100	30127	12048
2	BOBBY	A200	100	30127	3048
3	RINGO	A300	100	30127	30038
4	ANDY	A400	100	30127	3048
5	REGY	A500	50	30127	31038
6	MAGIE	A600	50	30127	30038
7	RIDLY	A700	50	30127	29038
8	BUSH	A800	50	30127	28038
9	HONDA	A900	50	30127	29038
10	NICK	A999	50	30127	27038

Table 1 (vii) Updated MPS Data

[viii] Capacity Requirements Data

Table 1(viii) is a summary of the capacity requirements by each part, at each work centre. The first column represents the part number and the second indicates the respective work centres on which a particular part is processed. The last column highlights the total capacity or time required to process a part at a particular work centre.

PART NUMBER	WORK CENTRE NUMBER	REQUIRED CAPACITY [MINUTES]
A100	WC100	200
A100	WC500	1000
A100	WC200	1200
A100	WC300	800
A100	WC600	600
A200	WC100	200
A200	WC400	400
A200	WC500	600
A200	WC200	800
A200	WC300	400
A200	WC600	600
A300	WC100	400
A300	WC400	400
A300	WC300	200
A300	WC500	200
A300	WC200	300
A300	WC600	200
A400	WC100	200
A400	WC200	400
A400	WC300	200
A400	WC400	200
A400	WC500	300
A400	WC600	200
A500	WC100	100
A500	WC200	200
A500	WC300	100
A500	WC400	100
A500	WC500	200
A500	WC600	400
A600	WC100	100
A600	WC200	100
A600	WC300	100
A600	WC400	300
A600	WC500	250
A600	WC600	200
A700	WC100	100
A700	WC200	100
A700	WC300	200
A700	WC400	200
A700	WC500	200
A700	WC600	400
A800	WC100	200
A800	WC200	200
A800	WC300	150
A800	WC400	300
A800	WC500	200
A800	WC600	400
A900	WC100	200

A900	WC200	300
A900	WC300	200
A900	WC400	100
A900	WC500	300
A900	WC600	400
A999	WC100	200
A999	WC200	200
A999	WC300	200
A999	WC400	400
A999	WC500	200
A999	WC600	400

Table 1 (viii) Capacity Requirements Data

[ix] Job Loading Sequence Report

Table 1 (ix) contains relevant information on all the parts which have been processed by the priority sorting program. It provides the order in which the different parts will be processed at various work centres. For example, the fifth column represents the day/date the customer placed an order for a part ; the sixth indicates the day on which an order was issued to the shopfloor for manufacture and in this case it represents the current day/date (i.e. "today") ; the seventh represents the customer specified due date and the eight highlights the difference between the actual start date determined by the backward scheduler and the current date which is the same as the issued date.

WORK ORDER NUMBER	PART NAME	PART NUMBER	QTY	ORDERED DATE	ISSUED DATE	DUE DATE	SLACK [DAYS]
10	SMK	A999	50	30127	15038	20038	69
8	SMH	A800	50	30127	10038	17038	63
7	SMG	A700	50	30127	10038	16038	59
9	SMJ	A900	50	30127	10038	14038	58
6	SMF	A600	50	30127	1038	13038	47
3	SMC	A300	100	30127	28028	10038	43
5	SME	A500	50	30127	1038	9038	42
2	SMB	A200	100	30127	28028	8038	40
4	SMD	A400	100	30127	1038	7038	37
1	SMA	A100	100	30127	28028	6038	35

Table 1 (ix) Job Loading Sequence Report

[x] Detail Capacity Requirements Report

Table 1(x) is a detail capacity requirements report which specifies the capacity required at each work centre on a specified date. This information is used in the assignment of operators using the manhours technique. The relevant dates and work centres are described in columns 1 and 2 respectively, whereas the third represents corresponding work pattern number. The actual capacity required at each work centre is highlighted in the fourth column.

DATE	WORK CENTRE NUMBER	WORK PATTERN NUMBER	PROCESS TIME REQD AT EACH WCN [MINS]
15038	WC100	1	1440
15038	WC200	1	960
15038	WC300	1	480
16038	WC300	1	1440
16038	WC400	1	480
16038	WC200	1	1440
16038	WC100	1	1920
17038	WC400	1	1440
17038	WC500	1	960
17038	WC200	1	960
17038	WC300	1	960
17038	WC100	1	1440
27038	WC600	3	1200
27038	WC500	1	480
20038	WC500	1	1440
20038	WC400	1	1920
20038	WC100	1	1440
28038	WC600	3	960
28038	WC500	1	480
28038	WC200	1	480
29038	WC600	3	1800
29038	WC200	1	960
29038	WC300	1	480
21038	WC500	1	960
21038	WC400	1	480
21038	WC300	1	480
30038	WC600	3	1440
30038	WC300	1	960
30038	WC200	1	480
22038	WC300	1	480
22038	WC500	1	480
22038	WC200	1	480

23038	WC200	1	960
23038	WC300	1	480
23038	WC400	1	480
24038	WC400	1	960
24038	WC500	1	960
31038	WC600	3	1200
31038	WC300	1	480
31038	WC400	1	480
31038	WC500	1	480
3048	WC600	3	1200
3048	WC500	1	960
4048	WC500	1	480
5048	WC500	1	480
5048	WC200	1	480
6048	WC200	1	480
7048	WC200	1	480
7048	WC300	1	480
10048	WC300	1	480
11048	WC300	1	480
11048	WC600	3	480
12048	WC600	3	600

Table 1 (x) Detail Capacity Requirements Report

[xi] Manhours Status Report

Table 1(xi) represents the status of manhours on each day envisaged within the framework of operator assignment, based on the first technique. For example, the first column indicates the date on which the actual total manhours (process time) specified in Table 1(x) are required to process a part. The actual available manhours quantified in hours (minutes) are specified in column two and this is equivalent to the total time that can be spared by four operators (i.e. 4 * 480 minutes or 4 * 8 hours), based on the assumption that each operator works 8 hours a day. The results indicated in column three is the difference between the gross available manhours (column 2) and the total required manhours on a particular date indicated in column 4, Table 1(x). The negative sign in column 3, highlights the shortage of manhours anticipated on the particular date and in reality it represents a critical situation because it affects the implementation of the production schedule.

DATE	GROSS AVAILABLE MANHOURS [MINS]	NET AVAILABLE MANHOURS [MINS]
15038	32 (1920)	- 16 (- 960)
16038	32 (1920)	- 56 (- 3360)
17038	32 (1920)	- 64 (- 3840)
27038	32 (1920)	4 (240)
20038	32 (1920)	- 48 (- 2880)
28038	32 (1920)	0
29038	32 (1920)	- 22 (- 1320)
21038	32 (1920)	0
30038	32 (1920)	- 16 (- 960)
22038	32 (1920)	8 (480)
23038	32 (1920)	0
24038	32 (1920)	0
31038	32 (1920)	- 12 (- 720)
3048	32 (1920)	- 4 (- 240)
4048	32 (1920)	24 (1440)
5048	32 (1920)	16 (960)
6048	32 (1920)	24 (1440)
7048	32 (1920)	16 (960)
10048	32 (1920)	24 (1440)
11048	32 (1920)	16 (960)
12048	32 (1920)	22 (1320)

Table 1 (xi) Manhours Status Report (First Technique)

[xii] Manhours Shortage Report

Table 1(xii) is a summary of the actual manhours shortages reflected over the planning horizon, as discussed in Table 1(xi). For example, the first column indicates the date on which the shortage is/was anticipated and the second highlights the actual shortages quantified in hours (minutes) and these are infact the same figures as that represented by the negative signs in column 3, Table 1 (xi). The last column represents the equivalent number of operators that corresponds to manhours specified in column 2. It is based on the assumption that each operator works 8 hours or 480 minutes per day.

DATE	MANHOURS SHORTAGE HOURS [MINUTES]	EQUIVALENT NUMBER OF OPERATORS
15038	16 (960)	2
16038	56 (3360)	7
17038	64 (3840)	8
20038	48 (2880)	6
29038	22 (1320)	3
30038	16 (960)	2
31038	12 (720)	2
3048	4 (240)	1

Table 1 (xii) Manhours Shortage Report (First Technique)

[xiii] Operator Status Report

Table 1(xiii) depicts the operator status report based on the second operator assignment technique discussed in Chapters 7 and 8 respectively. For example, the fourth column indicates the total number of operators required at a particular work centre (column 2) and date (column 1). The allocation of operators are carried out in accordance with standard operator assignment specification prescribed in Table 1(vi). The last column reflects the net available number of operators on a particular day and it is based on the difference between the total number of operators available (i.e.4 operators/day) and the numbers required on a particular day/date. For example, the number of operators required on 17038, at WC100 is 1; since there was no more operators available on that date, this resulted in a shortage of one operator. This is highlighted by the negative sign in the fifth column which indicates the operator shortage on the particular date. Obviously, this would affect the implementation of the production schedule.

DATE	WORK CENTRE NUMBER	WORK PATTERN NUMBER	REQUIRED NO OF OPERATORS	NET AVAIL NO. OF OPER
15038	WC100	1	1	3
15038	WC200	1	1	2
15038	WC300	1	1	1
16038	WC300	1	1	3
16038	WC400	1	1	2
16038	WC200	1	1	1
16038	WC100	1	1	0
17038	WC400	1	1	3
17038	WC500	1	1	2
17038	WC200	1	1	1
17038	WC300	1	1	0
17038	WC100	1	1	- 1
27038	WC600	3	1	3
27038	WC500	1	1	2
20038	WC500	1	1	3
20038	WC400	1	1	2
20038	WC100	1	1	1
28038	WC600	3	1	3
28038	WC500	1	1	2
28038	WC200	1	1	1
29038	WC600	3	1	3
29038	WC200	1	1	2
29038	WC300	1	1	1
21038	WC500	1	1	3
21038	WC400	1	1	2
21038	WC300	1	1	1
30038	WC600	3	1	3
30038	WC300	1	1	2
30038	WC200	1	1	1
22038	WC300	1	1	3
22038	WC500	1	1	2
22038	WC200	1	1	1
23038	WC200	1	1	3
23038	WC300	1	1	2
23038	WC400	1	1	1
24038	WC400	1	1	3
24038	WC500	1	1	2
31038	WC600	3	1	3
31038	WC300	1	1	2
31038	WC400	1	1	1
31038	WC500	1	1	0
3048	WC600	3	1	3
3048	WC500	1	1	2
4048	WC500	1	1	3
5048	WC500	1	1	3
5048	WC200	1	1	2
6048	WC200	1	1	3
7048	WC200	1	1	3
7048	WC300	1	1	2
10048	WC300	1	1	3
11048	WC300	1	1	3

Table 1 (xiii) Operator Status Report (Second Technique)

[xiv] Operator Shortage Report

Table 1(xiv) is a summary of the operator shortage report derived from Table 1(xiii) and it highlights the date and number of operators which need to be supplemented in order to implement the production schedule. For example, on the 17038, there is a shortage of one operator at work centre WC100. Under such circumstances, the cell control model would place a requisition for an operator from another cell.

DATE	WORK CENTRE NUMBER	NUMBER OF OPERATORS THAT NEEDS TO BE SUPPLEMENTED
17038	WC100	1

Table1(xiv) Operator Shortage Report (Second Technique)

[xv] Total Capacity Status Over Scheduling Horizon

Table 1(xv) highlights the global capacity status over the scheduling horizon. This information is used in the identification and sorting of potential travelling bottleneck work centre discussed in Chapters 7 and 8. The total required and available capacity over the scheduling horizon at a particular work centre are indicated in columns 2 and 3 respectively. The free capacity (column 4) at a particular work centre is the difference between the total available (column 3) and total required capacity (column 2).

WORK CENTRE NUMBER	REQUIRED CAPACITY [MINUTES]	AVAILABLE CAPACITY [MINUTES]	FREE CAPACITY [MINUTES]
WC100	1900	10080	8180
WC500	3450	10080	6630
WC200	3800	10080	6280
WC300	2550	10080	7530
WC600	3800	7200	3400
WC400	2400	10080	7680

Table 1(xv) Capacity Status Over Scheduling Horizon

[xvi] Bottleneck Work Centre Report

Table 1(xvi) represents the (potential) bottleneck work centre and it is based on the results shown in Table 1(xv). The actual bottleneck is represented by the work centre with the least capacity and in this case, it happens to be WC 600. As discussed in Chapters 7 and 8 respectively, the capacity problems at the bottleneck work centre is resolved by a combination of route and work pattern options.

WORK CENTRE NUMBER	REQUIRED CAPACITY [MINUTES]	AVAILABLE CAPACITY [MINUTES]	FREE CAPACITY [MINUTES]
WC600	3800	7200	3400

Table 1(xvi) Bottleneck Work Centre Report

[xvii] Backward Scheduling Results

Table 1(xvii) is a summary of the backward scheduling results and it indicates the start and finish date of each part at different work centres, working backwards from the required due date. For example, the third column represents the capacity required by a part, at a work centre ; the fourth indicates the free capacity available at the same centre ; the fifth highlights the start and end date of each part, at the above work centre. For example, PART A100 was started on 6038 at WC 600 and in accordance with the backward scheduling results, its first operation should have started on 24018 at work centre WC100. In reality, the start and finish dates are also determined by the current work centre load profile.

PART NUMBER	WORK CENTRE NUMBER	REQUIRED CAPACITY [MINS]	NET AVAILABLE CAPACITY [MINS]	START/END DAY
A100	WC600	1000	0	6038
A100	WC600	400	200	24028
A100	WC500	600	0	3028
A100	WC500	120	360	2028
A100	WC300	400	80	27018
A100	WC200	1000	0	27018
A100	WC200	920	0	26018
A100	WC200	440	40	25018
A100	WC100	200	0	25018
A100	WC100	160	320	24018
A400	WC600	400	80	23028
A400	WC500	300	180	1028
A400	WC400	200	0	1028
A400	WC400	20	460	31018
A400	WC300	200	280	26018
A400	WC200	400	80	24018
A400	WC100	300	180	23018
A200	WC600	1000	0	22028
A200	WC600	400	80	21028
A200	WC500	600	0	31018
A200	WC500	120	360	30018
A200	WC400	600	0	30018
A200	WC400	240	240	27018
A200	WC300	400	80	25018
A200	WC200	1000	0	23018
A200	WC200	520	0	20018
A200	WC200	40	440	19018
A200	WC100	200	240	19018
A500	WC600	200	400	20028

A500	WC500	150	330	27018
A500	WC400	100	380	26018
A500	WC300	100	380	24018
A500	WC200	200	280	18018
A500	WC100	100	180	18018
A300	WC600	400	200	17028
A300	WC500	300	180	26018
A300	WC400	200	280	25018
A300	WC300	200	280	23018
A300	WC200	400	80	17018
A300	WC100	300	0	17018
A300	WC100	220	260	16018
A600	WC600	200	280	16028
A600	WC500	200	280	25018
A600	WC400	100	380	24018
A600	WC300	100	380	13018
A600	WC200	100	280	13018
A600	WC100	100	180	13018
A900	WC600	400	200	15028
A900	WC500	300	180	24018
A900	WC400	200	280	23018
A900	WC300	400	80	12018
A900	WC200	300	0	12018
A900	WC200	220	260	11018
A900	WC100	200	60	11018
A700	WC600	400	80	14028
A700	WC500	200	280	23018
A700	WC400	300	180	20018
A700	WC300	150	330	11018
A700	WC200	100	380	10018
A700	WC100	100	280	10018
A800	WC600	500	100	13028
A800	WC500	200	280	20018
A800	WC400	200	280	19018
A800	WC300	200	280	10018
A800	WC200	300	180	9018
A800	WC100	200	0	9018
A800	WC100	20	460	6018
A999	WC600	400	200	10028
A999	WC500	400	80	19018
A999	WC400	300	180	18018
A999	WC300	400	80	9018
A999	WC200	300	180	6018
A999	WC100	200	280	5018

Table 1(xvii) Backward Scheduling Results

[xviii] Forward Scheduling Results

Table 1(xviii) is a summary of the forward scheduling results and it indicates the start and finish date of each part at different work centres. For example, the third column represents the capacity required by a part at a work centre ; the fourth indicates the corresponding work pattern at the above centre ; bottleneck work centre tends to have higher work pattern number (e.g. WC 600); the last column highlights the start and end date of each part. For example, PART A999 was started on 15038 at WC100 and completed its last operation on 27038 at work centre WC600. The same part started and finished its third operation on WC300 on the 15038 and 16038 respectively.

PART NUMBER	WORK CENTRE NUMBER	REQUIRED CAPACITY [MINS]	WORK PATTERN NUMBER	START/END DAY
A999	WC100	200	1	15038
A999	WC200	200	1	15038
A999	WC300	200	1	15038
A999	WC300	120	1	16038
A999	WC400	400	1	16038
A999	WC400	40	1	17038
A999	WC500	200	1	17038
A999	WC600	400	3	27038
A800	WC100	200	1	15038
A800	WC200	200	1	15038
A800	WC200	120	1	16038
A800	WC300	150	1	16038
A800	WC400	300	1	17038
A800	WC500	200	1	17038
A800	WC500	60	1	20038
A800	WC600	400	3	27038
A800	WC600	200	3	28038
A700	WC100	100	1	15038
A700	WC100	20	1	16038
A700	WC200	100	1	16038
A700	WC300	200	1	16038
A700	WC400	200	1	17038
A700	WC400	60	1	20038
A700	WC500	200	1	20038
A700	WC600	400	3	28038
A700	WC600	120	3	29038
A900	WC100	200	1	16038
A900	WC200	300	1	16038
A900	WC200	40	1	17038
A900	WC300	200	1	17038
A900	WC400	100	1	20038
A900	WC500	300	1	20038

A900	WC500	80	1	21038
A900	WC600	400	1	29038
A600	WC100	100	1	16038
A600	WC200	100	1	17038
A600	WC300	100	1	17038
A600	WC400	300	1	20038
A600	WC500	250	1	21038
A600	WC600	200	3	29038
A300	WC100	400	1	16038
A300	WC100	240	1	17038
A300	WC400	400	1	20038
A300	WC400	380	1	21038
A300	WC300	200	1	21038
A300	WC300	100	1	22038
A300	WC500	200	1	22038
A300	WC200	300	1	22038
A300	WC200	120	1	23038
A300	WC600	200	3	30038
A500	WC100	100	1	17038
A500	WC200	200	1	23038
A500	WC300	100	1	23038
A500	WC400	100	1	23038
A500	WC400	40	1	24038
A500	WC500	200	1	24038
A500	WC600	400	3	30038
A500	WC600	240	3	31038
A200	WC100	200	1	17038
A200	WC100	60	1	20038
A200	WC400	400	1	24038
A200	WC500	600	1	24038
A200	WC500	560	1	27038
A200	WC500	80	1	28038
A200	WC200	800	1	28038
A200	WC200	400	1	29038
A200	WC300	400	1	29038
A200	WC300	320	1	30038
A200	WC600	600	3	31038
A200	WC600	240	3	3048
A400	WC100	200	1	20038
A400	WC200	400	1	29038
A400	WC200	320	1	30038
A400	WC300	200	1	30038
A400	WC300	40	1	31038
A400	WC400	200	1	31038
A400	WC500	300	1	31038
A400	WC500	60	1	3048
A400	WC600	200	3	3048
A100	WC100	200	1	20038
A100	WC500	1000	1	3048
A100	WC500	580	1	4048
A100	WC500	100	1	5048
A100	WC200	1200	1	5048
A100	WC200	820	1	6048
A100	WC200	340	1	7048
A100	WC300	800	1	7048
A100	WC300	660	1	10048
A100	WC300	180	1	11048
A100	WC600	600	3	11048

A100	WC600	300	3	12048

Table 1(xviii) Forward Scheduling Results

APPENDIX B [TABLE 2]

RESULTS OF TEST RUN2

MAIN INPUT FILES

[i] Original MPS Data

WORK ORDER NUMBER	CUSTOMER NAME	PART NUMBER	QUANTITY ORDERED	ORDERED DATE	REQUIRED DUE DATE
1	JOHNS	A100	100	30127	6038
2	BOBBY	A200	100	30127	8038
3	RINGO	A300	100	30127	10038
4	ANDY	A400	100	30127	7038

Table 2 (i) Original MPS Data

[ii] Work Order Data

WORK ORDER NUMBER	PART NAME	PART NUMBER	QUANTITY ORDERED	ORDERED DATE	ISSUED DATE	DUE DATE
1	SMA	A100	100	30127	28028	6038
2	SMB	A200	100	30127	28028	8038
3	SMC	A300	100	30127	28028	10038
4	SMD	A400	100	30127	1038	7038

Table 2 (ii) Work Order Data

[iii] Process Route Data

ROUTE NO	PART NO	IDENT NO	SEQ NO	OPER. CODE	WORK CENTRE NO	SET TIME	OPERATION TIME
1	A100	1	10	1	WC100	50	50
1	A100	1	20	2	WC200	25	25
1	A100	1	30	3	WC300	10	10
1	A100	1	40	4	WC500	20	10
1	A100	1	50	5	WC600	25	25
2	A100	1	10	1	WC100	50	50
2	A100	1	20	2	WC300	15	15
2	A100	1	30	3	WC500	20	20
2	A100	1	40	4	WC200	10	10
2	A100	1	50	5	WC600	15	15
3	A100	1	10	1	WC100	50	50
3	A100	1	20	2	WC500	25	25
3	A100	1	30	3	WC200	30	30
3	A100	1	40	4	WC300	20	20
3	A100	1	50	5	WC600	15	15
1	A200	2	10	1	WC100	50	50
1	A200	2	20	2	WC200	25	25
1	A200	2	30	3	WC300	10	10
1	A200	2	40	4	WC400	15	15
1	A200	2	50	5	WC500	20	10
1	A200	2	60	6	WC600	25	25
2	A200	2	10	1	WC100	50	50
2	A200	2	20	2	WC300	20	20
2	A200	2	30	3	WC200	15	10
2	A200	2	40	4	WC500	10	5
2	A200	2	50	5	WC400	15	10
2	A200	2	60	6	WC600	20	25
3	A200	2	10	1	WC100	50	50
3	A200	2	20	2	WC400	10	10
3	A200	2	30	3	WC500	15	15
3	A200	2	40	4	WC200	20	20
3	A200	2	50	5	WC500	10	10
3	A200	2	60	6	WC600	15	15
1	A300	3	10	1	WC100	20	20
1	A300	3	20	2	WC200	10	10
1	A300	3	30	3	WC300	5	5
1	A300	3	40	4	WC400	5	5
1	A300	3	50	5	WC500	10	5
1	A300	3	60	6	WC600	10	10
2	A300	3	10	1	WC100	20	20
2	A300	3	20	2	WC300	10	10
2	A300	3	30	3	WC200	5	5
2	A300	3	40	4	WC500	5	5
2	A300	3	50	5	WC400	10	5
2	A300	3	60	6	WC600	5	5
3	A300	3	10	1	WC100	10	10
3	A300	3	20	2	WC400	10	10
3	A300	3	30	3	WC300	5	5
3	A300	3	40	4	WC500	5	5
3	A300	3	50	5	WC200	10	5

3	A300	3	60	6	WC600	5	5
1	A400	4	10	1	WC100	10	5
1	A400	4	20	2	WC200	10	10
1	A400	4	30	3	WC300	5	5
1	A400	4	40	4	WC400	5	5
1	A400	4	50	5	WC500	10	5
1	A400	4	60	6	WC600	10	10
2	A400	4	10	1	WC100	5	5
2	A400	4	20	2	WC300	10	10
2	A400	4	30	3	WC200	5	5
2	A400	4	40	4	WC500	5	5
2	A400	4	50	5	WC400	10	10
2	A400	4	60	6	WC600	5	5
3	A400	4	10	1	WC100	5	5
3	A400	4	20	2	WC200	10	10
3	A400	4	30	3	WC300	5	5
3	A400	4	40	4	WC400	5	5
3	A400	4	50	5	WC500	10	5
3	A400	4	60	6	WC600	5	5

Table 2 (iii) Process Route Data

MAIN OUTPUT FILES

[iv] New [Updated] MPS Data

WORK ORDER NUMBER	CUSTOMER NAME	PART NUMBER	QUANTITY ORDERED	ORDERED DATE	ACTUAL DUE DATE
1	JOHNS	A100	100	30127	5048
2	BOBBY	A200	100	30127	27038
3	RINGO	A300	100	30127	15038
4	ANDY	A400	100	30127	28038

Table 2 (iv) Updated MPS Data

[v] Capacity Requirements Data

PART NUMBER	WORK CENTRE NUMBER	REQUIRED CAPACITY [MINUTES]
A300	WC100	400
A300	WC400	400
A300	WC300	200
A300	WC500	200
A300	WC200	300
A300	WC600	200
A200	WC100	2000
A200	WC400	400
A200	WC500	600
A200	WC200	800
A200	WC300	400
A200	WC600	600
A400	WC100	400
A400	WC400	400
A400	WC300	200
A400	WC500	200
A400	WC200	300
A400	WC600	200
A100	WC100	2000
A100	WC500	1000
A100	WC200	1200
A100	WC300	800
A100	WC600	600

Table 2 (v) Capacity Requirements Data

[vi] Job Loading Sequence Report

WORK ORDER NUMBER	PART NAME	PART NUMBER	QTY	ORDERED DATE	ISSUED DATE	DUE DATE	SLACK [DAYS]
3	SMC	A300	100	30127	28028	10038	49
2	SMB	A200	100	30127	28028	8038	47
4	SMD	A400	100	30127	1038	7038	34
1	SMA	A100	100	30127	28028	6038	22

Table 2 (vi) Job Loading Sequence Report

[vii] Detail Capacity Requirements Report

DATE	WORK CENTRE NUMBER	WORK PATTERN NUMBER	PROCESS TIME REQD AT EACH WCN [MINS]
11038	WC100	1	480
13038	WC400	1	480
13038	WC300	1	480
13038	WC100	1	480
14038	WC300	1	480
14038	WC500	1	480
14038	WC200	1	480
14038	WC100	1	480
15038	WC200	1	480
15038	WC600	10	1440
15038	WC100	1	480
16038	WC100	1	480
17038	WC100	1	480
20038	WC100	1	480
21038	WC300	1	480
21038	WC400	1	480
21038	WC100	1	480
22038	WC400	1	480
22038	WC500	1	480
22038	WC400	1	480
22038	WC100	1	480
23038	WC500	1	480
23038	WC200	1	480
23038	WC400	1	480
23038	WC100	1	480
24038	WC200	1	480
24038	WC100	1	480
27038	WC200	1	480

27038	WC300	1	480
27038	WC600	10	1440
27038	WC300	1	480
27038	WC500	1	480
27038	WC200	1	480
27038	WC100	1	480
28038	WC200	1	480
28038	WC600	10	1440
28038	WC100	1	480
28038	WC500	1	480
29038	WC500	1	480
30038	WC500	1	480
30038	WC200	1	480
31038	WC200	1	480
3048	WC200	1	480
3048	WC300	1	480
4048	WC300	1	480
5048	WC300	1	480
5048	WC600	10	1440

Table 2 (vii) Detail Capacity Requirements Report

[viii] Manhours Status Report

DATE	GROSS AVAILABLE MANHOURS [MINS]	NET AVAILABLE MANHOURS [MINS]
11038	32 [1920]	24 [1440]
13038	32 [1920]	8 [480]
14038	32 [1920]	0
15038	32 [1920]	- 8 [- 480]
16038	32 [1920]	24 [1440]
17038	32 [1920]	24 [1440]
20038	32 [1920]	24 [1440]
21038	32 [1920]	8 [480]
22038	32 [1920]	0
23038	32 [1920]	0
24038	32 [1920]	16 [960]
27038	32 [1920]	- 40 [- 2400]
28038	32 [1920]	- 16 [- 960]
29038	32 [1920]	24 [1440]
30038	32 [1920]	16 [960]
31038	32 [1920]	24 [1440]
3048	32 [1920]	16 [960]
4048	32 [1920]	24 [1440]
5048	32 [1920]	0

Table 2 (viii) Manhours Status Report (First Technique)

[ix] Manhours Shortage Report

DATE	MANHOURS SHORTAGE HOURS [MINUTES]	EQUIVALENT NUMBER OF OPERATORS
15038	8 [480]	1
27038	40 [2400]	5
28038	16 [960]	2

Table 2 (ix) Manhours Shortage Report (First Technique)

[x] Operator Status Report

DATE	WORK CENTRE NUMBER	WORK PATTERN NUMBER	REQUIRED NO OF OPERATORS	NET AVAIL NO. OF OPER
11038	WC100	1	1	3
13038	WC400	1	1	3
13038	WC300	1	1	2
13038	WC100	1	1	1
14038	WC300	1	1	3
14038	WC500	1	1	2
14038	WC200	1	1	1
14038	WC100	1	1	0
15038	WC200	1	1	3
15038	WC600	10	3	0
15038	WC100	1	1	- 1
16038	WC100	1	1	3
17038	WC100	1	1	3
20038	WC100	1	1	3
21038	WC100	1	1	3
21038	WC400	1	1	2
22038	WC400	1	1	3
22038	WC500	1	1	2
22038	WC100	1	1	1
23038	WC500	1	1	3
23038	WC200	1	1	2
23038	WC400	1	1	1
23038	WC100	1	1	0
24038	WC200	1	1	3
24038	WC100	1	1	2
27038	WC200	1	1	3
27038	WC300	1	1	2
27038	WC600	10	3	- 1
27038	WC500	1	1	- 2

27038	WC100	1	1	-3
28038	WC200	1	1	3
28038	WC600	10	3	0
28038	WC100	1	1	-1
28038	WC500	1	1	-2
29038	WC500	1	1	3
30038	WC500	1	1	3
30038	WC200	1	1	2
31038	WC200	1	1	3
3048	WC200	1	1	3
3048	WC300	1	1	2
4048	WC300	1	1	3
5048	WC300	1	1	3
5048	WC600	10	3	0

Table 2 (x) Operator Status Report (Second Technique)

[xi] Operator Shortage Report

DATE	WORK CENTRE NUMBER	NUMBER OF OPERATORS THAT NEEDS TO BE SUPPLEMENTED
15038	WC100	1
27038	WC600	1
27038	WC500	2
27038	WC100	3
28038	WC100	1
28038	WC500	2

Table 2(xi) Operator Shortage Report (Second Technique)

[xii] Total Capacity Status Over Scheduling Horizon

WORK CENTRE NUMBER	REQUIRED CAPACITY [MINUTES]	AVAILABLE CAPACITY [MINUTES]	FREE CAPACITY [MINUTES]
WC100	4800	8080	3280
WC500	2000	12660	10660
WC200	2600	12560	9960
WC300	1600	12740	11140
WC600	1600	32720	31120
WC400	1200	12760	11560

Table 2(xii) Total Capacity Status Over Scheduling Horizon

[xiii] Bottleneck Work Centre Report

WORK CENTRE NUMBER	REQUIRED CAPACITY [MINUTES]	AVAILABLE CAPACITY [MINUTES]	FREE CAPACITY [MINUTES]
WC100	4800	8080	3280

Table 2(xiii) Bottleneck Work Centre

[xiv] Backward Scheduling Results

PART NUMBER	WORK CENTRE NUMBER	REQUIRED CAPACITY [MINS]	SURPLUS CAPACITY [MINS]	START/END DAY
A100	WC600	1000	440	6038
A100	WC500	600	0	6038
A100	WC500	160	320	3038
A100	WC300	400	0	3038
A100	WC300	80	400	2038
A100	WC200	1000	0	2038
A100	WC200	600	0	1038
A100	WC200	120	360	28028
A100	WC100	2000	0	10028
A100	WC100	1520	0	9028
A100	WC100	1040	0	8028
A100	WC100	560	0	7028
A100	WC100	80	400	6028
A400	WC600	400	1040	7038
A400	WC500	300	180	7038
A400	WC400	200	0	7038
A400	WC400	20	460	6038
A400	WC300	200	260	6038
A400	WC200	400	0	6038
A400	WC200	140	340	3038
A400	WC100	800	0	27018
A400	WC100	320	160	26018
A200	WC600	1000	440	8038
A200	WC500	600	0	8038
A200	WC500	160	320	2038
A200	WC400	600	0	2038
A200	WC400	280	200	1038
A200	WC300	400	0	1038
A200	WC300	200	280	28028
A200	WC200	1000	0	27028
A200	WC200	520	0	10028
A200	WC200	40	440	9028
A200	WC100	2000	0	25018
A200	WC100	1520	0	24018
A200	WC100	1040	0	23018
A200	WC100	560	0	13018
A200	WC100	80	400	12018
A300	WC600	400	1040	10038
A300	WC500	300	180	10038
A300	WC400	200	0	10038
A300	WC400	20	460	9038
A300	WC300	200	260	9038
A300	WC200	400	0	9038
A300	WC200	140	340	8038
A300	WC100	800	0	11018
A300	WC100	320	160	10018

Table 2(xiv) Backward Scheduling Results

[xv] Forward Scheduling Results

PART NUMBER	WORK CENTRE NUMBER	REQUIRED CAPACITY [MINUTES]	WORK PATTERN NUMBER	START/END DAY
A300	WC100	400	1	10038
A300	WC400	400	1	13038
A300	WC300	200	1	13038
A300	WC300	120	1	14038
A300	WC500	200	1	14038
A300	WC200	300	1	14038
A300	WC200	140	1	15038
A300	WC600	200	10	15038
A200	WC100	2000	1	10038
A200	WC100	1980	1	13038
A200	WC100	1740	1	14038
A200	WC100	1260	1	15038
A200	WC100	1020	1	16038
A200	WC100	700	1	17038
A200	WC100	560	1	20038
A200	WC100	80	1	21038
A200	WC400	400	1	21038
A200	WC400	100	1	22038
A200	WC500	600	1	22038
A200	WC500	220	1	23038
A200	WC200	800	1	23038
A200	WC200	540	1	24038
A200	WC200	60	1	27038
A200	WC300	400	1	27038
A200	WC600	600	10	27038
A400	WC100	400	1	21038
A400	WC400	400	1	22038
A400	WC400	20	1	23038
A400	WC300	200	1	27038
A400	WC500	200	1	27038
A400	WC200	300	1	27038
A400	WC200	20	1	28038
A400	WC600	200	10	28038
A100	WC100	2000	1	22038
A100	WC100	1520	1	23038
A100	WC100	1040	1	24038
A100	WC100	560	1	27038
A100	WC100	80	1	28038
A100	WC500	1000	1	28038
A100	WC500	600	1	29038
A100	WC500	120	1	30038
A100	WC200	1200	1	30038
A100	WC200	840	1	31038
A100	WC200	360	1	3048
A100	WC300	800	1	3048
A100	WC300	680	1	4048
A100	WC300	200	1	5048
A100	WC600	600	10	5048

Table 2(xv) Forward Scheduling Result