THE INVESTIGATION OF THE EFFECT OF SCHEDULING RULES ON FMS PERFORMANCE

BY

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DECLARATION

No part of the work described in this thesis has been submitted in support of an application for any other degree or qualification of this or any other University or C.N.A.A. or other institute of learning.

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DEDICATION

I never dedicate my works to people but death has stung me and now I dedicate this work to a man whose death has taught me to show people I love that I care before they go on.

BUT DEATH, DO NOT BE PROUD!

To the memory of my beloved Uncle Bimbo Balogun who died on the 17th of January, 2000. No death has touched me the way his did and still does.

ABSTRACT

The application of Flexible Manufacturing Systems (FMSs) has an effect in competitiveness, not only of individual companies but of those countries whose manufactured exports play a significant part in their economy (Hartley, 1984). However, the increasing use of FMSs to effectively provide customers with diversified products has created a significant set of operational challenges for managers (Mahmoodi et al, 1999). In more recent years therefore, there has been a concentration of effort on FMS scheduling without which the benefits of an FMS cannot be realized.

The objective of the reported research is to investigate and extend the contribution which can be made to the FMS scheduling problem through the implementation of computer-based experiments that consider real-time situations.

The research is centred on improving FMS performance through scheduling and involves modelling a dynamic FMS, developing custom-made scheduling rules and generating scheduling approaches applied to a hypothetical case study. The custom-made rules were compared with conventional rules and the effect of tool selection rules and scheduling environments were tested on schedule performances.

The main contributions of the research are as follows.

- The research illustrates the feasibility of enhancing the effectiveness of computer-based experiments to handle simultaneous scheduling of resources, multiple criteria and the dynamic nature of an FMS.
- Custom-made rules that compared favorably with conventional rules are developed.
- Scheduling approaches that out-performed both conventional and custom-made scheduling rules are presented.
- Based on the results of experimentation, a methodology is developed to determine scheduling rules for given system objectives.
- Based on the findings of the experiments and the understanding gained from the study, further work in this area of research is suggested.

The research shows that *new understanding of the way of combining scheduling rules and approaches can lead to an FMS scheduling methodology capable of maximising resource utilisation, minimising lead time and reducing the degree of tardiness.*

ABBREVIATIONS

FMS	Flexible Manufacturing System
FMC	Flexible Manufacturing Cell
WIP	Work In Process
EDD	Earliest Due Date
FCFS	First Come First Served
SPT	Shortest Processing Time
LPT	Longest Processing Time
PGLRM	Part Grouping, Loading and Routing Model
LM	Loading Model
CR	Critical Ratio
HRem	Highest Number of Remaining Operations First
LRem	Lowest Number of Remaining Operations First
HST	Highest Setup Time First
LST	Lowest Setup Time First
HPos	Highest Positional Factor Operations First
LPos	Lowest Positional Factor Operations First
LOR	Least Number of Operations Remaining)
SDT	Shortest Distance Travelled by tool transporter)
HVTL	High Value of Tool Life)
MML	Multi-Machine Loading
SML	Single Machine Loading
CML	Combined Machine Loading
MIP	Mathematical Integer Programming
MILP	Mathematical Integer Linear Programming
MWKR	Most Work Remaining
LWKR	Least Work Remaining
STT/D	Shortest Travel Time/Distance
DAA	Deadlock Avoidance Algorithm
M_X	resource Machine X
SF	Secondary Features experiments
NSF	Non-Secondary Features experiments

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CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION TO FLEXIBLE MANUFACTURING SYSTEMS

Flexible Manufacturing Systems (FMSs) are computer-controlled manufacturing systems consisting of machines or workstations linked together with automated material handling systems and capable of simultaneously producing multiple part types (Nof *et al.*, 1980). They frequently have tool-changing capability and adaptable fixtures that make it possible to carry out several operations in one set-up. Other activities such as controlled chip removal, heat treatment and inspection may also be available in these systems.

FMS originated in London, England in the 1960s when David Williamson invented a flexible machining system capable of operating continuously under computer control, with little human assistance. The applications were later broadened to take care of other aspects of manufacturing hence the name being changed to Flexible Manufacturing System. The first major steps towards FMS was made in 1975 when the first numerical control (NC) machining center successfully operated unmanned, utilizing an automated tool changing system as well as 10 static pallet tool and an automated pallet changing facility in Japan (Ranky, 1990). And since the 1970s, there has been explosive growth in system controls and operational enhancements, which has allowed FMS to grow, develop and gain wider acceptance (Luggen, 1991).

Though a new technology, FMSs offer several advantages over conventional systems. Some users in the United States such as Rockwell (truck axles), Caterpillar (construction equipment), and AVCO-Williamsport (aircraft engines) have reported a reduction in costs associated to floor space requirements, set-up, labour, part holding devices and throughput times (Miller, 1985). Similar reports have been given from surveys by Rush et al (1992), Greenwood (1988) and United Nations (1986). An FMS can increase flexibility, resource utilisation, quality, part variety, and decrease production costs, inventory, lead times, scrap and rework, especially more so, with good schedules.

The setbacks can however not be ignored and include the fact that an FMS is very capital intensive and it is difficult to economically justify its use. It is therefore not surprising that Kearney & Trecker, a pioneer in the manufacture of FMSs, have found that it typically takes three years of planning between the time a customer decides to buy an FMS and the time a system is installed (Kearney & Trecker Corp., 1982). Also, FMSs are complex and hence require a highly supportive and knowledgeable management and an adaptable workforce that has been involved in developing the system requirements (Talavage and Hannam, 1988). Furthermore, because of their added operation, machine and routing flexibility and the increased part type varieties, FMSs' increased capabilities imply additional constraints that complicate the scheduling of the system.

1.2. FMS SCHEDULING PROBLEM

In more recent years there has been a concentration of effort on scheduling of flexible manufacturing systems as these offer a controlled and predictable environment and allow the benefits of the systems to be more easily realized. Much research has been done on FMS scheduling and this is not surprising considering the diversity of scheduling problems. Few, if any, of the above-mentioned benefits can be achieved without efficient scheduling of work through the FMS.

A typical FMS scheduling problem consists of several conflicting objectives, some restrictive assumptions and multiple resource constraints in a dynamic environment. Making independent schedules, for example, for each of the resources does not always synchronize their availability and the associated costs can be too significant to be ignored. Most works also ignore the dynamic[1] nature of FMSs.

[1] A system is said to be dynamic if new operations arrive before completion of the schedule or the number of resources varies with time (for example, failure or repair of a machine) or the characteristics of the constraints are unknown or variable.

This research aims to look at multiple criteria, multiple resource constraints and the dynamic nature of an FMS.

1.3. FOCUS OF THE RESEARCH

Most researches of this nature use one of two approaches. Either, data is received from industry and attempts are made to improve system performance through the proposed research. Or hypothetical cases are worked on and later applied to industry by relaxing or further constraining existing assumptions. The latter approach has been adopted here primarily because it is easier to apply the developed scheduling approaches to almost any industry. The data derived from an industry is more difficult to use to investigate the problem in another industry.

Four major research issues are addressed namely:

1. The design of a planning module that considers the simultaneous scheduling of workpieces, cutting tools, fixtures, buffers and material handling devices in dynamic scheduling problems. Random arrivals of orders, machine breakdowns, tool wear, arrival of rush orders and withdrawal of orders are considered in the planning module.
2. The generation of planning strategies that aim to maximise resource utilisation, minimise lead time and force the orders (jobs) to conform to due dates or at least reduce the degree of tardiness.
3. Presentation of scheduling approaches that offer better schedule performances than those by the conventional rules and the custom-made scheduling rules analysed.
4. Presentation of the methodology for selecting appropriate scheduling rules given the required system objective.

1.4. ORGANISATION OF THESIS

The body of the thesis is broadly divided into three subgroups comprising of background and review, experimental research and research conclusions.

The background and review comprise of Chapters 1 and 2 and include an introduction to FMSs and the literature review of FMS scheduling. Chapter 1 defines an FMS, its history and highlights its reported benefits and limitations. It also emphasizes the FMS scheduling problem. Most FMS scheduling is directed towards the generation of schedules which must be evaluated in the light of one or two criteria considering one or two resources and a static environment. This research however looks into dynamic scheduling problems considering several resources (primary and secondary resources) and multiple criteria. Chapter 2 looks into the various aspects of the FMS scheduling problem and particularly concentrates on resource loading, methodologies used, assumptions and common objectives that have been considered in past research.

The experimental research section comprising of Chapters 3 – 9 highlights the scope of the research, the capabilities of the planning module and describes the design of the experiments and the analysis of the results. Chapter 3 summarises the work undertaken and Chapter 4 illustrates how Preactor was used to model the scheduling problem. In Chapter 5, an explanation of how the scheduling rules were evaluated and a definition of the scheduling output terminologies are presented. Chapter 6 presents the design of the experiments, elaborating on the scheduling inputs and outputs. The chapter further elaborates the scope of research, identifying all the possible experiments and the logical process of deciding on which experiments to perform. Chapter 7 presents the results of the experiments and Chapter 8, the analysis of the results and the scheduling approaches that provide better schedule performance than the custom-made and the conventional scheduling rules. Chapter 9 deals with the application of the scheduling approaches presented in Chapter 8 to a hypothetical case study order set.

The final section of the thesis - Chapters 10 – 12 - analyses research issues reported. Based on the results of Chapter 8, Chapter 10 presents a methodology for selecting the scheduling rules for given system objectives. Chapter 11 presents a conclusion from the experiments carried out and Chapter 12 provides some recommended further work in the area of research.

The appendices include a related published paper by the author, the manufacturing database used, an explanation on how the custom-made rules were written in Visual Basic V and the results of the experiments.

The thesis layout is graphically presented in Figure 1-1. As can be seen in the figure, Chapters 3, 5 and 6 are related and encompassed in Chapter 4, the structure of the research. The scope of research guides design of the computer-based experiments and chapter 5 defines all that have been used to design these experiments. These chapters form the structure of the research. The literature review opened up areas for further research and a part of this (illustrated by the greyed patch in Figure 1-1) has been focussed on.

While the size of the chapters gives an indication of the magnitude of work done in that chapter as predicted by their representative blocks in Figure 1-1, it does not relate to their importance. The conclusions chapter for instance is one of the smallest blocks although it is by no means less important than the structure of research which is the second largest.

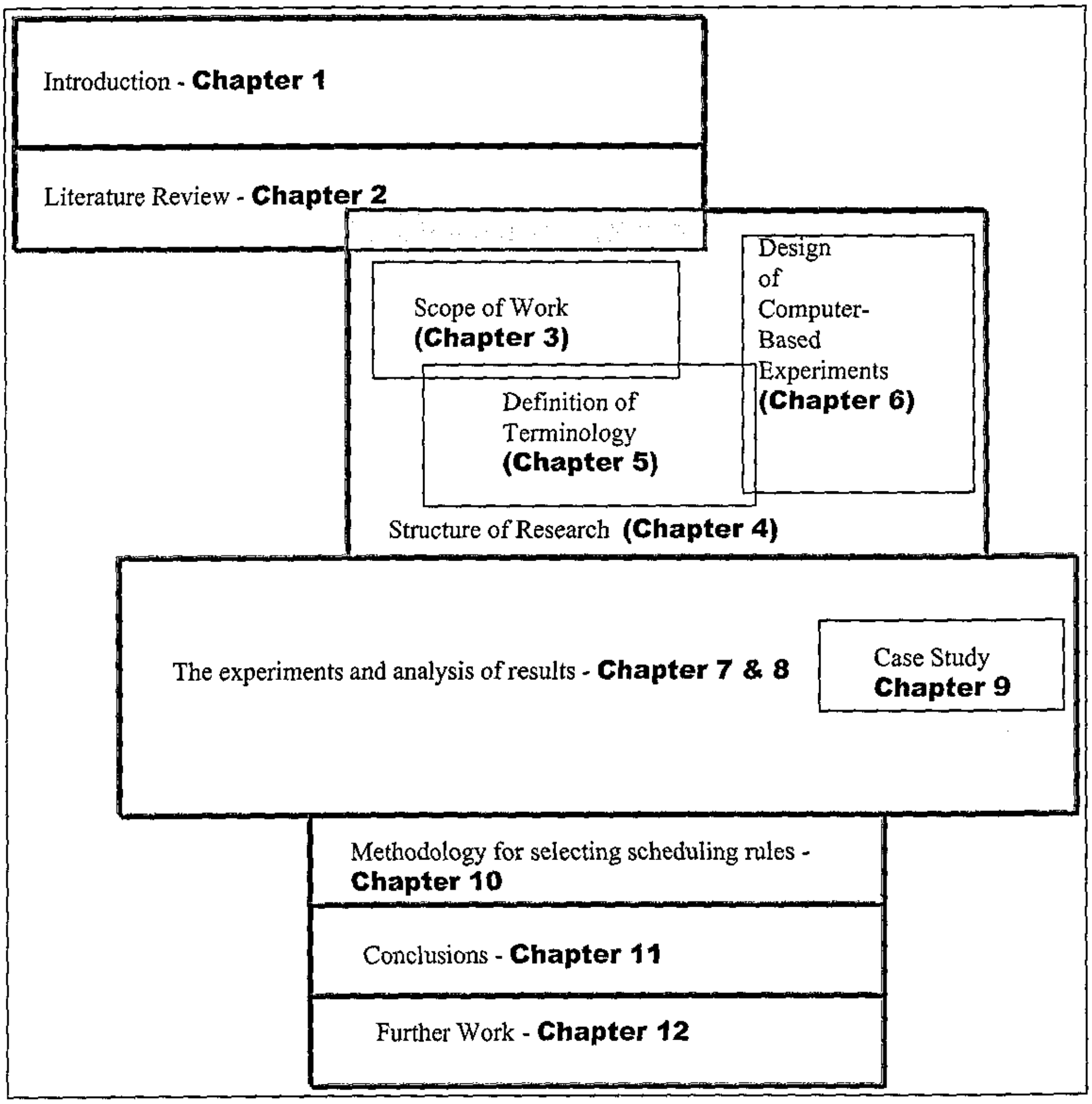

Figure 1-1: The Structure of the Thesis

CHAPTER 2

LITERATURE REVIEW

FMS scheduling is very complex and difficult to solve because an FMS is highly dynamic and its scheduling task requires additional resource constraints such as tools, fixtures, material handling equipment and limited buffer space (Sabuncuoglu, 1998). Previous research has often simplified the problem by decomposing the whole problem into sub-problems each considering one type of decision and most often by ignoring resource constraints other than machines (Liu and MacCarthy, 1999). Several researchers have considered some of the FMS features and resources simultaneously and some of their considerations and approaches are reviewed in the following sections.

2.1 SUB-PROBLEMS OF THE FMS SCHEDULING PROBLEM

The FMS scheduling problem comprises mainly of part and machine family selection, resource allocation, routing and sequencing. To date, these subproblems have been looked into either individually or combined. Although each sub-problem can be optimised independently, this results in sub-optimisation of the global scheduling problem. Below are some researches that have been reported on FMS scheduling.

2.1.1 PART AND MACHINE FAMILY SELECTION

When large production orders of several part varieties are to be handled by the resources in a manufacturing system, they can be divided into batches. Creating these part families has the objective of ensuring that system utilization is maximized and that the number of trips taken by automated material handling devices is optimal. There is also the tendency to minimise total production time, the time between two successive batches and the time within each batch. The total throughput time of parts, and the number of batches required to process all parts can also be minimised and the average machine utilisation over all batches (Suri and Whitney, 1984)) maximised. Past research in this area has focused primarily on the formation of manufacturing-oriented part families in which similarities among parts are predominantly established on the basis of machine or operation requirements.

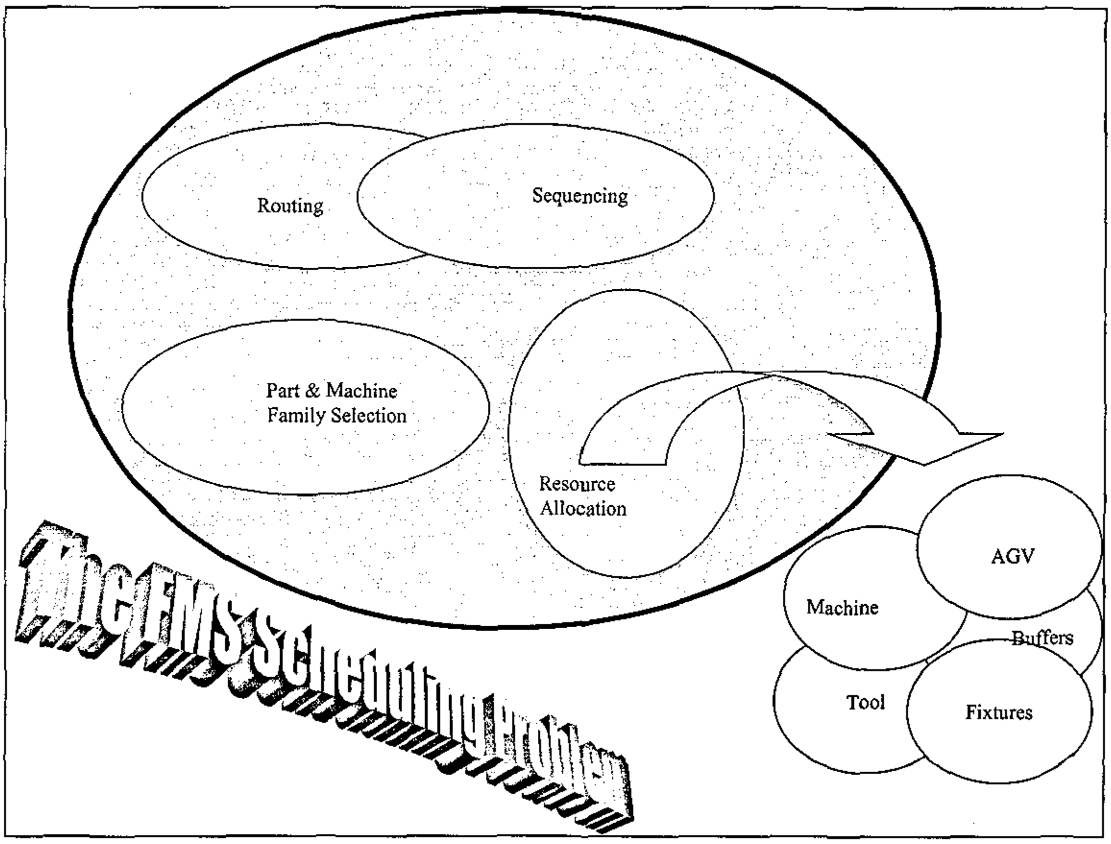

Figure 2-1: The Sub-problems of the FMS Scheduling Problem

A review of research done in this area can be found in Balogun and Popplewell (1999). More recently, creating part families from parts having similar sequence of operations have been handled by Suresh et al (1999).

Machines can be grouped together based on the similarity in their capabilities. This could result in a reduction in operating costs resulting from the minimisation of cost or distance of intercellular moves and the minimisation of cost of duplicating machines (Seiffodini 1989). A review of research done in this area can be found in Balogun and Popplewell (1999).

2.1.2 RESOURCE ALLOCATION

The primary resources of an FMS include tooling, machines and transport, and it is the efficient allocation of these resources in meeting production orders which provides an FMS with the flexibility to respond quickly to dynamic changes. The effective allocation of resources lowers the total cost of a project and often frees resources for projects that might not have been undertaken otherwise. However

Stecke and Browne (1985) and Kulatilaka (1988) observed that most FMS scheduling researchers ignore this, most probably to ease analysis. Were resources unlimited, then scheduling difficulty would be trivial as all jobs could then be set to start at their earliest starting times.

Typical objectives in allocating resources include obtaining minimum total machining time, minimum total machining cost, minimum makespan and minimum disparity in utilization of different machines (Ram et al 1990).

The following sub-sections deal with the main types of resource allocation.

2.1.2.1 MACHINE ALLOCATION

This involves assigning operations, and implicitly parts, to machines. A part in an FMS can have alternative machines for its operations, with different degrees of preference for different machines (Chandra and Talavage 1991). Maximization of work progress rate can be achieved by loading parts on their most preferred machines as often as possible.

Machine loading could lead to the minimisation of the number of movements from machine to machine and the balancing of the workload per machine for a system of groups of pooled machines of equal sizes. Maximization of the utilization of resources, minimization of tooling and processing costs, and the maximization of throughput rates (Rajamani and Adil 1996) could also result. Most researchers have considered one or more of these objectives.

A review of research done in this area can be found in Balogun and Popplewell (1999).

2.1.2.2 TOOL LOADING

Potential costs resulting from poor management of tool requirements and tooling activities can be quite significant (Chung, 1991). Recently, the tool management problem has become particularly more acute with the increasing automation of production. The capital outlay for tooling could approach 25% of the initial cost of an FMS (Tomek, 1986). Up to 80% of a foreman's time may be spent looking for or expecting materials and tools, and operators may spend up to 20% of their time searching for cutting tools (Mason, 1986). This statistics show that tool unavailability may hamper the smooth flow of products resulting in long work in process (WIP) inventory and frequent tool changes resulting in under-utilization.

Cantamessa and Lombardi (1993) stated that simple tool management techniques may force one to have many tools and make part flow management more complicated. It does not seem very likely since this implies that the amount of time wasted waiting for a tool is minimised.

Where the objective of an FMS is the simultaneous manufacture of a mix of parts without costly time-consuming changes between part mixes, tooling can be of great concern. The selection of the most suitable job from a queue waiting for machining could be based on work-piece priority, minimum of tool transport for the machining operation on a given machining center, and the effort to complete the part (Tomek,1986). And by sequencing jobs that require the same tools adjacent to each other, the amount of setup time could be significantly reduced (Reddy et al, 1992).

Alberti et al (1991) have proposed an architecture of tool database, part database and rules for tool loading, the tool database containing relevant information related to each tool required by the process plan and include tool life, and the part database, the duration of each of the fixturing and defixturing operations. The rules for loading were based on longest or shortest residual tool life. Also, tool assignment rules based on tool availability, tool changes and the criticality of jobs have been employed (Ghosh et al, 1992).

Chandra et al (1993)'s research on tool management at the machine level have focused on four issues: selection of tool equipment, selection and placement of tools in a magazine, tool replacement and tool sequencing on a flexible machine. The objective of their research was to find an optimal sequence of jobs that minimized the total time of changing tools and fixtures while guaranteeing that jobs were finished before their due dates.

Rahimifard (1996) has considered the allocation of batches of a single job across different machines in the cell, MML, and an alternative job allocation policy SML, where all batches of a job were allocated to a single machine. While MML could result in very high tooling costs because identical sets of cutting tools were loaded on different machines at the same time, SML prevented the duplication of identical toolkits on different machines and the generation of a large number of partially used cutting tools. A novel job allocation policy, CML, was then presented that incorporated the advantages of both by minimizing tool and fixturing requirements and achieving the completion dates of jobs. This involved pre-allocating jobs to resources using SML and re-allocating jobs that will be late by using the MML to achieve the due date.

Kashyap and Khator (1996) have assessed the operating status and considered a situation where tools required for the next operations were determined by evaluating the status and condition of a tool required while the current operation was in progress. Request selection rules used include FCFS, LOR (least number of operations remaining) and SPT (shortest processing time) and tool selection rules were used to select the machine from which tool was to be transported to fulfil a selected request. These included SDT (shortest distance travelled by tool transporter) and HVTL (high value of tool life) and the conclusion was that SDT performed better than HVTL.

Tsukada (1998) has focussed on the problem caused by unexpected tooling requirements and expressed that while some of the constraints of scheduling may need to be relaxed to get a solution, the tool availability problem may be less restrictive if a required tool assigned to another machine could be borrowed. The goal of allocating tool time slots to tasks was to maximize the number of tasks allowed use of each of the required tools. Three ways of handling tool availability was considered - reject task, request for tool rescheduling and negotiation to relax local constraints.

A review of research done in this area can be found in Balogun and Popplewell (1999).

2.1.2.3 AGV ALLOCATION

Ramana et al, 1997 say that handling cost can be as high as 2/3 of the total manufacturing cost and that most of production time can be consumed in handling materials before, during and after the manufacturing. Although that is a rather high ratio of handling cost to total manufacturing cost, handling cost can indeed be significant. The reasons for the losses and inefficiencies during operation of the system include loading, unloading times, return trips without loads, traffic scheduling and poor schedules.

Sabuncuoglu and Hommertzheim (1989) have considered AGV and machine scheduling with finite buffer capacity.

Sabuncuoglu and Hommertzheim (1992) have proposed an algorithm which considered important interactions between machines and AGVs during the scheduling process based on the idea that a job should not be scheduled on a machine (or AGV) if it will have to wait for an AGV (or machine) in the next activity. A hierarchical approach was used and the logic associated to scheduling jobs on the AGV consisted of four levels of push, buffer, pull and push-pull logics.

The push logic identifies workstations that are blocked or with full queues and since they could not accept parts, one of the outgoing parts had to be delivered to its next workstation. Either the criticality of workstations, the highest demand for such workstations, queue levels at workstations, location of workstation to the idle AGV, the least amount of work remaining or even EDD determined which part was done first. If there was consistently a tie, FCFS rule was used to break tie.

In the buffer logic level, if there were some parts in the central buffers, a part with the most available destination queue space was serviced first and if there is a tie, a part with the least amount of work remaining or EDD was selected.

In the pull logic level, if there are some idle machines, other workstation queues are searched to locate a workstation that can immediately deliver a part to this idle workstation. If there is more than one idle workstation and more than one station which can deliver the parts, then the AGV is scheduled based on the workstation nearest to the current location of the idle AGV or a part with the least amount of work remaining or EDD.

In the push-pull logic, the AGV selects the part with the lowest expected waiting time. The logic associated with scheduling jobs on the machine whenever a workstation completed processing a part and became available for other parts in the queue, was by selecting a part with the smallest calculated priority index value first.

Ulusoy and Bilge (1993) have formulated the combined machine and material handling problem as a nonlinear MIP model which they have solved by an iterative heuristic procedure. The procedure was based on three components, an algorithm that generates the machine schedules, another that finds a feasible solution to the vehicle scheduling problem, and an iterative structure that links the two and facilitates the search for a good solution. Rules used for the machine schedule generation included most work remaining (MWKR), least work remaining (LWKR), and shortest processing time (SPT). The AGV schedule was an integral part of the schedule rather than a reaction to the machine schedule.

Ganesharajah and Sriskandarajah (1995) have considered AGV-conflict avoidance, AGV dispatching policies and AGV routeing apart from job scheduling. Klein and Kim (1996) proposed multi-attribute decision models to meet multiple objectives such as minimizing waiting times, queue lengths, travel distance, and maximizing throughput and vehicle and machine utilization. They focussed on the vehicle-initiated task assignment problem since, according to Egbelu and Tanchoco (1984), vehicles are rarely free to allow the invoking of work-center-initiated rules when material flow rate is high. Single-attribute dispatching rules include the STT/D (shortest travel time/distance) rule which is affected by system layout such that some cells may be chosen less often than others or never chosen, leading to abnormally long queue length resulting in system blockage.

Akturk and Yilmaz (1996) have proposed an approach to incorporate AGVs into the overall decision-making hierarchy considering the job-based approach to schedule the tightly constrained jobs first without considering unloaded travel times of vehicles and the vehicle-based approach to minimize the unloaded travel times. While the latter eliminates the disadvantage of the former, it disregards the critical jobs. The proposed algorithm combined these two approaches such that both critical jobs and the unloaded travel times are considered simultaneously.

Ulusoy et al (1997) have addressed the simultaneous scheduling of machines and AGVs in an FMS to minimize the makespan by using genetic algoritm.

A review of research done in this area can be found in Balogun and Popplewell (1999).

2.1.2.4 WORK HOLDING SUPPORT MANAGEMENT

Fixtures for machining operations amount on average to 10-20% of the total production cost (Fuh et al, 1993). Inadequate allocation of fixturing elements may result in inefficient production, poor machine utilization and job tardiness (Pandey and Ngamvinijsakul, 1995). Also, fixturing may present serious problems for FMS production that copes with a great variety of parts and may also influence its quality since fixtures could determine the precision of finished parts and clamping stiffness (Tomek, 1986).

Zavanella and Bugini (1992), Stecke (1992), Chandra et al (1993), Rahimifard (1996) and Maimon et al (2000) have considered fixture scheduling in their research.

2.1.2.5 BUFFER ALLOCATION

Buffers affect the efficiency of a production line. Ineffective allocation of buffers could lead to deadlocking which could inhibit further part movement. It could cripple entire systems and render automation operations impossible, as manual clearing of buffers or machines and restarting of machines becomes necessary. There is thus a loss in production and labor cost (Viswanadham et al, 1990). Also where machine breakdowns cause starvation or blocking to other machines due to sequence dependency, buffers tend to isolate the effect on the rest of the system (Alvarez-Vargas et al, 1994).

Sabuncuoglu and Hommertzheim (1989) have been able to conclude that to prevent blocking, the number of incoming part in the queue had to be limited to one less than the queue capacity. If the machine was still blocked, then one of the outgoing parts was transferred to the nearest central buffer area. They also concluded that at high utilization level, the system can easily be congested and that there then had to be a limit to the number of parts in the system. This limit is dependent on scheduling rules, queue capacities and the capacities of the machines and the AGV system.

Banaszak and Krogh (1990) have noted that four conditions are necessary for deadlocks to occur. There needs to be mutual exclusion concerning resources (resources can be allocated to only one job at a time), a hold on resources while waiting for additional required resources to become available, no preemption, and circular wait. To avoid deadlocks at least one of these conditions must be unsatisfied. They focused on not satisfying the fourth condition. A deadlock avoidance algorithm (DAA) was presented, a feedback policy that uses the current states of the resources and the known operation sequences for the active jobs to inhibit requests for resources only when they will potentially lead to circular wait conditions. This maximised resource usage and prevented potential deadlock states.

Viswanadham et al (1990) have proposed a petri-net based on-line monitoring and control system for deadlock avoidance. They noted that deadlock prevention could lead to inefficient resource utilization because it involved the use of static resource allocation policies in the design stage for eliminating deadlocks. They therefore used deadlock avoidance which involved dynamic resource allocation policies and which, when enforced during the operation of the system leads to better utilization and throughput.

Wysk et al (1991) have also presented a solution to resolving deadlocks by using a storage buffer although the improper use of the available storage could result in system deadlock. Two approaches often used to design deadlock-free systems are ensuring that all parts flow in the same direction and batching of parts waiting to be processed according to their flow direction. Unfortunately, both approaches undermine the 'flexibility' of an FMS, as the first limits the types of parts that can be processed, and the second reduces total machine utilization.

Leung and Sheen (1993) have defined deadlocking as occurring when various products with different routings compete for a finite number of resources and then proposed two algorithms to resolve this, one following the deadlock detection/recovery strategy and the other avoids a deadlock state. The strategies revolved round reserving a buffer space in the central buffer, the first using it solely for the purpose of recovering from a deadlock. In the second strategy, noting that the throughput of an FMC decreases as the number of spaces in the central buffer increases, and that if the reserved buffers space can be used more often and yet carefully to resolve deadlocks, the performance of the FMC can be improved.

Sabuncuoglu and Karabuk (1998) have proposed an algorithm that considered the scheduling factors of machines, material handling, finite buffer capacity, routeing and sequence flexibilities and specifically utilizes system and job-related information to generate machine and AGV schedules. They used a heuristic based on the filtered beam search technique that offered the advantages of aggressive search, speed and flexibility (incorporation of machine, AGV and buffer considerations). In the proposed algorithm, prevention (the potential paths that may lead to deadlocks are avoided as much as possible) and recovery were used to handle deadlocks.

2.1.3 ROUTING AND SEQUENCING

Traditional job shop scheduling problems generally assume that there is a single feasible routing with which a part can be processed in a shop, an assumption which is rarely true in today's flexible production system (Kim and Egbelu, 1999). For most manufactured parts, it is possible to have more than one sequence of operations and although this increases production flexibility, it also further complicates the scheduling problem. Nevertheless, when more than a sequence of operations exist, it becomes necessary to select a route that optimises the system's performance. Two main objectives for determining operation sequences are the minimization of transportation of parts between and within cells, and the minimization of set-up and tool changes. Other objectives include minimizing mean flow times, makespan, lateness and the number of tardy jobs (Co et al 1988).

A review of work done in this area has been reported in Balogun and Popplewell (1999). More recently, Mahmoodi et al (1999) has examined the effects of scheduling rules and routing flexibility on the performance of a constrained FMS. Shop load, shop configuration and system breakdowns were considered and results indicated that in the presence of total routing flexibility, the effects of shop load, system breakdowns and scheduling rules were significantly dampened.

2.1.4 INTEGRATED APPROACHES

The sub-problems of the scheduling problem are interrelated. Independent solutions to each may lead to sub-optimal solutions. For this reason, researchers have attempted solving some of these problems simultaneously.

A review of work done in this area has been reported in Balogun and Popplewell (1999). Other works in this area include:

- 0-1 mixed integer program formulation for batching, loading and routing (Chen and Chung 1996);
- Heuristic on routing and sequence flexibilities and generation of machine and AGV schedules considering finite buffer capacity (Sabuncuoglu and Karabuk 1998);
- Simulation-based approach on loading, part inputting, routing and dispatching issues (Mohamed 1998);
- 0-1 mixed integer program formulation for batching, loading and routing (Atlihan et al 1999);
- Mixed integer linear program for machine loading, routing and part type selection (Guerrero et al 1999)

Mohamed et al (1999) have proposed two models, model LM which required no part grouping and model PGLRM (refer to abbreviations) which required part grouping. These two models addressed machine loading and part routing concurrently. Model PGLRM results in a lower value of makespan and also imparts higher routing flexibility as compared to existing part grouping model.

2.2 SCHEDULING ASSUMPTIONS

To model and solve the scheduling problem in a mathematically feasible way, many researchers have greatly simplified the problem. Analytical solutions are infeasible for problems of much complexity. For this reason, most scheduling problems are assumed to be deterministic and static, with only a small number of resources, operations and constraints considered. But the complexity of the FMS scheduling problem is high because of the dynamic environment, the multi-criteria optimization objective, the presence of secondary resources and the other sub-problems of FMS scheduling. Some researchers consider machining and assembly systems as independent because of the uncertainties involved with assembly. Also, most reported research consider none, one or at most some of the factors of route flexibility, tool slots, part transportation, machine availability, buffer spaces and pallets (Basnet and Mize, 1994).

2.3 SCHEDULING OBJECTIVES

In discussing the FMS scheduling problem and its component sub-problems, researchers propose working towards a variety of objectives. According to Rinnooy Kan (1976), objectives can be based on completion times, utilization and inventory costs, and on due dates. And according to Smith et al (1986), the most important criteria are meeting due dates, maximizing system and machine utilizations, minimizing in-process inventories, maximizing production rates, minimizing setup and tool change times, minimizing mean flow times and balancing machine utilizations. Grant and Clapp (1988) observed that the main consideration was maximizing throughput while ensuring that delivery due dates are met, inventory costs are maintained at acceptable levels, equipment, personnel and other limited resources are well-utilized, workloads balanced and adaptations made quickly in the event of an unexpected event. However an attempt to achieve several objectives simultaneously would lead to conflicts and contradictions.

A dichotomy of scheduling objectives exists in FMS scheduling. One class of objectives is directly related to satisfying the needs of the FMS customers, whether these are true customers of the enterprise as a whole, or downstream processes dependant on supply from the FMS. These objectives are centered around minimizing lateness, meeting due dates, minimizing order lead times and achieving a high degree of flexibility.

The second class of objectives is essentially aimed at the internal efficiency of the FMS. Whilst this may well lead to some improvement from the customers' perspective, it need not: for example a higher utilization and setup performance can be achieved at the cost of flexibility. These secondary objectives may be better applied to the design of an FMS, as their achievement is frequently of little real value once the FMS capacity and configuration is realized.

2.4 SCHEDULING METHODOLOGIES

Considerable research work has been done in the area of job shop scheduling including those by Blackstone et al (1982), French (1987), Foo and Takefuji (1988) and Zhou et al (1991). Although a job shop can be designed to handle part variety and be automated to some degree, it does not have the structural complexities of an FMS. Also, the techniques for job shop scheduling usually result in fixed schedules that do not provide for the flexibilities of an FMS (Nauman and Gu, 1997). Besides, the existing general job shop scheduling theory offers exact solutions for only small-sized problems. The proposed use of optimization modeling generates a large number of variables and constraints that lead to non-optimal solutions. In an FMS, the numbers of variables and constraints are even greater.

For these reasons coupled with the fact that most manufacturing systems need scheduling for dynamic and unpredictable conditions, artificial intelligence, simulation-based and heuristic-based approaches are often considered in FMS scheduling. There are however five basic approaches to the scheduling problem namely combinatorial optimization, artificial intelligence, simulation-based scheduling with dispatching rules, heuristics-oriented and multi criteria decision making.

2.4.1 COMBINATORIAL OPTIMIZATION

The discipline of operational research has contributed a number of techniques to scheduling based on combinatorial optimization methods. The scheduling problem can be handled as sub-problems and each sub-problem can be optimized independently resulting in suboptimization of the global scheduling problem. Alternatively, the global problem can be presented as a system of mathematical equations. Most of these formulations do not however consider the complexity and unpredictability in an FMS. Also, mathematical programming can be time consuming and very difficult to solve. Stecke (1983) observed that large problem sizes can not be feasibly handled by mathematical programming but recent theoretical advances in integer programming and advances in computer hardware have resulted in commercial software that can handle large integer programs (Jiang and Hsiao, 1994).

Mathematical programming formulations have been proposed by Hitz (1979), Finke and Kusiak (1985), Raman et al (1986), Sawik (1990) and Aanen et al (1993). To date these formulations have been used to evaluate optimal performance measures in scheduling problems, but this is limited to problems with little complications or uncertainties.

2.4.2 ARTIFICIAL INTELLIGENCE (AI)

Until recently, methods of tackling the scheduling problem were dominated by combinatorial optimization approaches. Their limitations necessitated rapid expansion in the application of AI. AI techniques can, to some extent, handle dynamic conditions in manufacturing systems. It is therefore not surprising that new AI techniques are evolving and established ones are being improved. AI embraces a number of paradigms and some of these are discussed below.

2.4.2.1 EXPERT SYSTEMS

Expert systems have been used to generate schedules using experience or expert knowledge. They have thus been able to handle a variety of scheduling problems, and have been especially effective in handling dynamic problems.

A review of research in this area can be found in Balogun and Popplewell (1999).

2.4.2.2 NEURAL NETWORKS

Neural networks have been used to generate schedules in various manufacturing systems. They do not however guarantee optimal solutions (Sabuncuoglu 1998). Also, very little has been reported on their application to complicated (unpredictable) FMS scheduling problems.

A review of research in this area can be found in Balogun and Popplewell (1999).

2.4.2.3 GENETIC ALGORITHM (GA)

Genetic algorithms can be used to improve generated behavior or characteristics and have been used to generate schedules. A review of research in this area can be found in Balogun and Popplewell (1999).

More recent research has been carried out by Rossi and Dini (2000) who generated alternative plans using genetic algorithms, following part-flow changes and unforeseen situations with the objectives of reducing machine idle times and makespan.

2.4.2.4 OTHER AI TECHNIQUES

Other AI approaches include fuzzy logic, simulated annealing and tabu search.

A review of work done in this area has been reported in Balogun and Popplewell (1999).

2.4.3 SIMULATION-BASED WITH DISPATCHING RULES

Simulation research has been used in conjunction with simple dispatching rules. Askin and Subramanyam (1986) point out that the rules on their own are somewhat general and are considered inappropriate for FMS scheduling problems as they do not exploit its flexibility. It is therefore not surprising that recent research has exploited the use of more modern hardware and simulation software to combine simulation with AI and heuristic methods.

A review of work done in this area has been reported in Balogun and Popplewell (1999).

2.4.4 HEURISTICS-ORIENTED

Mathematical solutions are infeasible even for deterministic formulations of the FMS scheduling problem, as the computation time for deriving even a moderate-sized FMS schedule is unacceptable. This has led to the development of heuristic procedures (Tiwari 1997).

A review of work done in this area has been reported in Balogun and Popplewell (1999).

More recently, Sabuncuoglu and Karabuk (1998) have proposed a heuristic based on filtered beam search which considered finite buffer capacity, routing and sequence flexibilities and generated machine and AGV schedules. Liu and MacCarthy (1999) have presented two heuristic procedures for FMS scheduling. The heuristics decompose the complex scheduling problem into a series of relatively easily handled sub-problems and solve them using MILP models and heuristics. Procedures considered machine sequencing and critical resource constraints.

Heuristics have been used to make dispatching decisions. They are excellent for dynamic problems (Basnet and Mize 1994). They do not however guarantee optimal solutions.

2.4.5 THE DYNAMIC FMS SCHEDULING

Little research has been done in the area of dynamic scheduling of FMSs and a review of some of these works can be found in Ramasesh (1990) and Suresh and Chaudhuri (1993).

Two methods have been adopted for the dynamic scheduling of FMSs namely

- Rule-oriented which allows the identification of priority dispatching rules from a set of heuristic scheduling rules with respect to a given set of jobs. Approaches have included AI techniques such as Neural Networks (Wang, 1995), Fuzzy Logic (Perrone et al, 1995), Knowledge Based Systems (O'Kane et al, 1994) and Hybrid systems (Fujimoto et al, 1995)
- Job-oriented which generate the schedule through the analysis of most efficient alternatives in order to select the optimal (or near optimal) solutions (Liu and MacCarthy, 1999).

Rossi and Dini (2000) generated alternative plans using genetic algorithms, following part-flow changes and unforeseen situations with the objectives of reducing machine idle times and makespan.

SUMMARY

Several reported methods of generating schedules ranging from conventional to artificial intelligence and heuristic-based, assumptions ranging from static, deterministic environments to more complicated, unpredictable situations, and single to multiple criteria objectives have been identified. Different factors and assumptions have been simultaneously considered with the objective of reducing non-productive times. Few researchers have considered simultaneous scheduling of parts and resources and even fewer have considered assembly.

The essential point is that FMS scheduling is a process of prioritizing and balancing conflicting objectives, and that to be successful, no single objective can be applied, and no single sub-problem can be solved in isolation from the others. All the sub-problems must be addressed simultaneously with the common objective of meeting customer demand.

It is proposed that only objectives directly relevant to customers' demands should be employed as the primary objectives in dynamic scheduling of an FMS, and that the objectives related to internal efficiency of the FMS can play at most a secondary role.

This research will use simulation-based scheduling coupled with heuristic methods to handle multiple criteria, dynamic scheduling problems considering several resources (primary and secondary) and assembly. The multiple resource constraints proposed to be considered in this work would inherently take into account the following sub-problems - machine allocation, tool loading, AGV allocation, fixture loading and buffer allocation.

CHAPTER 3

THE SCOPE OF RESEARCH

The huge investment and operating costs of an FMS required the systems to be economically justified and one way of achieving this is by improving FMS performance through the scheduling of work. Incidentally, most FMS scheduling researchers have not adequately considered the simultaneous scheduling of resources, multiple criteria and the dynamic nature of an FMS. To adequately represent an FMS, these features cannot be ignored. Thus the identification of the FMS scheduling problem and the need for economic justifications led to research that concentrates on a combination of these features.

This chapter identifies the areas of investigation the research will pursue. This consists of:

1. The development of a planning module to evaluate the simultaneous scheduling of FMS elements.

The simultaneous scheduling of work-pieces, cutting tools, fixtures, buffers and material handling devices will be considered by assuming finite capacity of each resources. A minimum number of buffers to prevent blocking or locking[1] in the system based on the number of resources in the system and on the number of products being made will be determined. Since an AGV is required only when there is a request for a different tool kit with each subsequent operation, AGVs will be treated like machines, as primary resources and the rest as secondary resources. Primary resources in this research refer to the machines that are needed for processing the operations. Tools, fixtures and buffers will be used in addition to these machines, to support the primary resources.

[1] Locking occurs when the system is totally prevented from functioning. A shop is locked if the input and output queues are simultaneously full or if all the vehicles transporting unit loads cannot make their deliveries because the input queues are full and there are no available vehicles to free some spaces from the output queues (Egbelu and Tanchoco, 1984).

2. The development of a planning module to simultaneously evaluate the simultaneous scheduling of resources with an emphasis on multiple objectives and the dynamic nature of an FMS.

In addition to 1, the planning module will consider the random arrivals of orders, machine breakdowns, tool wear, arrival of rushed orders and the withdrawal of orders. The objectives that will be considered include:

i. The maximisation of resource utilisation,
ii. The minimisation of the number of tardy jobs,
iii. The minimisation of lead time
iv. The minimisation of total late time
v. The minimisation of resource idle %
vi. The minimisation of setup time and tool changes.

3. The design of a series of experiments (using the planning module devised in 1) that will lead to

I. The generation of planning strategies that aim to maximise resource utilisation, minimise lead time and force the orders (jobs) to conform to due dates or at least reduce the degree of tardiness.

II. The presentation of scheduling approaches that offer better schedule performances than those by the conventional rules and the custom-made scheduling rules analysed.

In the experiments, an FMS is considered to have operations such as assembly, variable operation (and setup) times effected by operating machines, routing flexibility, machine breakdowns and tool wear. In addition, changes in the orders will be considered, with high priority orders added, and orders removed from the job list.

A major assumption in the experiments will be the prevention of pre-emption of operations and the fact that only one tool can be used in a tool kit at a time. This inevitably implies that a machine can perform only one operation at a time. Also, it will be assumed that the AGVs can only travel in such a way that there can not be collisions. The AGVs are multi-load (i.e., they can carry more than a part at a time) and have capacity up to the maximum batch size of the orders in the experiments[2].

Custom-made scheduling rules that take advantage of the flexibility of operations[3], or consider the position of the operation in a job, the number of tools required, the number of tool or machine changes, and the duration of job, either remaining or as a total will be considered. Standard rules such as EDD, SPT, LPT, FCFS (see abbreviation), maximum and minimum setup time will also be considered.

Where tools are considered as secondary resources, it is possible that in some cases, more than one available tool is capable of performing a ready operation. In this case, one tool must be selected. To effectively use the tools (avoiding too many partially worn-out tools), it may be necessary to use a tool selection rule. For this purpose, three tool selection rules have been defined (section 6.1.2), namely:

i The tool life rule

ii The tool cost rule and

iii The tool flexibility rule.

4. Presentation of the methodology for selecting appropriate scheduling rules given the required system objective.

The experiments that will be carried out in 1, 2 and 3 will be used to develop a scheduling methodology. This methodology will provide a user with a series of steps that will enable him to evaluate the scheduling rule likely to give the best schedule in terms of the system objective he has chosen in a given scheduling environment.

[2] Only one AGV travel was required per batch for each transportation.

[3] Some operations can be done by a greater number of tools and/or resources hence having a greater degree of flexibility.

CHAPTER 4

THE STRUCTURE OF THE RESEARCH

The FMS scheduling problem can be approached using combinatorial optimization, artificial intelligence (AI) or simulation-based scheduling with dispatching rules (section 2.4.1). Combinatorial optimization methods are somewhat limiting in the ability to handle the dynamic nature of FMSs. Heuristics in conjunction with simulation-based scheduling with dispatching rules has therefore been employed for this research. Heuristics has been applied for the creation of a rule base and simulation has been used to model the scheduling problem. The result is a strong flexible modeling tool that combines the advantages of both methodologies (section 2.4).

With the research intent being to develop a scheduling rule that ultimately considers several other features of an FMS, it was necessary to identify a software package with such capability. The package had to be able to cater for changes in orders, allow the use of secondary resources and the development of custom-made scheduling rules. This capability was found in PREACTOR which will be discussed shortly.

4.1 STRUCTURE OF THE SIMULTANEOUS PLANNING MODULE

A major focus of the research is the ability to consider simultaneously, multiple resources, multiple criteria and the dynamic nature of an FMS. The ultimate goal was to be able to press a button to activate a scheduling rule that considered multiple criteria such as the minimization of lead time, minimization of late time, and the maximization of resource utilization, while also considering secondary resources. The scheduling system was also required to be able to accommodate changes in orders. While a push button of such a rule was not presented, a scheduling approach that performed in a similar way by combining a scheduling rule with scheduling strategies such as batch splitting, concurrent operations and increased operation/resource flexibility, is presented.

It is also intended for the research to evaluate the potentials of scheduling rules that considered operational parameters. To do this, custom-made scheduling rules (Section 4.1.2) have to be developed and tested against the conventional scheduling rules, in several scheduling environments. Also, it is proposed that a means of reducing the number of partially worn out tools would be considered. In developing and testing some tool selection rules in varying scheduling environments, a behavior was to be identified to give an insight into how this could be achieved.

The following sections concentrate on defining the scheduling problem of this research by identifying the generic structure and later, representing the scheduling problem within PREACTOR.

4.1.1 THE MAJOR MODELLING ELEMENTS

A schedule is created when there are a number of products to be made by a certain time. Usually, the products need to undergo one or more manufacturing operations ranging from machining, welding, painting to assembly and even inspection. In some of these instances, there are specialised machine tools to carry out the operations. However, there are cases where more than one machine tool can be used for an operation and more than one operation can be done on one machine tool. This is often the case in a flexible manufacturing system, the system under investigation.

Usually, when an order is received, the manufacturer decides on the most suitable material to use and the most effective way of converting this material into finished product. This material may be a bar stock (needing significant material removal) or in a near net shape[1]. Then, the number (and the order) of operations the material has to pass through; the types of machines that can be used for the operations and any additional resources that the machines may need to function are identified. The main resources are referred to as primary resources and the additional supporting resources are henceforth referred to as secondary resources.

[1] forged, cast or fabricated into a form nearer that of the finished product and thus needing little material removal

To adequately represent the scheduling problem, the main modelling elements have been identified and included the jobs and both the primary and secondary resources. This section will describe these elements.

4.1.1.1 JOBS

An order can represent one or more jobs[2], each having specific requirements. A job may for example, specify a high level of surface finish in which case one of the secondary resources may have to be an operator or a supervisor to oversee the operation. A high quality grinding tool may be required. A job may also specify a certain notch or cut that may be done on only one machine, and more commonly, a job may specify a due date.

To model a part, one has to be aware of the operations that will capture the design intent with minimum variation. Recognising the process capability of the machines could also ensure that the allocation of operations to machines is most effective. In this research, it has been assumed that most of the machines have similar process capabilities and that the operations were allocated to machines with satisfactory capability.

Requirements that have been considered in modelling the parts include:

I. Product Requirement

This depends on the quality and the type of features and characteristics wanted in the product. If as an example, a keyway and a hole are needed in a splined shaft, one of the commonest operations for the former is milling and the latter, drilling and boring. Also, if the level of surface finish is required to be relatively high, then another operation, which may need to follow the milling and drilling operations, is rough grinding followed by fine grinding. In this research, the operations for the different jobs were assumed to be known at the time of scheduling because they were obtained from an existing product database.

II. Time

For the product, the due date is usually given and one of the best ways of meeting due dates is by backward scheduling, whereby calculating backwards from this date, and determining how soon the job needs to be started. To effectively use this method, the operation (and setup) times for each operation need to be determined. This can be evaluated approximately once the necessary operations needed to make the necessary features are determined, and based on past experience. The operation and setup times were assumed to be known at the time of scheduling because they were obtained from an existing product database.

III. Routing flexibility

It is possible that by one or more sequences of operations, a job of similar quality can be made. One advantage of the flexibility is that when an operation cannot be done at a point in time because of resource unavailability, another route can be taken, one that does not make use of the operation or at least not at the time the operation cannot be done. Such a factor has been taken into account by identifying the jobs that could be done by more than one route. Two main routes were identified, namely, the standard and the alternate and these were allocated at random to the operations in the experiments.

IV. Operation definitions

Each job had a number of operations, each given operational parameters[3] that made it easier to distinguish which operation had to be chosen first for loading on an available machine. These parameters are referred to in Table 4-1 and the evaluation is in Section 4.1.2.

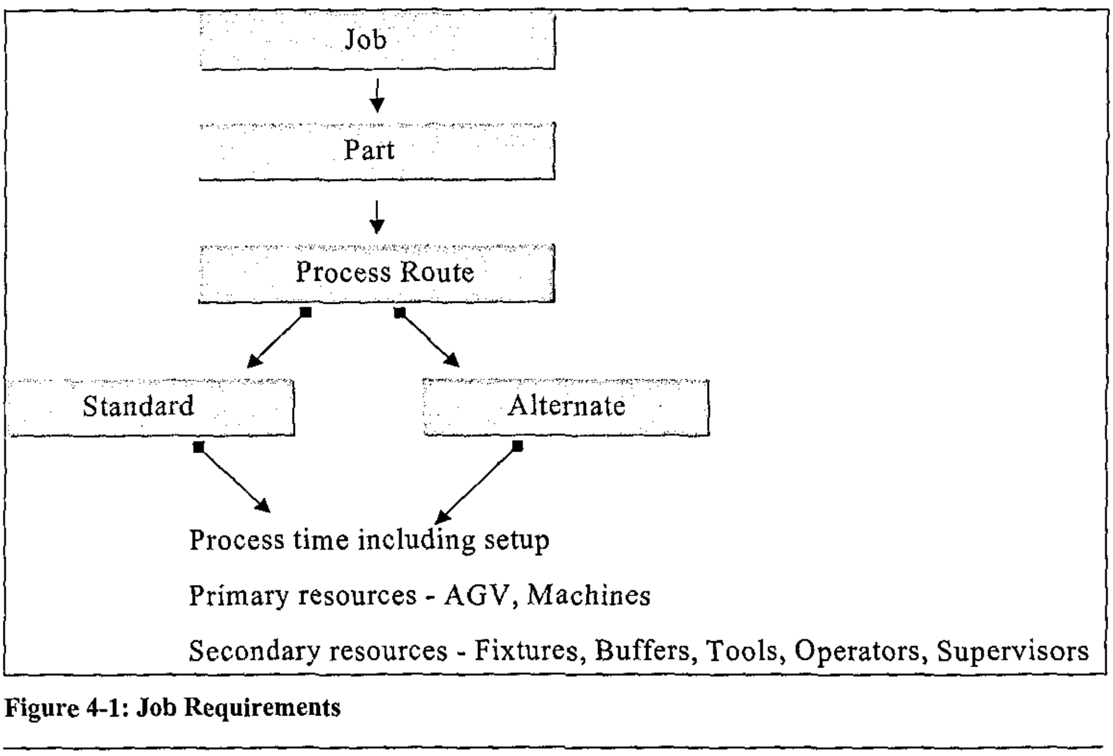

Figure 4-1: Job Requirements

[2] where a job consists of a batch quantity for a specific part type
[3] such as number of operations, amount of work remaining and used in the scheduling rules

4.1.1.2 RESOURCES

The other modelling elements were both the primary and secondary resources. The appropriate machines (primary resources) had to be identified for each operation in the order sets by considering process capability and the associated operation time. For as long as two or more machines could satisfactorily perform an operation, a machine able to do the operation in the shortest possible time was chosen unless there was the possibility of it being a bottleneck.

For each machine selected for an operation, most often than not, a secondary resource is needed. A tool is usually needed for every machining operation. In addition to this, fixtures and/or buffers may be needed, the number of which may vary with the job size. In this research, the following resources have had to be modelled.

1. Machines

The machines were randomly selected for the operations by assuming similar process capability and in such a way as to balance workload. A tool kit was loaded on each machine and to a large extent, this determined the process capability. Thus an operation that required a tool that was not available on the machine was done on another machine.

In some cases, the machine (plus the tool kit of tools) was not sufficient for the operations and the secondary resources had to be specified. This included fixtures, buffers, operators and/or supervisors.

2. AGVs

An AGV was modelled as a primary resource for the operations labelled 'transportation'. 'Transportation' was put in between the set of operations for a job once there was a change in machine requirement. Transportation time was dependent on the proximity of the AGV to the machine it was required to travel to and the AGV stayed at its last port of call until it was called. The AGV was assumed to be fully automated not requiring any operators or supervisors. However, because the scheduling problem assumed no defixturing until a job was completed, a job loaded on an AGV had fixtures as inherited secondary resources.

3. Tools

Each tool kit loaded on the machines was loaded with a number of tools that invariably determined whether or not an operation could be performed based on tool properties and on operation requirement. Each tool had properties (tool life, tool cost and tool flexibility) that determined which tool was selected for an operation based on selected tool rule (section 4.1.2). Where an operation required a tool with insufficient tool life, another capable tool had to be selected or the machine reloaded with a similar tool.

4. Fixtures

All of the jobs were assumed to need fixtures for the entire production duration. Therefore, this resource served as a critical secondary resource. Once a set of fixtures was available, a job was loaded onto it. If more than one available operation required it, then an operation sequencing rule was made active and the job that had to start the earliest was loaded on it.

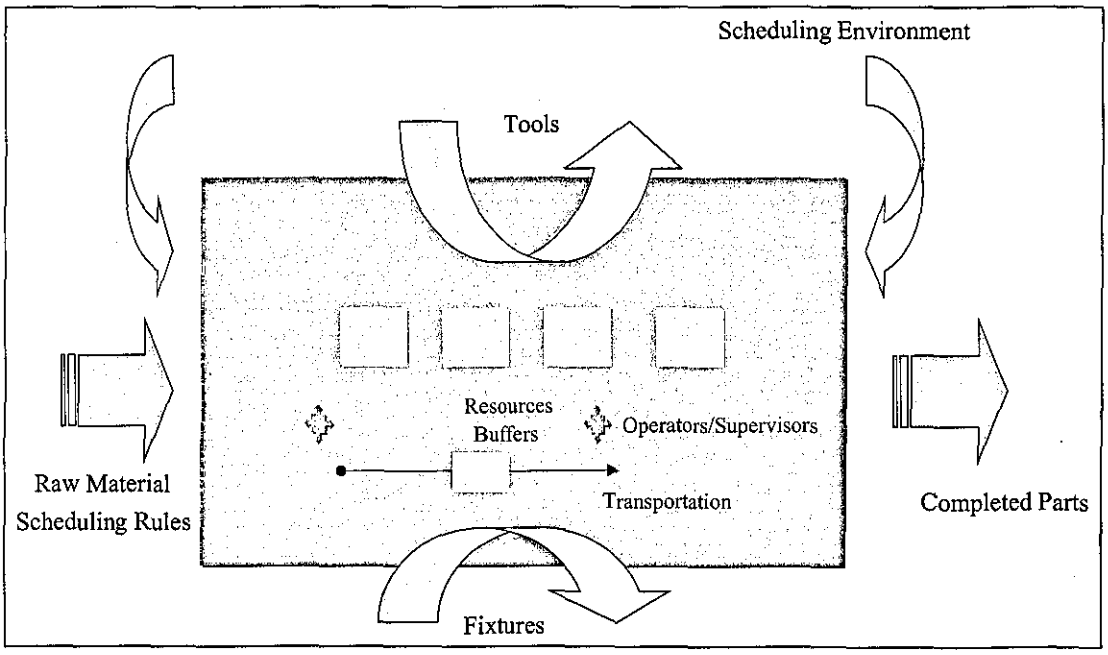

Figure 4-2: Graphical representation of elements of an FMS

5. Buffers

Buffers were considered as secondary resources and were modelled as such. An assumption of the work was that each buffer could hold a single part, from the batch quantity of a job.

6. Operators and Supervisors

There were instances where the required level of surface finish required that an operator or supervisor was around to oversee the operations. In this case, operators and/or supervisors acted as secondary resources. They could also have been considered for loading and unloading operations but these operations were not considered.

Databases	Content	Features
Products	All information related to all the products made within the system	Operation-related: Op/Tool Flexibility, Op/Resource Flexibility, Positional Factor, Remaining Work, Number of operations, Cost of Operation, Tool Index, Operation Time
		Resource-related: Tool Kit, Secondary Resource, Resource Group, Resource Data
Resources	The resources that are necessary before an operation can be carried out	Tool Kit, Tools, Secondary Resources. Some of the resources may need supporting (secondary) resources such as fixtures to function
Resource Groups	All resource groups within the system	Resources
Secondary Resources	The supporting resources that are necessary before an operation can be carried out	Maximum and minimum values. If the available is less than that required, operations requiring them cannot commence.
Tools	All information related to all the tools within the system	Tool Flexibility, Tool Life, Tool Cost
Tool Kits	All tool kits within the system	Tools

Table 4-1: Some scheduling modelling elements

For the secondary resources (with the exception of the operators and/or supervisor), except when the required number was available when needed, the job was unable to start. If a job for instance needed 4 fixtures and only 3 were available, the job had to wait until 4 fixtures were available. Table 4-1 and Figure 4-2 summarise and illustrate the main modelling elements.

4.1.2 SIMULTANEOUS DECISION MAKING STRUCTURE

The decision making structure of the simultaneous planning module is based on:

1. *A scheduling rule to select the operations for loading into the FMS.*

If a set of orders was handled randomly (that is, anytime there was an available machine, an operation was chosen at random to be loaded on it), then there is a tendency for higher priority orders to be late. This is one of the reasons for the use of operation sequencing rules (also known as scheduling rules).

This sub-section defines some of the operational parameters that have had to be incorporated into the scheduling rules aimed at either increasing the flexibility of the system and testing the effect on schedule performance, or considering how to minimise the degree of lateness of jobs. Increasing the flexibility of the system could lead to shorter lead time and lower the degree of lateness of jobs if it can be assumed that there are then more resources to handle operations. Also, when cost is a factor, it could be a prompt for manufacturers not to default.

i. **Op/Resource Flexibility (Used in the generation of the LopRes and HopRes rules)**

This is the percentage of resources from the whole set of resources that can perform an operation. If for example, an operation can be performed by 3 resources out of a possible 6, then the operation/resource flexibility is 3/6, an equivalent of 50%.

ii. **Op/Tool Flexibility (Used in the generation of the LopFlex and HOpFlex rules)**

This is the percentage of tools from the maximum number of tools that can perform an operation. As an example, 3 tools can perform each of the operations in the research but as shown in Table 4-2, only 2 tools from the set of tools available in the system can perform Op10. Hence, for that operation, operation/tool flexibility is 2/3, an equivalent of 66.7%. Operation/tool flexibility for the other operations is 33.3%.

iii. **Positional Factor (Used in the generation of the LPos and HPos rules)**

This refers to the position of operation within a job. If a product has 10 operations, then for operation 5 in the set, the positional factor is 5/10, that is 0.5.

It is expected that if jobs nearer completion are done first, queues are shortened and so also, WIP[4]. It could also be interesting to investigate the effect of doing first the jobs farther away from completion.

iv. **Tool Index (Used in the generation of the MinToolIndex and MaxToolIndex rules)**

Tool Index, TI = PF * PI where PF is the positional factor and PI is the tool change factor which was taken as 4 for operations requiring no tool change and 2 for those requiring tool change. PI is taken as 0 for all starting operations so jobs have the same opportunity of being chosen to start first. Table 4-2 illustrates how to determine whether or not there is tool change.

[4] Work in process

Operations	Tool Kits	Tool Requirements	PI
Op10	T1	T102, T103	0
Op20	T1	T102	4
Op30	T2	T106	2
Op40	T2	T106	4

Table 4-2: Determination of Tool Index

Operation 20 has a PI of 4 because it has the same tool kit requirement as the preceding operation. If Op10 uses T103, then for Op20 to commence, the operating tool in the tool kit has to be changed to T102. This is a tool switch operation which is assumed to be negligible in this research. Alternatively, Op10 can use T102 which is the same needed for Op20. Therefore, either way, we can safely assume that there is no tool change between Op10 and Op20.

v. Cost of operation

The cost of operation is calculated in this research as $TC_o = TC + C$ where $C = S + P$. The S value is higher for operations requiring greater precision, and the P values, for operations requiring more secondary resources. TC is the addition of labour and material cost.

vi. Tool Flexibility

For a system with 30 operations, if a tool is capable of 10 operations, its flexibility is 10/30, an equivalent of 33.3%.

2. A rule for the transporter to move the jobs from resource to resource.

In this research, the rule used has been the shortest travel time/distance (STT/D) in which the transporter nearest to the resource (on which the job is) is selected.

3. A tooling rule to select a tool from the tool kit to perform an operation on a job.

Three tool selection rules (section 6.1.2), namely:

i. The tool life rule
ii. The tool cost rule and
iii. The tool flexibility rule, have been used.

4. A rule for selecting which operation was loaded on an available fixture

If more than one operation required a set of available fixtures, then an operation sequencing rule is made active and the job that has to start the earliest is loaded on it.

4.2 REPRESENTATION OF THE SCHEDULING PROBLEM

To adequately represent the proposed scheduling problem, the standard PREACTOR configuration had to be altered to accommodate features appropriate to our testing. This included adding operation parameters such as tool features in the jobs format, operation flexibility, number of tools and cost of operation, adding formats such as tool kits and tools. Tables 4-3 to 4-7 show the alterations made.

Standard PREACTOR Databases	**Amended PREACTOR Databases**
Products	Products
Setup Groups	Setup Groups
Resource Groups	Resource Groups
Resources	Resources
Secondary Resources	Secondary Resources
Routes	Routes
Calender States	Calender States
	Tool Kits
	Tools

Table 4-3: Re-configuration of formats in PREACTOR

Fields in the PRODUCTS Database	
Standard PREACTOR Databases	**Amended PREACTOR Databases**
Parent Part	Parent Part
Part No.	Part No.
Operation Number	Operation Number
	Tool Kit
	Cost of Operation
	RemWork
	Positional Factor
	Tool Index
Resource Data	Resource Data
Advanced Options	Advanced Options
Setup Time	Setup Time
Setup Group	Setup Group
Operation Time	Operation Time
Secondary Resources	Secondary Resources
Routing Options	Routing Options

Table 4-4: Re-configuration of databases in PREACTOR (1)

Fields in the RESOURCES Database	
Standard PREACTOR Databases	**Amended PREACTOR Databases**
Name	Name
Bucket Units	Bucket Units
Bucket Size	Bucket Size
Bucket Capacity	Bucket Capacity
Bucket Size	Bucket Size
Waiting Plot Color	Waiting Plot Color
Secondary Resources	Secondary Resources
	Tool Kit
	List of Tools

Table 4-5: Re-configuration of databases in PREACTOR (2)

Fields in the TOOL and TOOL KIT Database	
Amended PREACTOR Databases	
Tool Database	**Tool Kit Database**
Name	Name
Tool Life	Tools
Tool Flexibility	
Tool Cost	

Table 4-6: Re-configuration of databases in PREACTOR (3)

Scheduling Rules			
Standard PREACTOR			**Amended PREACTOR**
Forward Seqg	Backward Seqg	EDD	LOpRes, HOpRes
		FCFS	MaxToolIndex, MinToolIndex
		SPT	LPos, HPos
		LPT	LRemWork, HRemWork
		Priority,	Cost
		Reverse Priority	LNoOfOps, HNoOfOps
			LOpFlex, HOpFlex
			Minimum Tool Life
			Minimum Tool Cost
			Minimum Tool Flexibility
**Seqg - Sequencing*			

Table 4-7: Addition of scheduling rules in PREACTOR

Table 4-8 shows the standard PREACTOR performance measures that were adopted for the experiments carried out.

4.3 THE SIMULATION-BASED SCHEDULER

This research proposes to handle the dynamic nature of an FMS. This requires that the simulated manufacturing system to be adequately represented considering assembly, resource dependency (of operation time), machine breakdowns and planned maintenance, routing flexibility, secondary resources and the integration of a rule base. For simulation-based scheduling, several software packages are available. At Loughborough University for instance, there are Arena and Witness. Global solutions include the CA scheduler for OS/390, ECAS, and auto schedulers by Profax Ltd. (Appendix 1). All these packages can simulate a manufacturing system and present statistics of schedule performance. However, PREACTOR was selected primarily because it can adequately model the proposed scheduling problem and at no extra cost to the project since it is available in the University.

Schedule Parameter	Definition
Schedule Duration	The time span from the start to the end of the performance data calculation
Total Lead Time	The sum, for all orders, of the times between the setup start of the first operation to the end time of the last operation of the order
Total Late Time	The sum, for all orders, of time between the due date and the end time of the last operation of the order
Added Value for an Order	The sum of the process times for all operations divided by the lead time.
Idle Percentage	The capacity that the resource has which is available but not used expressed as a percentage of the total time span
Utilization Percentage	The resource capacity spent in processing jobs (not setups) expressed as a percentage of the total time span minus the unavailable time
Working Percentage	The resource capacity spent in processing jobs (not setups) expressed as a percentage of the total time span
Overall Best Scheduling Rule	In determining the overall best scheduling rules, this is the rule which appears the most number of times with regards to schedule performance measures. A rule is considered one of the best for a schedule performance measure if it is one of the best in the ***three*** resource scenarios.

Table 4-8: Definition of Scheduling Performance

PREACTOR has in-built scheduling rules and also permits the generation of custom-made scheduling rules. It can allow extensive data entry and some of its versions (PREACTOR 300 upwards) can handle multiple resource constraints. PREACTOR enables its users to take advantage of both algorithmic[5] and simulation-based sequencing[6], to utilise a combination of algorithms and to monitor the scheduling performance by generating the schedule performance data. Also, the PREACTOR database is highly configurable to suit the needs of most processes.

The PREACTOR 400 version has been selected for this research because it has the power of a simulation based sequencer. By loading individual operations rather than entire jobs, it has finer control over the way the operations are loaded onto the planning board. It can also be integrated with Visual Basic, the programming tool used to write the customized rules.

4.4 THE PREACTOR STRUCTURE

This research requires adequate representation of the dynamic nature of an FMS considering unexpected arrivals and withdrawal of orders, assembly, tool wears and machine breakdowns. It also requires that calendar states and shift patterns be adequately represented such that the system is aware of when the resources can operate and at what percent of their capacity. These are features that can be represented in PREACTOR 400.

To represent all the orders that may be sent into the system, a products database need be created with all the possible products' process plans, making allowance for routing and machine (also known as resource) flexibility. For each product and its operations, there are machines and/or secondary resources (also known as secondary constraints), possible routes, operation and setup time, and other operation features as have been developed. Some of the operation features developed include "number of operations", "remwork" (remaining work), "cost of operation", "op/tool flexibility", "op/resource flexibility" and "positional factor", all of which are determining factors in the custom-made scheduling rules.

[5] Algorithmic scheduling involves selecting a job and then putting each operation for that job on the planning board and repeating the process until all jobs have been loaded. Each operation is loaded on its specified resource at the first available time slot that satisfies the constraints for that operation
[6] Simulation-based scheduling involves selecting and loading an operation from the entire set of jobs when an applicable resource is available.

"Tools" and "Tool Kits" are some other operation features developed to decide on the tools for each operation and for this purpose, tool and tool kit databases were created. Figure 4-3 shows the typical products database.

To better understand the PREACTOR databases, a splined shaft is used as an illustration in Table 4-9 and one of its operations, "rough turn diameter" is taken in isolation and its data represented in Table 4-10. This data is fed into the Products database and used as an illustration in Figures 4-3 to 4-12.

Table 4-9 shows that the splined shaft is produced after the raw material goes through 5 operations, each of which has unique operational data: allocation of resources, tool kit, route, setup group, operation time, etc.

Product	Operation Names	Tool Kits	Applicable Resource	Applicable Route	Applicable Setup Group
Splined Shaft	Rough turn diameter	TK1	M1	Standard , Alternate	F1
	Mill keyway	TK2	M2	All	F1
	Mill splines	TK2	M2	All	F1
	Harden keyway	TK3	M3	All	F2
	Grind to size	TK2	M2	All	F1

Product	Operation Names	Operation Time	RemWork	Secondary resources	
				Fixtures	Others
Splined Shaft	Rough turn diameter	15	47	4	Buffers, 20
	Mill keyway	5	32	4	Buffers, 20
	Mill splines	10	27	4	Buffers, 20
	Harden keyway	5	17	4	Buffers, 20 Operators, 1
	Grind to size	12	12	4	Buffers, 20 Operators, 1

Products	Operation Names	Tool Index	Op/Tool Flexibility	Cost of Operation
Splined Shaft	Rough turn diameter	0	100	9.33
	Mill keyway	0.8	66.67	16.66
	Mill splines	2.4	100	16.66
	Harden keyway	1.6	100	10.50
	Grind to size	2.0	66.67	49.07

Table 4-9: The operational data of a product

As an example, the first operation, the 'rough turn diameter' operation has the following operational data:

Rough Turn Diameter			
Resource	M1	Cost of Operation	9.33
Resource Group	MA1	Tool Index	0
Tool Kit	TK1	Route	Standard, Alternate
RemWork	47	Op/Tool Flexibility	100
Operation Time	15		
Setup Group	F1	Secondary Resources	Fixtures (4), Buffers (20)

Table 4-10: Operational data of the "rough turn diameter" operation

Figure 4-3 shows the products database with the operations of splined shaft. The dialog screen leads to more information on the operations of the products by double-clicking on the operations. To know more about the "rough turn diameter" operation for instance, the patch labelled X would need to be double-clicked opening up a dialog screen similar to that in Figure 4-4.

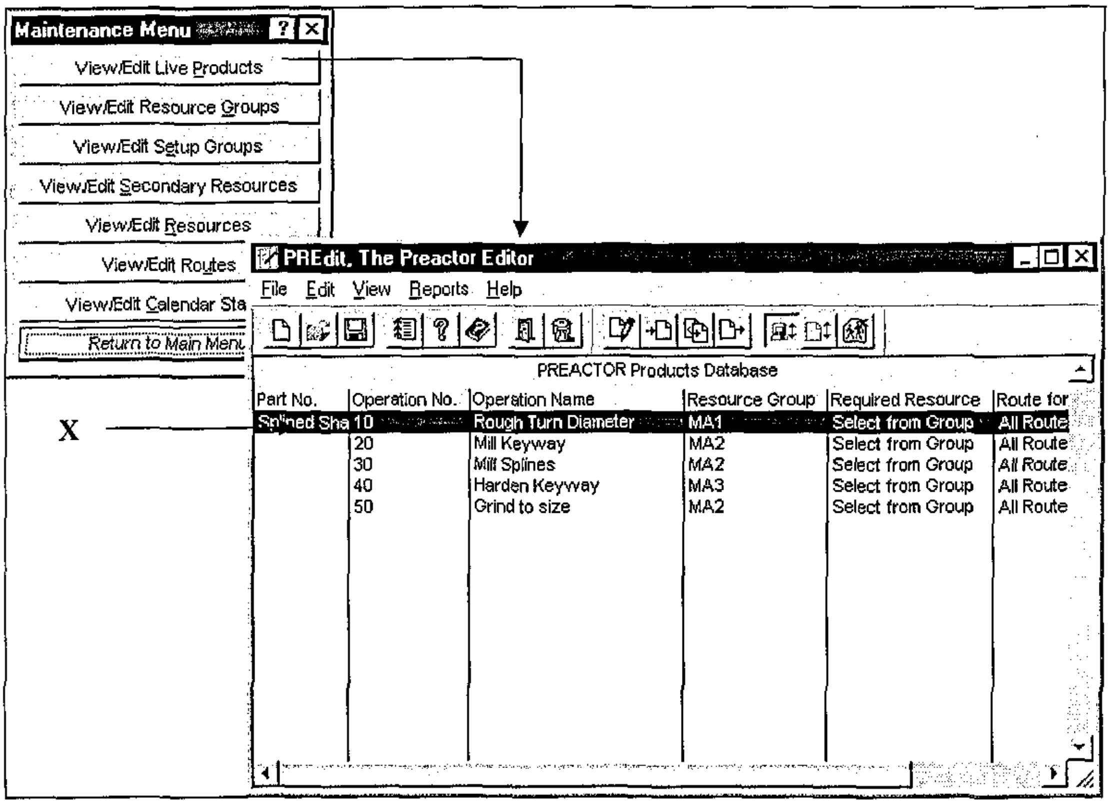

Figure 4-3: The Products Database

It is possible to load an operation on more than one resource. If this is the case, then there are two options: either the operation time is dependent on the resource selected or it is the same irrespective of the resource selected. If it is dependent on the resource selected, then the process time type selected in the products database would be "Res. Specific Time per Item" (Figure 4-5). When this is the case, the Op. Time per Item field (Figure 4-4) is automatically removed from the Products database

(Figure 4-5) and an equivalent appears in the 3rd level dialog screen (Figure 4-6) as Res. Specific Op Time.

In the example above, the resource group for the "rough turn diameter" operation is MA1. Clicking the "Resource Data" field of the Products database reveals the resources within the resource group, MA1 and as shown in Figure 4-6, these are resources M1 and M2. This means that either of these resources can be used for the operation. Double-clicking on either of the resources further reveals the resource-dependent operation time (Res. Specific Op Time) and other resource specific parameters such as Res. Specific Sec. Const. (secondary constraints) that may need to be used with the selected resource. In the case above, if the "Res. Specific Time per Item" option is selected, the operation is then done in 5 minutes as opposed to 15 minutes for a process time type of "Time Per Item".

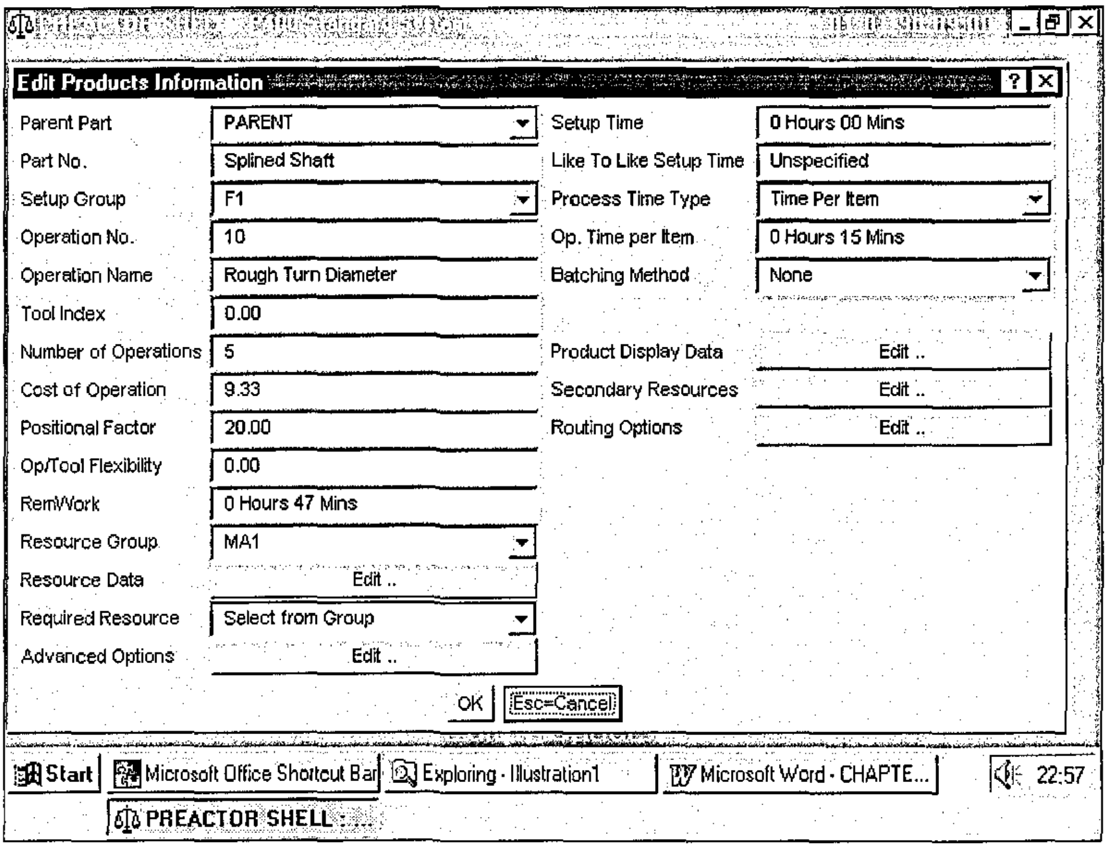

Figure 4-4: The Products Database dialog screen

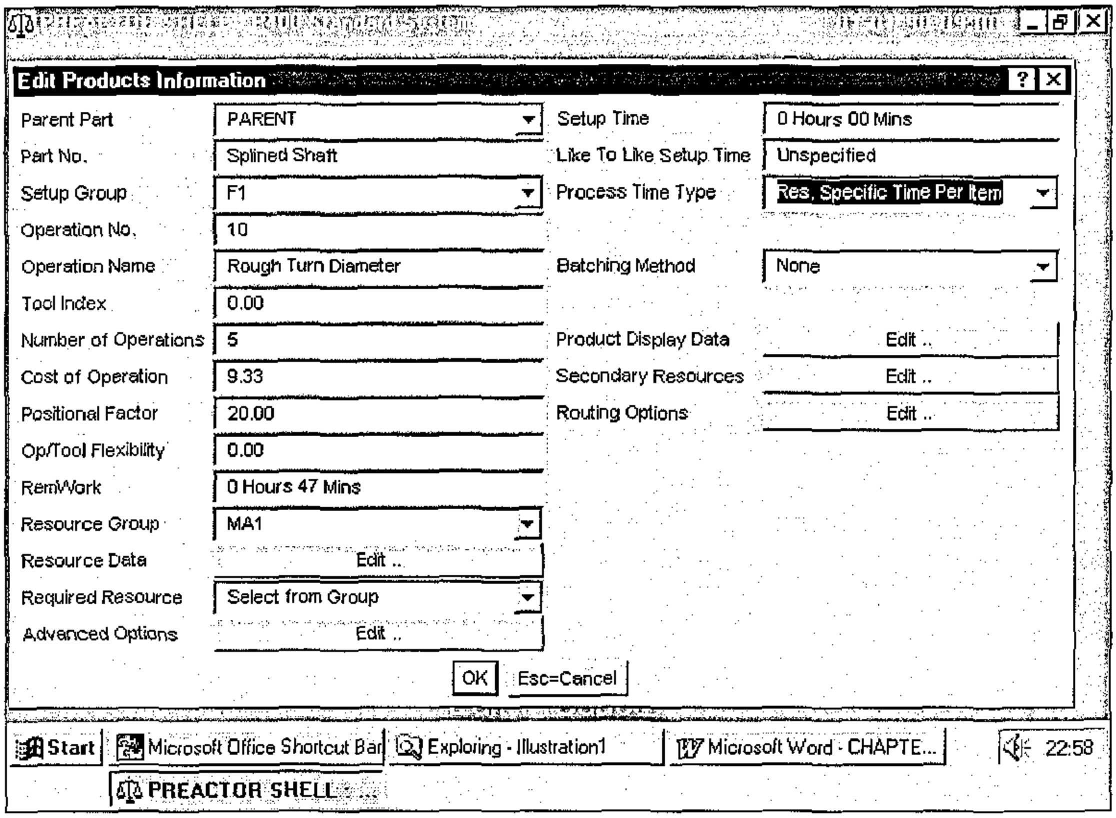

Figure 4-5: The Products Database - Process Time Type

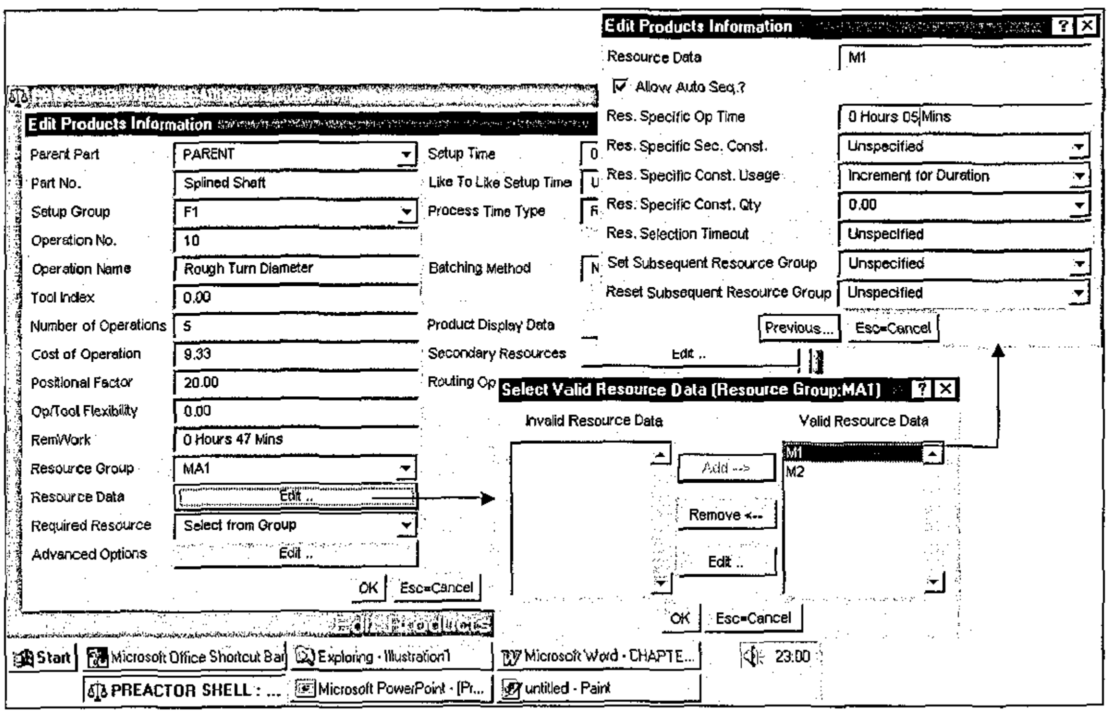

Figure 4-6: Products Database's Dialog 1 - resources' dialog

In Figure 4-7, the advanced options field opens up a dialog screen that allows a correct loading of operations that are related to assembly. While operation numbers indicate the sequencing of the operations within the job, for assembly, the key and level values indicate the independence and sequence of operations. PREACTOR finds the lowest level value and then loads all operations with the lowest key value for that level. However, in checking the next highest level and the highest key value within the level, it takes into account the sequence of the operation numbers in the lower level for numerically lower operation numbers. Because of this, consideration has to be given to the operation numbering to avoid unnecessary synchronisation between operations in different levels.

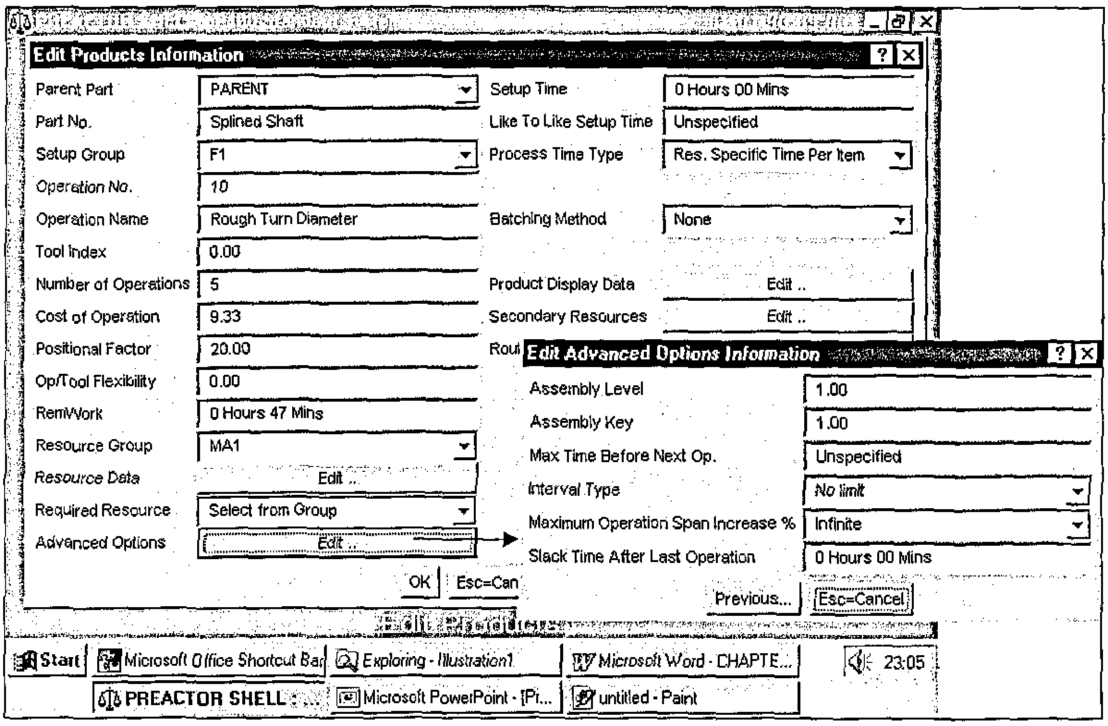

Figure 4-7: Products Database's Dialog 2 - assembly data

As an illustration, Table 4-11 shows the support plate's assembly data. The different key values for subassemblies A and B indicate that the operations of the two subassemblies are independent. The level values also ensure that subassemblies A and B (level 1) are loaded before the assembling processes (level 2). Although the operations for the two subassemblies have the same operation numbers, the subassembly operations will not be synchronised because the different key values are within the same level value.

Figure 4-8's final dialog screens open up the product's display data as seen on the planning board and the routing options (Table 4-12). Also, Table 4-9 shows that the "rough turn diameter" operation requires 4 fixtures and 20 buffers (for 20 splined shafts) in addition to resource M1 and these are as shown in Figure 4-9.

The prerequisite to creating a comprehensive products database is the successful creation of other databases such as resources, secondary resources, tools, tool kits and routes, data which the operations of the products rely on.

The tools database has been created to provide tool information on tool life, flexibility and cost and based on these, tool selection rules can be effectively used.

Product	Operation Names	Operation Number	Level	Key
Support Plate	Press subassembly A	10	1	1
	Drill subassembly A	20	1	1
	Deburr & fit subassembly A	30	1	1
	Press subassembly B	10	1	3
	Drill subassembly B	20	1	3
	Deburr & fit subassembly B	30	1	3
	Assemble plate	40	2	2
	Paint support plate	50	2	2

Table 4-11: The assembly data

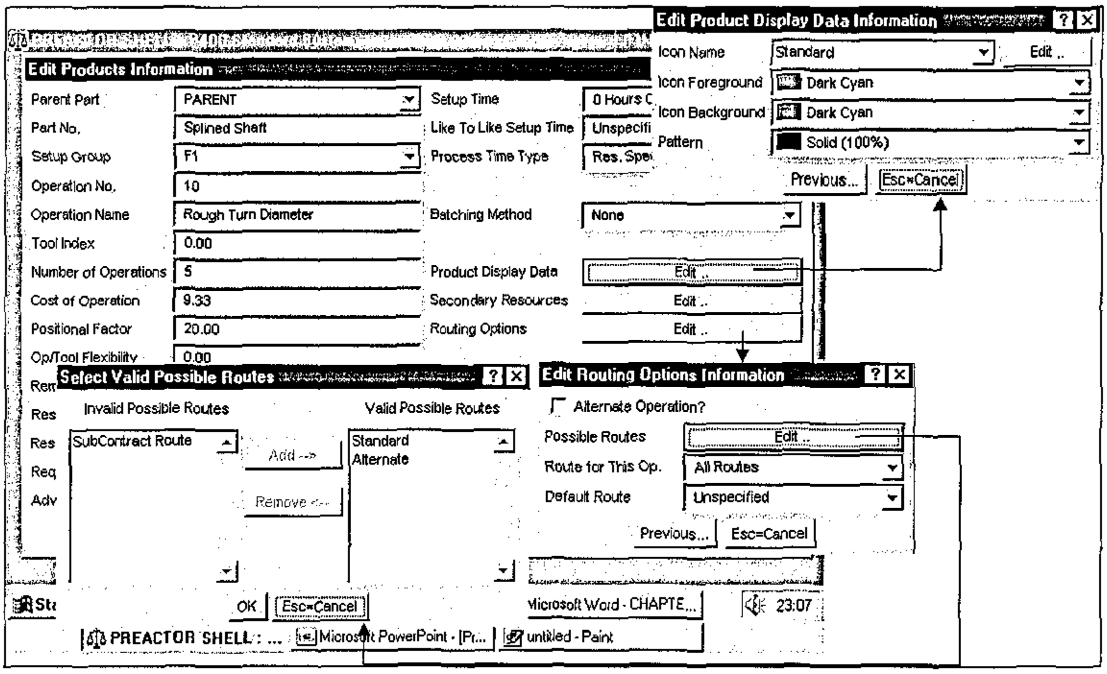

Figure 4-8: Products Database's Dialog 3 - display data and routing options

The routes database is a listing of all possible routes for each of the operations in a product. As an example, in Table 4-12, the first operation of the support plate shows that the possible routes for the product are standard and alternate. The table also shows the routes that are applicable to each of the other operations. The operations that have "All" in the routes field can use either of the routes listed in the first operation of that product while the other operations can use only the routes listed against them. Therefore, if for the support plate, it is decided to use the standard route, operation 4 can not be included amongst the operations required to produce it. If the alternate route is selected, 'Deburr & Fit SubA' and 'Deburr & Fit SubB' can not be included. This is explained further by Figure 4-10.

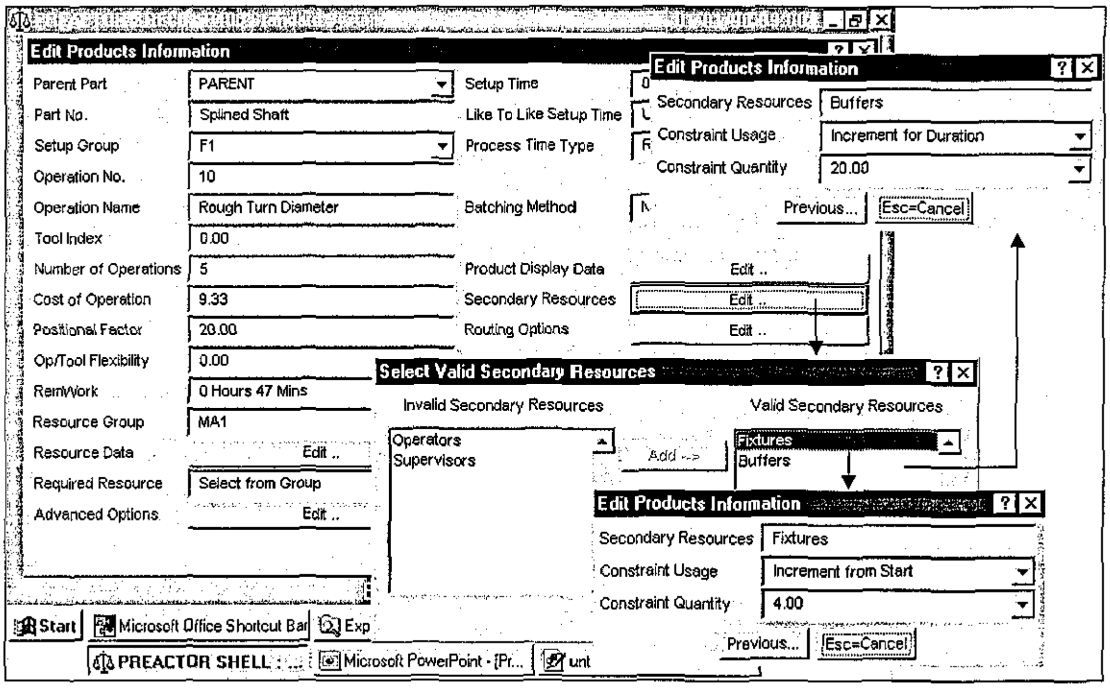

Figure 4-9: Products Database's Dialog 4 - secondary resources

Product	Operation Names	Operation Number	Route	Setup Group
Support Plate	Press subA	10	Standard , Alternate	F3
	Drill subA	20	All	F3
	Deburr & fit subA	30	Standard	F4
	Press subB	10	Alternate	F3
	Drill subB	20	All	F3
	Deburr & fit subB	30	Standard	F4
	Assemble plate	40	All	F5
	Paint support plate	50	All	F5

Table 4-12: The Routing and Setup Group Options

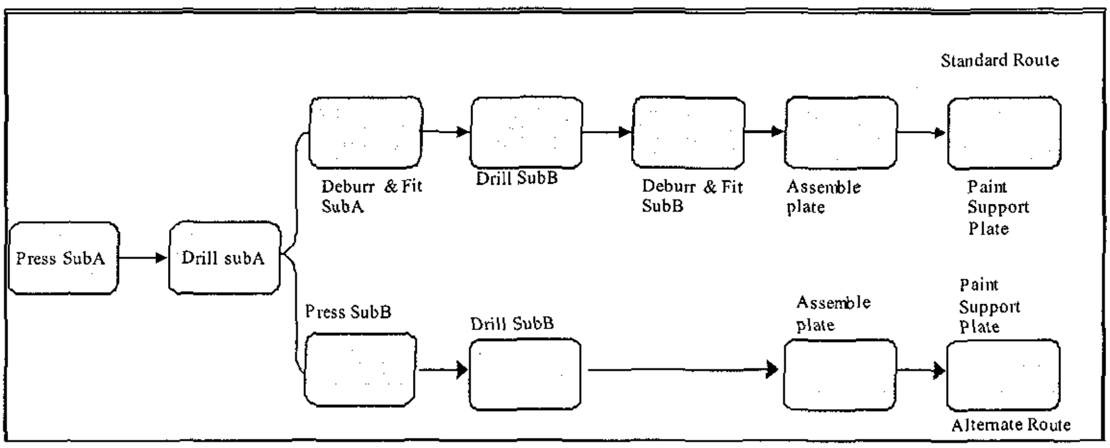

Figure 4-10: Illustration of the routes

In the same way, the setup group database allows for a listing of all possible setup groups. This group allows the calculation of variable setup time dependent on which setup group the preceding or succeeding operation on a resource belongs. As an example, let us suppose that as in Table 4-12, "Assemble plate" immediately precedes "Paint support plate" on the planning board and both need to be done on the same resource. Because they both have the same setup group, no setup time will be accrued to "Paint support plate. However, if "Deburr and fit subassembly B" immediately precedes "Assemble plate" and both need to be done on the same resource, then because both have different setup groups, based on Table 4-13, there will be a setup time of 15 minutes before "Assemble plate" can commence.

	F1	F2	F3	F4	F5
F1	0	15	10	10	20
F2	15	0	15	15	15
F3	10	10	0	5	15
F4	10	10	5	0	15
F5	20	15	15	10	0

Table 4-13: The setup group dependent setup times

Figure 4-11 shows how the setup group database appears in Preactor.

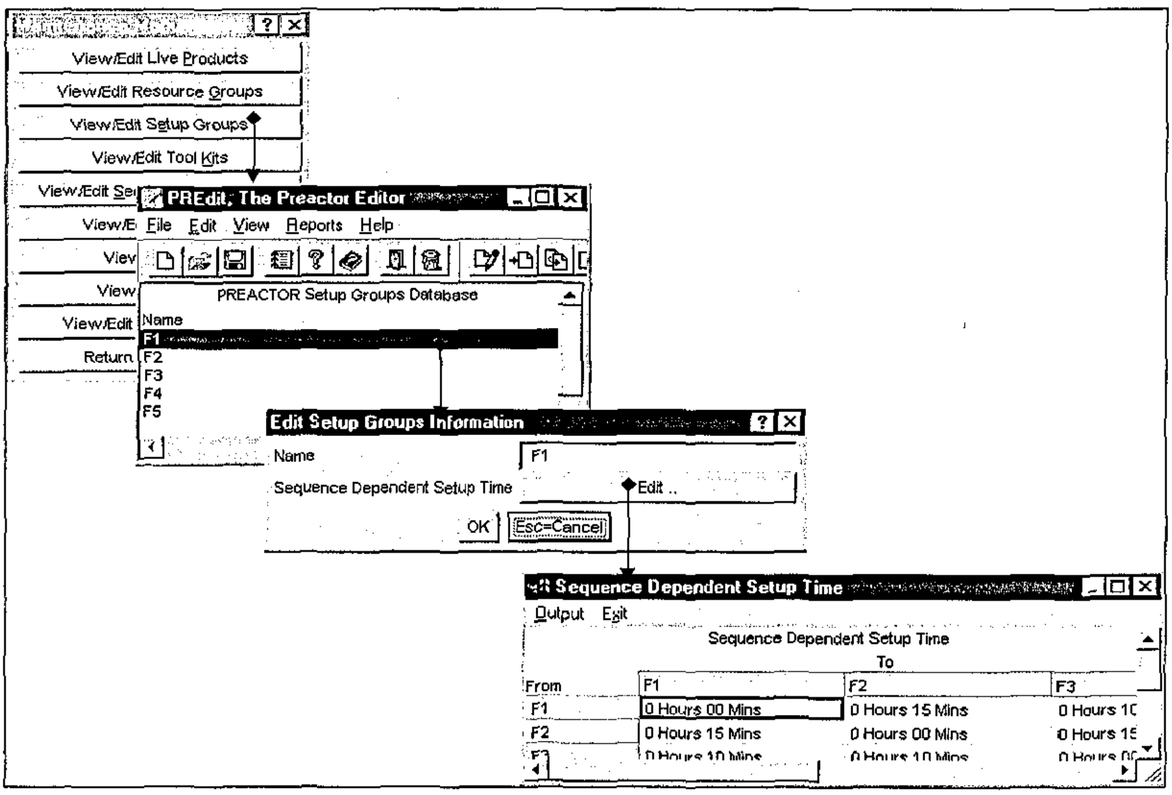

Figure 4-11: Setup Groups Database and Dialog

The secondary resources database gives a list of all the secondary resources in the system and their maximum and minimum values such that these act as limiting factors when operations are being scheduled. For example, if 5 fixtures are needed for an operation at time t and the maximum number of fixtures in the system at any one time is 3, the operation will never be done. If however the maximum number of fixtures in the system is 7 and at that time, only 3 fixtures are available, the operation is put on hold until 5 fixtures are available. Figure 4-12 shows how the secondary resource database appears in PREACTOR. In this case, there are 18 fixtures in the system at full capacity.

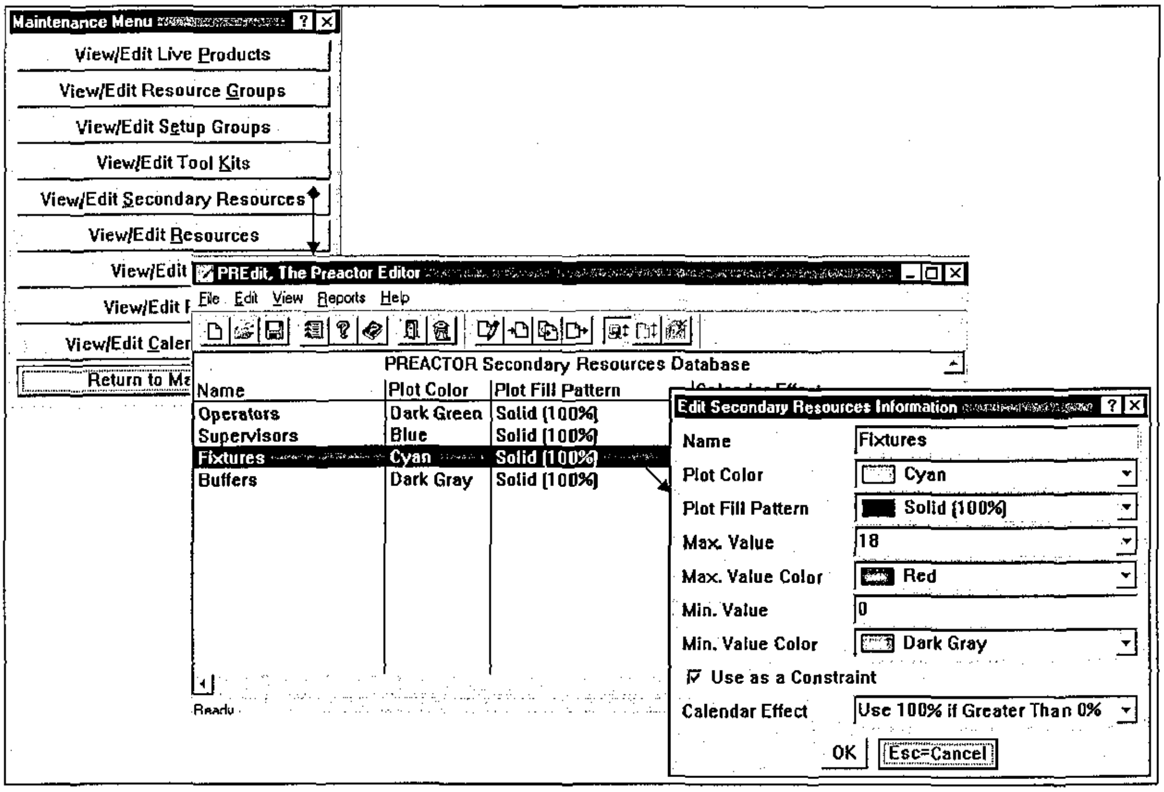

Figure 4-12: Secondary Resources Database and Dialog

The positions of the resources are useful in determining transportation time. For all operations that are either succeeded or preceded by operations with different resource requirements, transportation operations are inserted in between and the times are dependent on the distance between the required resources. As in Table 4-9, "Mill splines" of the splined shaft does not require transportation because its resource requirement is the same as was used by the preceding operation, "Mill keyway". However, "Mill keyway" requires transportation because its preceding operation was done on resource M1 and the part needs to be transported to resource M2 for the next operation. Based on Table 4-14, this transportation operation should take 6 minutes as soon as an AGV is available.

	M1	M2	M3	M4	M5	M6
M1	0	6	8	8	4	3
M2	6	0	10	8	3	5
M3	8	10	0	2	8	6
M4	8	8	2	0	3	9
M5	4	3	8	3	0	5
M6	3	5	6	9	5	0

Table 4-14: The travel times with respect to resource separation distances

CHAPTER 5

DESIGN OF THE COMPUTER-BASED EXPERIMENTS

Chapters 1 and 3 already indicate that this research involves designing a planning module that considers the simultaneous scheduling of workpieces, cutting tools, fixtures, buffers and AGVs in a dynamic environment. The generation of the planning strategies is intended to maximise resource utilisation, minimise lead time and force the orders (jobs) to conform to due dates or at least, to reduce the degree of lateness. The problem has been modelled using Preactor, a computer-based scheduling simulation package and the following sections focus on how the experiments have been designed. Section 5.1 concentrates on the inputs for the scheduling system, and section 5.2, on the outputs, the measure of schedule performance.

5.1 SCHEDULING INPUTS

The research setup is such that some variable inputs to the scheduling system result in different schedule performances. The schedule inputs include the structure of the shop, the orders and the scheduling rules. The shop structure can be held constant in three forms - simple, moderate or complicated (in terms of the number of machines) so that results can be validated and tested. The variability of the order sets is to establish that the rules are not just applicable to certain order types, and/or to establish why the rules behave the way they do. The following sub-sections focus on these inputs.

5.1.1 STRUCTURE OF THE SHOP

Three testbeds have been used, each designed such that the number of machines within the layout dictate how simple or complicated they are. Holding constant all other inputs, it can be established that if the three testbeds are subjected to the same scheduling conditions, the schedule performance can be attributed only to the system layout.

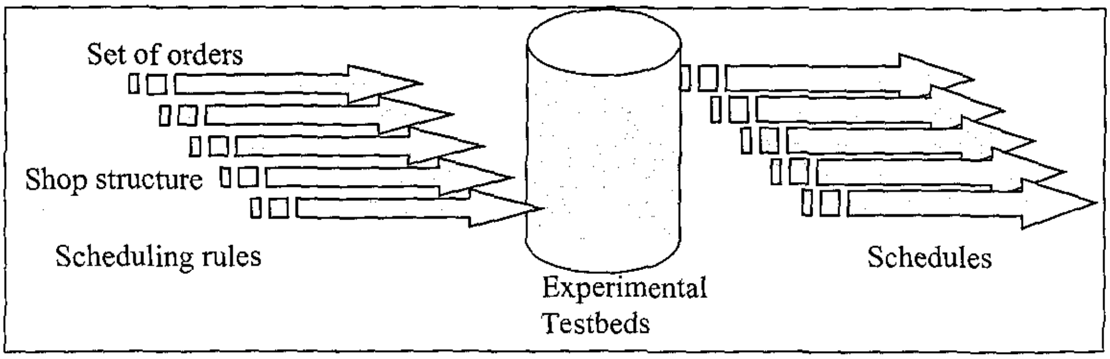

Figure 5-1: Relationship between the scheduling inputs and outputs

Because of the flexibility of the machines being considered, similar amount and type of work can be done in both a simple and a complicated testbed. The simplest testbed (3-resource scenario) would typically be used to explain how the experiments work and to present results and generate predictions. It may be too simple to be realistic. The moderate testbed (6-resource scenario) is more realistic and could be used to test and validate predictions which could be further tested and validated on an 8-resource scenario testbed.

Each of the testbeds has a buffer space capacity of up to 100 although for the benefit of this work, usage was restricted to 60. The first testbed has 3 machines in the system layout, spaced out as shown in Figure 5-2. The 2nd and 3rd testbeds comprising of 6 and 8 machines respectively are as shown in Figures 5-3 and 5-4. Each of the machines in these three testbeds has a tool kit of 10 tools. There is a request for a material handling device when adjacent operations require different tool kits and invariably, different machines. The distance run by the AGV is dependent on the position of the AGV in relation to the machine requesting for it. Preactor would normally select the AGV that would travel in the shortest time if there is more than one free AGV. The use of the 3 testbeds is to test if the schedule performance would be consistent irrespective of the size and structure of the manufacturing system.

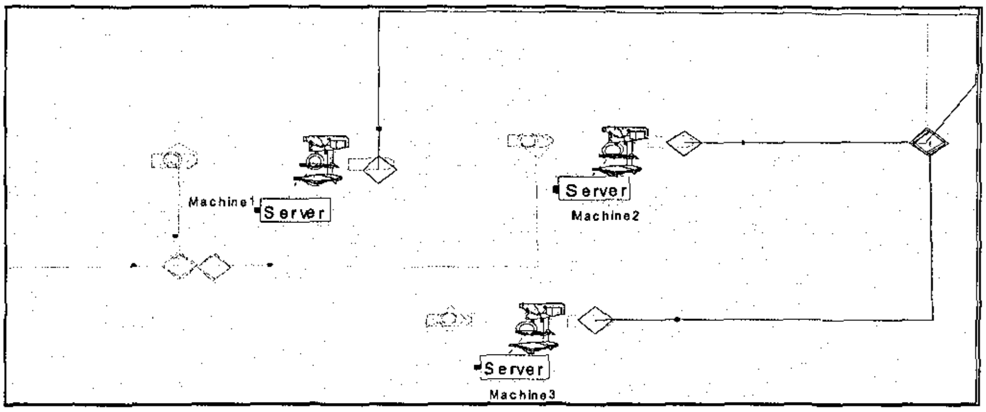

Figure 5-2: The 3-resource scenario

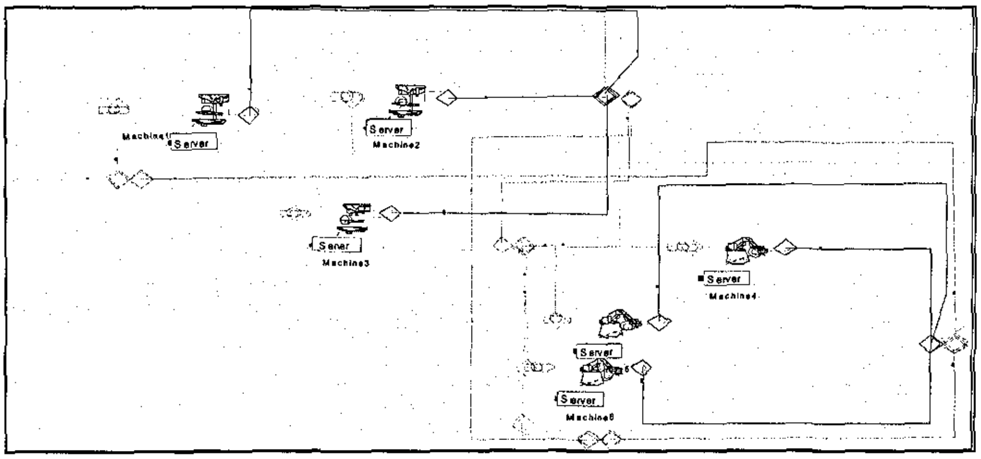

Figure 5-3: The 6-resource scenario

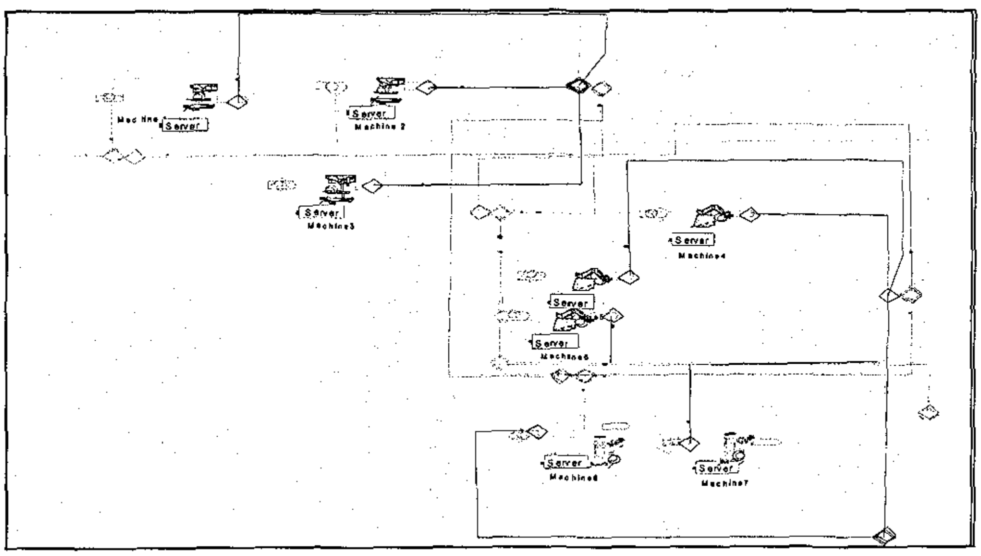

Figure 5-4: The 8-resource scenario

5.1.2 SCHEDULING RULES

When there is more than one operation awaiting processing, there is the need to select an operation when a resource is free. There is however the probability that when this happens, more than one operation can go on the resource: hence the need to select the operation based on some rule. For these purposes, the following operation sequencing rules have been developed.

i. Op/Resource Flexibility

This is the percentage of resources from the whole set of resources that can perform an operation. In using this criterion, it is possible to give preference to either higher or lower operation/resource flexibility operations. If that with a lower value is selected first, operations with higher values are left unscheduled leaving a higher chance of subsequent operations being able to go on the available resources. The converse should be true if preference is given to higher operation/resource flexibility operations. Both rules have been considered.

ii. Op/Tool Flexibility

This is the percentage of tools from the whole set of tools that can perform an operation. In using this criterion, it is possible to give preference to either higher or lower operation/tool flexibility operations. The flexibility of the system increases if more flexible operations are left unscheduled until later. Therefore if that with a lower value is selected first, operations with higher values are left unscheduled but with a higher chance of being put on an available resource. The converse should be true if preference is given to higher operation/tool flexibility operations. Both rules have been considered.

iii. Positional Factor

This refers to the position of an operation within a job. Using the "highest-positional-factor operation first" rule (HPos) involves prioritising jobs closer to completion and thereby reducing the size of the scheduling task. This should thus cut down on delays. With the "lowest-positional-factor operation first" rule (LPos), jobs further away from completion, that is, jobs with higher number of remaining operations are started first. Both HPos and LPos have been considered.

iv. Tool Index

This parameter considers tool changes and number of operations left undone in a job. An operation with a higher tool index (maximum value of 4) would typically require no tool change. The tool index rule can give preference to operations with either higher or lower tool indexes. Both rules have been considered.

v. Cost of Operation

This evaluates the cost of an operation to a customer by considering the processes and the resources needed. Higher values are given to operations requiring greater precision and more resources. However, cost of operation is more of a constraint since there could be a higher demand for costlier jobs to meet due date. The aim of any industry is to make money and as such, the objective when considering the cost of operation, would be to minimise the cost of operation by giving preference to jobs with higher costs of operation.

vi. Remaining Work (remwork)

This refers to the remaining work in terms of duration, depending on the operation position within the job. Table 5-1 illustrates this. After the first operation of the splined shaft is done, the remaining work is the total operation time minus the operation time of that first operation, which is 32 minutes in this case. This rule could involve either prioritising jobs closer to or further away from, completion.

Products	Operation Names	Operation Time	Remaining Work
Splined Shaft	Rough turn diameter	15	47
	Mill keyway	5	32
	Mill splines	10	27
	Harden keyway	5	17
	Grind to size	12	12
Total Operation Time		47	

Table 5-1: Illustration of "remwork"

It is expected that if operations with lower values of flexibility are selected first, higher flexibility operations remain with a lower chance of having to wait because of resource unavailability. By using tool index, operations requiring no tool change and nearer the end of the job can be given higher priority. Also, in making most decisions, there is cost implication and if the aim of a schedule is to reduce cost, then the use of the "cost of operation" rule is advisable.

For each operation, a set of tools can be used. In the selection of a tool from a pool of applicable tools, a tool selection rule may need to be used. The following are three such rules considered.

1. The tool life rule

The rule allows a search through the applicable tool set for the tool with the minimum tool life, provided the tool life is greater than the operation time of the operation in question. It then selects this for the operation. Otherwise, it picks the next lowest tool life whose value is greater than the operation time.

2. The tool cost rule

The rule allows a search through the applicable tool set for the tool with the minimum tool cost, provided its tool life is greater than the operation time of the operation in question. It then selects this for the operation. Otherwise, it picks the next lowest tool cost whose tool life value is greater than the operation time.

3. The tool flexibility rule

The rule allows a search through the applicable tool set for the tool with the minimum tool flexibility, provided its tool life is greater than the operation time of the operation in question. It then selects this for the operation. Otherwise, it picks the next lowest tool flexibility whose tool life value is greater than the operation time.

5.1.3 SET OF ORDERS

Another variable input is the set of orders. By generating more than one set of orders, schedule performances can be validated to a large extent. The set of orders can be varied by varying batch size for the products of the orders, the size of orders (number of products in the order) or by changing the order of the jobs. By changing the order, it is possible for instance to verify whether or not some rule behaviours favour order sets with the starting jobs having either the longest or the shortest total number (or duration) of operations. Most of the jobs have between 4 and 15 operations.

Table 5-2 shows the order sets that have been used. In order set 1, 3 additional products (compared with the 3- and 6-resource scenario) were considered for the 8-resource scenario. The other order sets had the same amount of work until secondary resources were considered. Then some changes were made to enable a fair evaluation of schedule performance. The initial order set of Table 5-2 resulted in incomplete allocation of operations for some rules when secondary resources were considered. Because of this, as shown in Table 5-3, some amendments were made to the initial order sets. These amendments were used on experiments 6NSF[1], and the experiments in the special features category apart from experiments 1SF[2], 7SF and 8SF.

5.2 SCHEDULING OUTPUTS

The variable inputs are the set of orders, the scheduling rules and the testbeds, any of which should lead to a change in output. This output is a measure of the schedule

[1] NSF represents experiments that do not require secondary resources

performance. Ideally, before a scheduling rule is selected, there is a required schedule performance that dictates the objective for the system. As an example, if the objective of generating schedules for a system is to minimise operation time, then it is advisable to consider both resource-dependent and resource-independent operation times and to compare schedule performances derived from both.

<table>
<tr><th colspan="4">Orders and their Products</th></tr>
<tr><th colspan="4">Order set 1</th></tr>
<tr><td>3/6 Resource Scenario</td><td>Quantity</td><td>8-Resource Scenario</td><td>Quantity</td></tr>
<tr><td>Splined Shaft</td><td>20</td><td>Splined Shaft</td><td>20</td></tr>
<tr><td>Gearbox Mounting</td><td>30</td><td>Gearbox Mounting</td><td>30</td></tr>
<tr><td>Safety Cover 200</td><td>30</td><td>Safety Cover 200</td><td>30</td></tr>
<tr><td>Support Plate</td><td>25</td><td>Support Plate</td><td>25</td></tr>
<tr><td>Switch Box</td><td>25</td><td>Switch Box</td><td>25</td></tr>
<tr><td>Torque Tube</td><td>30</td><td>Torque Tube</td><td>30</td></tr>
<tr><td colspan="2"></td><td>Safety Cover 300</td><td>30</td></tr>
<tr><td colspan="2"></td><td>Flanged Bushing</td><td>30</td></tr>
<tr><td colspan="2"></td><td>Axle Casing</td><td>40</td></tr>
<tr><th colspan="4">All Other Order sets</th></tr>
<tr><td colspan="2">Case Study Order, The 3 Scenarios</td><td colspan="2">Splined Shaft, 20
Gearbox Mounting, 30
Safety Cover 200, 50
Support Plate, 25
Gearbox Mounting, 45
Torque Tube, 30</td></tr>
<tr><td colspan="2">Order set 3, The 3 Scenarios</td><td colspan="2">Safety Cover 200, 50
Support Plate, 25
Splined Shaft, 20
Gearbox Mounting, 30
Support Plate, 25
Safety Cover 200, 50</td></tr>
<tr><td colspan="2">Tool Consideration, Order Set A, 3- and 6- Resource Scenarios</td><td colspan="2">Splined Shaft, 20
Gearbox Mounting, 30
Safety Cover 200, 50
Support Plate, 25
Switch Box, 20
Gearbox Mounting, 30</td></tr>
<tr><td colspan="2">Tool Consideration, Order Set B, 3- and 6- Resource Scenarios</td><td colspan="2">Splined Shaft, 20
Safety Cover 200, 25
Support Plate, 25
Torque Tube, 30
Switch Box, 20</td></tr>
</table>

Table 5-2: The order sets used in the research

5.2.1 SCHEDULE PERFORMANCE

Table 5-4 shows the situations where certain rules could be used because of the required objectives of the system.

[2] SF represents experiments that do require secondary resources. The numbers adjacent to either SF or NSF refer to exact experiments defined in Tables 6-1 and 7-1.

Order Names	Products	3-Resource Scenario		6-Resource Scenario		8-Resource Scenario	
		Qty	Due Dates	Qty	Due Dates	Qty	Due Dates
Order set 3	Safety Cover 200	50	5/1	50	6/1	50	5/1
	Support Plate	25	6/1	25	4/1	25	6/1
	Splined Shaft	20	3/1	20	3/1	20	3/1
	Gearbox Mounting	-	-	30	8/1	-	-
	Support Plate	25	7/1	-	-	25	7/1
	Switch Box	-	-	25	7/1	-	-
Order set 1	Splined Shaft	20	4/1	20	4/1	20	4/1
	Gearbox Mounting	30	7/1	30	7/1	30	7/1
	Safety Cover 200	-	-	50	5/1	50	5/1
	Support Plate	25	6/1	25	6/1	25	6/1
	Switch Box	25	4/1	25	4/1	25	4/1
	Torque Tube	30	5/1	30	5/1	30	5/1
Case Study	Splined Shaft	20	4/1	20	4/1	20	4/1
	Gearbox Mounting	30	7/1	30	7/1	30	7/1
	Safety Cover 200	50	5/1	50	5/1	50	5/1
	Support Plate	25	6/1	-	-	25	6/1
	Switch Box	-	-	25	6/1	-	-
	Torque Tube	30	5/1	30	5/1	30	5/1

Table 5-3: The amended order sets with secondary resources

Objectives of the System	**Scheduling Rules Selected**
Time-related	Earliest Due Date, Minimum Setup Time, Sequence dependent Setup Time, Remaining Work, Positional Factor
Utilization-related	Operation/Resource Flexibility, Operation/Tool Flexibility, Tool Flexibility, and Batch-splitting and Re-allocating to other resources
Cost-related	Cost of Operation, Tool Cost
Tool Change-related	Tool Index
Flexibility-related	Operation/Tool Flexibility, Operation/Resource Flexibility, Tool Flexibility

Table 5-4: Objectives of the system dictating the scheduling rules

Tables 5-5 and 5-6 list the typical objectives that may be used in manufacturing systems as have been reported by researchers over the years.

	Objectives	Ranking
1	Meeting due dates	57 (Most important to scheduling practitioners)
2	Maximizing system/machine utilization	44 (Researchers pay most attention to 2 and 5)
3	Minimizing in-process inventory	23
4	Minimizing setup times and tool changes	13
5	Maximizing production rate	13
6	Minimizing mean flow time	8
7	Balancing machine usage	3

Table 5-5: The Importance of the Scheduling Objectives (Smith et al, 1986)

5.3 ASSUMPTIONS

For ease of evaluation and to reduce some of the complexities of an FMS, a number of assumptions have been made. These include:

- A dynamic situation where jobs can be deleted or inserted in the order set at any time, with the priority of jobs changing.
- Started jobs cannot be withdrawn.
- There are breakdowns of machines at any time and tool wear is also considered.
- Tool switch times (that is, within a tool kit on the same machine) are negligible.
- Each operation has a definite work content but there may be the option of more than one machine, tool and route for the operations.
- Operation times may vary depending on the machine used for the operations.
- Operations may be constrained by secondary resources.
- Setup and transportation times are dependent on operation sequence.
- De-fixturing time is negligible and set-up times are for a batch, not for each job within the batch[3].
- At time t = 0, all machines are loaded with the appropriate tool kits.
- There can only be one tool working from a toolkit at any one time.
- Tools do not need to be re-conditioned. They are used continuously until their tool lives are fully exhausted.
- Pre-emption of an operation is not allowed.
- AGVs travel in such a way that there is never a collision.
- AGVs stay at the last machines they visited until called elsewhere.

[3] For a batch of products if a product for example needs 4 fixtures, then the batch needs 4 fixtures, not (batch size * 4).

- An AGV has unlimited carrying space at all time.

5.4 OPERATIONAL CONSTRAINTS

- All operations in a job[4] must be performed.
- Precedence relationships for the operations must be maintained.
- To perform an operation, the machine must be equipped with appropriate tools.
- When scheduling optimisation strategies are used, operation/resource status changes are limited to 6 to ensure that workload is not just being transferred from one resource to another.

In applying the approaches that utilise the scheduling optimisation strategies, most often, the operation/resource flexibility is increased from 1 (which likens it to an FMS) such that more than one resource can perform some operations. This operational constraint however ensures that this variable is not changed too often in the jöb to prevent the scheduling problem from being severely altered.

- A part can only be transported when there is an available AGV.
- A part can only be stored in a buffer when there is an available buffer space.

5.5 THE EXPERIMENTS

The earlier sections introduced a set of control variables: the shop structure, the order set and the scheduling rules, and the performance measures which are a type of scheduling output. Assumptions and operational constraints were also listed. With these variables, several experiments were performed, a matrix of which has been drawn up in Table 5-7. Performing all these experiments can be exhaustive and very time-consuming as a result of which experiments carried out were selected logically based on the results from previous experiments.

This section summarises the different experiments possible and explains how logical conclusions were drawn that showed that certain experiments were not necessary. For each set of experiments, the fixed and the investigated control variables, the objectives of the experiments and the expected significant performance measures are highlighted. In Table 5-8, the XXXX stands for any considered features in the experiments. Some of these features include the consideration of transportation,

[4] Specified by the route

secondary resources, operation/resource flexibility, planned maintenance, machine breakdowns and tool selection rules.

Table 5-7 shows that some of these experiments were carried out with the consideration for late orders (B products), and some without (A products). This means that some of the experiments were made so restrictive that there had to be late orders. This was to make it easier to see how and when the schedule performances were improved in terms of % late orders. TheYs represent the considered features. As an example, the experiments that involved the "maximum tool change" rule did not make use of transportation, routing, machine breakdowns or sequence dependent setup times but did consider tool selection rules and secondary resources.

Ideally, any of the scheduling rules in Tables 5-7 and 5-8 can be used in the approaches that utilise the scheduling optimisation strategies that will be described in detail in Chapter 7 but for the benefit of the work reported, only those with the best schedule performances have been advised.

Figures 5-5, 5-6 and 5-7 show how some of these experiments were derived to adequately represent an FMS and to improve schedule performance. The first experiment was the basic with a relaxed shift pattern, no secondary resources and no operational flexibility. By constraining the shift pattern, the experiments were more representative of a real manufacturing system. By further restricting operations by the addition of secondary resources, the resulting manufacturing system was made more real. Increasing operation/resource flexibility ensured that the model was more representative of a flexible manufacturing system.

Secondary Objectives	Concerned with internal efficiency of FMS, and in particular:	Other	Minimising total throughput time. Minimising number of batches. Minimising total cell load variation. Maximising machine similarity within cells. Maximising association of part operations with machines. Minimising in-process inventories.
		Capacity Utilisation	Maximising FMS utilisation. Minimising duplicate machines. Minimising makespan.
		Machining Efficiency	Maximising average machine utilisation. Minimising total machining time and cost. Minimising disparity in utilisation of machines. Minimising tool changes. Minimising unproductive time. Flexibility to meet rapidly changing resource availability.
		Transport Efficiency	Optimising material handling movements. Minimising cost or distance of inter-cellular moves. Minimising total number of part transfers. Optimising AGV flow path. Minimising empty AGV journeys.
Primary Objectives	Directly concerned with satisfying customer demand		Minimising total production time. Minimising time between production batches. Minimising lateness. Minimising number of tardy jobs. Flexibility to meet rapidly changing resource demands.

Table 5-6: FMS Scheduling Objectives

Figure 5-6, slightly different from Figure 5-5, is more representative of the decision-making process involved. The basic experiment forked out into the transportation and the stricter shift pattern experiments, and the latter experiments considered either the OpRes or the SecRes experiments. The SecRes experiments were later to consider operation/resource flexibility. The OpRes experiments considered either job splits, variable operation times or machine disturbances to either improve system performance or to imitate real systems. Figure 5-7 shows that the last experiments used the approaches that utilise the scheduling optimisation strategies to imitate a real flexible system while also showing that it can offer better performance than any of the other experiments considered.

The initial results of increasing operation/resource flexibility showed that the flexibility could not be taken advantage of because of the large batch sizes of the jobs. By splitting the jobs, it was possible to reduce the jobs to manageable sizes such that squeezing them in between available resource spaces was fairly easier. The results of this experiment made one draw a conclusion that perhaps the schedule performance would have been better if secondary resources had not been considered in which case, additional resource constraints would not have hidden the benefits of flexibility. This led to the inclusion of the job-splits + no secondary resources experiment (5aNSF, 5bNSF).

Considering machine breakdowns and planned maintenance in an FMS allowed for a dynamic scheduling problem in such a system, an effect which is expected to be nullified in a system whose operational flexibility is increased via the allowance for variable routes.

In the same vein, some experiments supposed to be carried out were excluded because previous experiments showed that they were unnecessary. As an example, in using tool selection rules, the first set of experiments produced the same schedule performance results regardless of the operating tool selection rule. Therefore, the set of experiments that followed thereafter considered only one tool selection rule (as opposed to three) in the evaluation of schedule performance. This greatly reduced the number of experiments done and consequently, the amount of computation involved.

For the 3, 6 and 8 Resources-cell	B Products for late orders to exist A Products for late orders not to exist							Tool Selection Rules		
Scheduling Rules/Features Considered	None (No tool consideration)	Transportation	Secondary Resources	Routing	Sequence Dependent Setup Time	Machine Breakdowns	Shift Patterns	Minimum Tool Life	Minimum Tool Cost	Minimum Tool Flexibility
Earliest Due Date	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
First Come First Served	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Critical ratio	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Minimum Setup Time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum Setup Time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Minimum Operation Time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum Operation Time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Lowest Position of Operation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Highest Position of Operation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Lowest Remaining Duration	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Highest Remaining Duration	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Lowest Operation/Tool Flexibility			Y				Y			
Highest Operation/Tool Flexibility			Y				Y			
Lowest Operation/Resource Flexibility	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Highest Operation/Resource Flexibility	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Cost of Operation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Minimum Tool Change			Y				Y	Y	Y	Y
Maximum Tool Change			Y				Y	Y	Y	Y

Table 5-7: The possible experimental considerations

Below are the experiments that were carried out in this research, their highlighted control variables, fixed and variable, objectives and expected schedule performances.

<u>**RELAXED SHIFT PATTERNS**</u>: Experiment 1NSF

<u>CONTROL VARIABLES FIXED</u>: Order set 1

<u>CONTROL VARIABLES INVESTIGATED</u>: Shop structure and scheduling rules were investigated in that the experiments were performed for all shop structures, and all scheduling rules under investigation.

<u>OBJECTIVES OF THE EXPERIMENTS</u>: To form a basis for comparison with other experiments

<u>EXPECTED SIGNIFICANT PERFORMANCE MEASURES</u>: Overall good schedule performance since no restrictions were imposed apart from normal operational constraints.

For the 3, 6 and 8 Resources-cell, XXXX					Resource Data			
Scheduling Rules \ Schedule Performance	% Late Orders	Total Late Time	Total Lead Time	Added Value Percentage	Working Percentage	Idle Percentage	Utilization Percentage	Schedule Duration
Earliest Due Date								
First Come First Served								
Critical Ratio								
Minimum Setup Time First								
Maximum Setup Time First								
Minimum Operation Time First								
Maximum Operation Time First								
Lowest Position Of Operation First								
Highest Position Of Operation First								
Lowest Remaining Duration First								
Highest Remaining Duration First								
Lowest Operation/Tool Flexibility First								
Highest Operation/Tool Flexibility First								
Lowest Operation/Resource Flexibility First								
Highest Operation/Resource Flexibility First								
Maximum Cost Of Operation First								
Minimum Tool Change								
Maximum Tool Change								

Table 5-8: The possible evaluations from the experiments

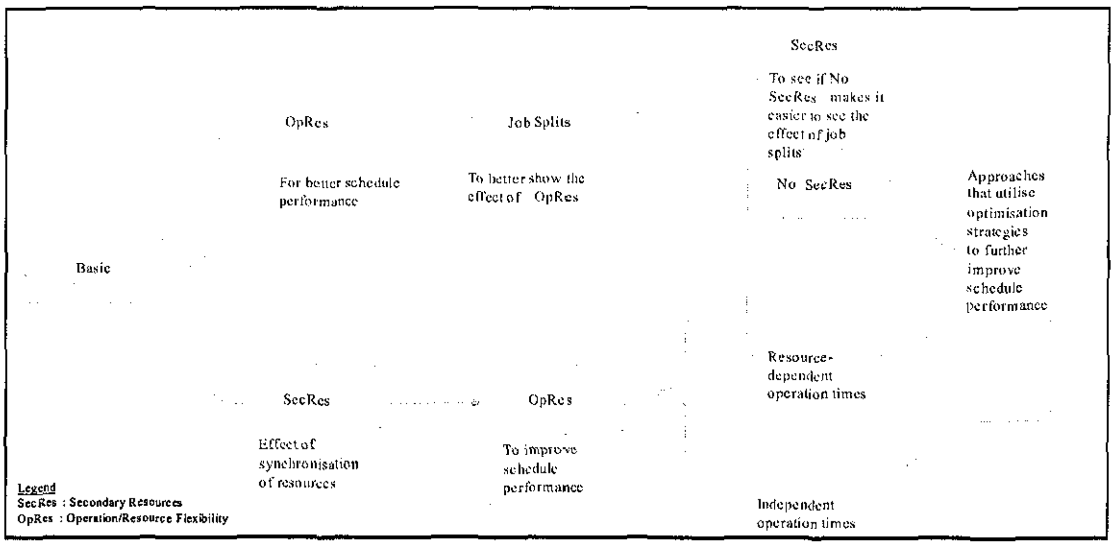

Figure 5-5: The experiments tree

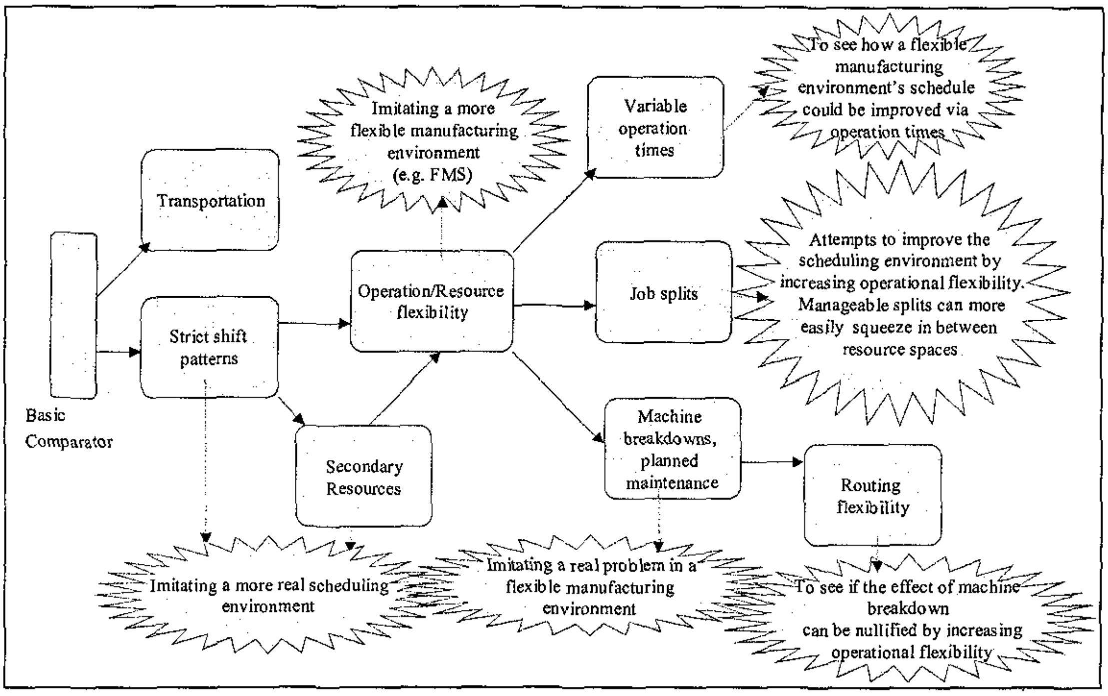

Figure 5-6: The experiments tree 2

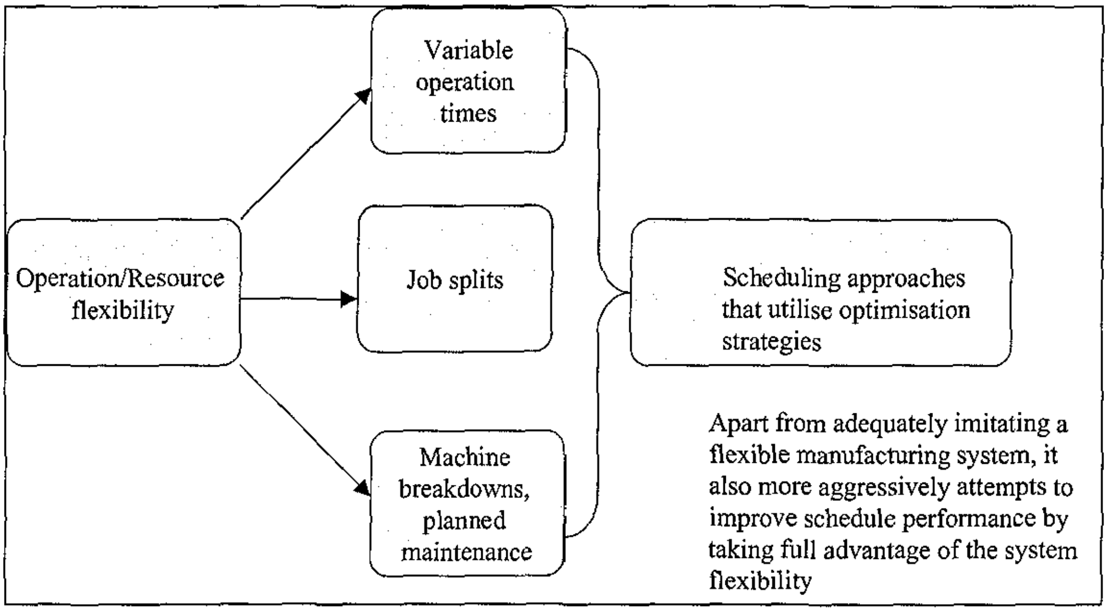

Figure 5-7: The experiments tree 3

STRICTER SHIFT PATTERNS: Experiments 3NSF and 4NSF

CONTROL VARIABLES FIXED: Order set 1 and the Case Study Order set respectively

CONTROL VARIABLES INVESTIGATED: Shop structure and scheduling rules were investigated in that the experiments were performed for all shop structures, and all scheduling rules under investigation.

OBJECTIVES OF THE EXPERIMENTS: To imitate more real scheduling problems with a view to finding a way to improve schedule performance

EXPECTED SIGNIFICANT PERFORMANCE MEASURES: Not as good a schedule performance as Experiment 1NSF since available machine-hours restrictions were imposed apart from normal operational constraints.

TRANSPORTATION: Experiment 2NSF

CONTROL VARIABLES FIXED: Order set 1

CONTROL VARIABLES INVESTIGATED: Shop structure and scheduling rules were investigated in that the experiments were performed for all shop structures, and all scheduling rules under investigation.

OBJECTIVES OF THE EXPERIMENTS: To see the effect of transportation on the basic scheduling problem

EXPECTED SIGNIFICANT PERFORMANCE MEASURES: Overall good schedule performance although not as good as Experiment 1NSF since operational constraints were increased

SECONDARY RESOURCES: Experiments 1SF to 8SF

CONTROL VARIABLES FIXED: Order sets concerned (see Table 6-1)

CONTROL VARIABLES INVESTIGATED: Shop structure and scheduling rules were investigated in that the experiments were performed for all shop structures, and all scheduling rules under investigation.

OBJECTIVES OF THE EXPERIMENTS: To imitate more real scheduling problems with a view to finding a way to improve schedule performance and to investigate the effect of having to synchronise resources

EXPECTED SIGNIFICANT PERFORMANCE MEASURES: Not as good schedule performances as when secondary resources are not considered since the availability of a resource did not guarantee the availability of a supporting resource needed for any of the operations.

OPERATION/RESOURCE FLEXIBILITY: Experiments 5NSF, 6NSF, 7NSF, 4SF, 5SF, 6SF

CONTROL VARIABLES FIXED: Order sets concerned (see Table 6-1)

CONTROL VARIABLES INVESTIGATED: Shop structure and scheduling rules were investigated in that the experiments were performed for all shop structures, and all scheduling rules under investigation. The HOpRes and LOpRes rules were also investigated.

OBJECTIVES OF THE EXPERIMENTS: To improve the schedule performance by increasing the system's flexibility and to investigate the OpRes rules

EXPECTED SIGNIFICANT PERFORMANCE MEASURES: Better schedule performance since most operations could be done on more than one resource, hence reducing resource idle %, schedule duration, late and lead time and increasing resource working and utilisation %

OPERATION/RESOURCE FLEXIBILITY JOB SPLITS: Experiments 5NSF (5aNSF), 7NSF (7aNSF, 7bNSF), 5SF(5aSF, 5bSF). This involves completing the jobs by splitting them up into smaller manageable batches.

CONTROL VARIABLES FIXED: Order sets concerned (see Table 6-1)

CONTROL VARIABLES INVESTIGATED: Shop structure and scheduling rules were investigated in that the experiments were performed for all shop structures, and all scheduling rules under investigation. The HOpRes and LOpRes rules were also investigated. This was done on both experiments that considered secondary resources (5SF, 5aSF, 5bSF) and those that did not (5NSF, 5aNSF: 7NSF, 7aNSF, 7bNSF).

OBJECTIVES OF THE EXPERIMENTS: To improve the schedule performance by increasing the system's flexibility and to investigate the OpRes rules and where secondary constraints were considered, to see whether this would have any significant effect on schedule performance

EXPECTED SIGNIFICANT PERFORMANCE MEASURES: Better schedule performance since apart from the fact that most operations could be done on more than one resource, there was the added advantage that the operations could more easily be squeezed in between other operations on available resources. This was expected to lead to a reduction in resource idle %, schedule duration, late and lead time and an increase in resource working and utilisation %. Without secondary resources, it was expected that schedule performance would be remarkably better since there was no need to have supporting resources whose availability could not be guaranteed when the other resources were available.

ROUTING FLEXIBILITY: Experiment 8SF

CONTROL VARIABLES FIXED: Case Study Order Set

CONTROL VARIABLES INVESTIGATED: Shop structure and scheduling rules were investigated in that the experiments were performed for all shop structures, and all scheduling rules under investigation.

OBJECTIVES OF THE EXPERIMENTS: To improve the schedule performance by increasing the system's flexibility.

EXPECTED SIGNIFICANT PERFORMANCE MEASURES: Good schedules are expected since flexibility of the system is increased both in terms of routing and operation/ resource flexibility. It is expected that resource performance measures and schedule duration will improve.

OPERATION/RESOURCE MACHINE BREAKDOWNS AND PLANNED MAINTENANCE: Experiment 7SF

CONTROL VARIABLES FIXED: Case Study Order Set

CONTROL VARIABLES INVESTIGATED: Shop structure and scheduling rules were investigated in that the experiments were performed for all shop structures, and all scheduling rules under investigation. The HOpRes and LOpRes rules were also investigated.

OBJECTIVES OF THE EXPERIMENTS: To improve the schedule performance by increasing the system's flexibility, to investigate the OpRes rules and to see the effect of disturbances on schedule performances of a flexible system.

EXPECTED SIGNIFICANT PERFORMANCE MEASURES: Not as good a schedule performance as other experiments that considered operation/resource flexibility only since available machine-hours restrictions were imposed apart from normal operational constraints.

OPERATION/RESOURCE FLEXIBILITY: RESOURCE-DEPENDENT OR INDEPENDENT OPERATION TIMES: Experiments 10aNSF and 10bNSF

CONTROL VARIABLES FIXED: Case Study Order Set

CONTROL VARIABLES INVESTIGATED: Shop structure and scheduling rules were investigated in that the experiments were performed for all shop structures, and all scheduling rules under investigation. The HOpRes and LOpRes rules were also investigated.

<u>OBJECTIVES OF THE EXPERIMENTS</u>: To improve the schedule performance by increasing the system's flexibility, to investigate the OpRes rules and to see the effect of resource-dependency (of operation times) on schedule performance.

<u>EXPECTED SIGNIFICANT PERFORMANCE MEASURES</u>: Better schedule performance since it was expected that when the operations had the option of choice between resources, those with lower operation times would be chosen. This was expected to lead to a reduction in schedule duration, late and lead time.

<u>TOOL-RELATED EXPERIMENTS</u>: Experiments 1TSF and 2TSF

<u>CONTROL VARIABLES FIXED</u>: Order Set A and B

<u>CONTROL VARIABLES INVESTIGATED</u>: 3- and 6-Resource scenarios, tool selection rules and operation scheduling rules (those used in all the previous experiments) were investigated.

<u>OBJECTIVES OF THE EXPERIMENTS</u>: To determine how tool selection rules affect schedule performance and tool utilisation rates since these tool selection rules are aimed at reducing the number of partially worn out tools. The tool selection rules used are tool life, tool flexibility and tool cost.

<u>EXPECTED SIGNIFICANT PERFORMANCE MEASURES</u>: This was not predicted but it was expected that the best tool selection rule in terms of tool utilisation rates and overall schedule performance would be determined.

<u>SCHEDULING OPTIMISATION STRATEGY EXPERIMENTS</u>: Experiments 8NSF and 9NSF

<u>CONTROL VARIABLES FIXED</u>: Order Set 1 and Case Study Order Set respectively

<u>CONTROL VARIABLES INVESTIGATED</u>: Shop structure and scheduling rules were investigated in that the experiments were performed for all shop structures, and all scheduling rules under investigation. Resource flexibility for operations that had the tendency to be late was variable and so also, the techniques for ensuring that operations could be slotted in available resource spaces. These techniques include variable operation/resource flexibility, allowance for concurrent operations, batch-splitting, backward sequencing and a combination of scheduling rules

<u>OBJECTIVES OF THE EXPERIMENTS</u>: To improve schedule performance

<u>EXPECTED SIGNIFICANT PERFORMANCE MEASURES</u>: Better schedule performance since most operations could be done on more than one resource, concurrently, and in

smaller batches that can be made even smaller depending on available resource spaces. This was expected to lead to a reduction in resource idle %, schedule duration, late and lead time and an increase in resource working and utilisation %

Another class of experiments was carried out. This involved scheduling the FMS in a dynamic environment by assuming that the orders were increased or decreased impromptu. Results obtained in this class of experiments were only demonstrative because it was difficult for any two cases to be identical and as such, no fair comparison could be made between scheduling rules. The dynamic situation was dealt with by stopping the loading process, deleting the jobs no longer required (provided it had not been started) and resuming the loading process. Adding more products (orders) was treated in a similar manner.

To dynamically assume machine breakdowns, the in-built planned system in Preactor was used. This was however only possible for jobs that had variable operation/resource flexibility such that the broken down resources were never the only possible resource for any operation. Ignoring this leads to incomplete allocation of resources and severe disruption to the system if such operations were preceding operations to other operations.

The experiments in this category have not been fully investigated primarily because of the difficulty of comparing the results fairly. This area has thus been suggested as a feasible area for further research work.

CHAPTER 6

PRESENTATION OF RESULTS

This chapter summarises all the experiments performed (Table 6-1). It lists the main considerations and control variables and refers to Appendix 3 for the results to the experiments.

For the experiments, the order sets used are the case study's, order set 1 and order set 3, and in the tool selection experiments, order sets A and B, details of which are in Table 6-3. And for all the experiments, the Products database in Appendix 2 was used.

With the 3-resource scenario, the scheduling rules were compared for the given scheduling conditions. By repeating the experiments with the 6- and 8-resource scenarios, a possible confirmation of the results with the 3-resource scenario was expected. In all of the experiments (apart from those of operation/resource flexibility which had additional rules: LOpRes and HOpRes), a fixed number of scheduling rules was investigated (Tables 5-7 and 5-8). Also, some of the experiments that involved operation/resource flexibility and secondary resources did not consider the LST, HST, LPT and SPT rules. This is because they are conventional scheduling rules whose relationships with the custom-made rules had been established from previous experiments and also because there were additional OpRes rules to consider.

In all of the experiments, except those using tool selection rules, the 3 resource scenarios were used. The use of the 3- and 6-resource scenarios for the tool selection experiments was to minimise the amount of computation involved and to concentrate efforts. The sections below briefly explain what was done in each experiment and direct the reader to the appropriate table for the results.

6.1 NO SPECIAL FEATURES

In experiment 1NSF[1], schedules were generated for order set 1 (Table 6-3). Due date for all products was taken as one week (1^{st} to the 8^{th} of January[2]) and the resources' efficiency was taken as 100% for 23 hours in a day, an hour break being allowed between 12 noon and 1pm. No additional operation information was considered. Tables A3-1 to A3-3 show the results of the experiments. In experiment 2NSF, transportation was considered in addition to the considerations of Experiment 1NSF. Results are as shown in Tables A3-4 to A3-6.

In experiment 3NSF, transportation was not considered and the shift pattern was more restrictive. There was the one-hour break but work stopped at 6pm and on Sunday, resources' efficiency dropped to 50%. Also, the individual due dates were brought forward to create late orders and to enable the separate investigation of the FCFS and the EDD scheduling rules. With the existence of late orders, it was easier to see how to improve schedule performance by reducing the degree of lateness and/or the number of late orders. Results of the experiments are presented in Tables A3-7 to A3-9.

In Chapter 8, we will look at the case study order set which was used in experiment 4NSF with the restrictive shift patterns and due dates as shown in Tables 6-2 and 6-3 respectively. No other operation information was required. Results are shown in Tables A3-10 to A3-12.

Experiment 5NSF considered the case study order set with the operations having varying operation/resource flexibility as shown in Tables A2-10 to A2-12 (Appendix 2). These experiments allowed more tests to compare and confirm the rule performances and also to include the operation/resource flexibility rule. The operation/resource flexibility information is shown in Tables A2-2 and A2-3 in Appendix 2 and the products data in Table 6-3. Results of the experiments are shown in Tables A3-13 to A3-15.

[1] NSF represents experiments that do not require secondary resources.
[2] The start date of experimentation was the 1^{st} of January, 1990.

Another set of experiments in this category created smaller batches of the jobs (Table 6-4) to better investigate the effect of operation/resource flexibility on schedule performance. Results of these are shown in Tables A3-16 to A3-18.

Experiment 6NSF performed similar experiments to Experiment 5NSF but on order set 3 and without the job split. Results are shown in Tables A3-19 to A3-21. In experiment 7NSF, similar experiments to Experiment 5NSF was conducted on order set 3 of Table 5-3 and job splits were considered. Results are shown in Tables A3-22 to A3-30.

Experiment 8NSF worked from the results of experiment 3NSF. The aim of these experiments was to reduce the degree of lateness and/or the number of late orders if lateness could not be completely eliminated. In experiments 1NSF to 4NSF, the operation/resource flexibility was assumed to be the same (value of 1) for all operations because it was assumed that only one resource could carry out each operation. To improve the schedules however, in experiment 8NSF, this measure was varied in some operations. Other scheduling optimisation strategies that include batch splitting, backward sequencing, increasing resource flexibility for operations that had the tendency to be late due to resource constraints, were used. Workload was balanced in the 6- and 8- resource scenarios. The results of these experiments are shown in Tables A3-31 to A3-33.

Experiment 9NSF attempted improving the schedule performance of experiment 5NSF by applying the scheduling optimisation strategies used in experiment 8NSF. Results are shown in Table A3-34.

Experiment 10NSF considered the case study order set with the operations having varying operation/resource flexibility as shown in Tables A2-10 to A2-12 (Appendix 2). One set of experiments in this category considered resource-dependent operation times (10bNSF) and another considered the same operation time regardless of the resources selected (10aNSF). This allowed more tests to compare the rule performances and also to include the operation/resource flexibility rule. In addition, it allowed the evaluation of the effect of operation time dependent on resources selected and comparing with when operation time is independent of the resources selected.

Category	Experiments	Considerations
No Special Features	1NSF	Order set 1, Same Due Date, 23 Hours a Day
	2NSF	Order set 1, Same Due Date, 23 Hours a Day, Transportation
	3NSF	Order set 1, Different Due Dates, 9 Hours a Day
	4NSF	Case Study order set, Different Due Dates, 9 Hours a Day
	5NSF	Case Study order set, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility
	5aNSF	Case Study order set, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility – Split job set as shown in Table 7-4
	6NSF	Order set 3, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility (order set of Table 6-2)
	7NSF	Order set 3, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility (order set of Table 6-3)
	7aNSF	Order set 3, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility- Split job set as shown in Table 7-4a
	7bNSF	Order set 3, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility- Split job set as shown in Table 7-4b
	8NSF	Order set 1, Different Due Dates, 9 Hours a Day, Scheduling optimisation strategies
	9NSF	Case Study order set, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility, Scheduling Optimisation Strategies
	10aNSF	Case Study order set, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility – Operation times independent of resources used
	10bNSF	Case Study order set, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility – Resource-dependent operation times
	11NSF[3]	*Case Study order set, Different Due Dates, 9 Hours a Day, Dynamic Insertion of Orders*
	12NSF	*Case Study order set, Different Due Dates, 9 Hours a Day, Dynamic Deletion of Orders*
Special Features	1SF	Case Study order set, Different Due Dates, 9 Hours a Day, Secondary Resources
	2SF	Order set 1, Different Due Dates, 9 Hours a Day, Secondary Resources
	3SF	Order set 3, Different Due Dates, 9 Hours a Day, Secondary Resources
	4SF	Order set 1, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility
	5SF	Order set 3, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility
	5aSF	Order set 3, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility– Split job set as shown in Table 7-4a
	5bSF	Order set 3, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility– Split job set as shown in Table 7-4b
	6SF	Case Study Order Set, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility
	7SF	Case Study order set, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility, Machine Breakdowns, Planned Maintenance
	8SF	*Case Study order set, Different Due Dates, 9 Hours a Day, Secondary Resources, Machine Breakdowns, Planned Maintenance, exploration of Routing Flexibility*
Tool Considerations	1TSF	Order set A, Different Due Dates, 9 Hours a Day, Secondary Resources, Tool Selection Rules
	2TSF	Order set B, Different Due Dates, 9 Hours a Day, Secondary Resources, Tool Selection Rules

Table 6-1: The various experiments conducted

The resource information is shown in Tables A2-2 and A2-3 in Appendix 2 and the products data is shown in Table 6-2. Results of these experiments are presented in Tables A3-35 to A3-40. Experiments 11NSF and 12NSF considered the dynamic insertion and deletion of orders to the case study order set.

	Normal Shift Pattern	Restrictive Shift Pattern
Mon-Sat, Sun 8am – 12pm	100, 100	100, 50
Mon-Sat, Sun 12pm – 1pm	0, 0	0, 0
Mon-Sat, Sun 1pm – 6pm	100, 100	100, 50
Mon-Sat, Sun 6pm – 8am	100, 100	0, 0

Table 6-2: The relaxed and restrictive shift patterns used

Due Dates:	Expts 1NSF and 2NSF	**Case Study Order Set**	**Order Set 1**		**Order Set 3**	
			3, 6-Resource	*8-Resource*	*6/8-Resource*	*3-Resource*
Splined Shaft	8/1	4/1(J1)	4/1	4/1	3/1 (J3)	3/1 (J3)
Gearbox Mounting	8/1	7/1(J2), 6/1 (J5)	7/1	7/1	8/1 (J4)	-
Safety Cover 200	8/1	5/1(J3)	5/1	5/1	6/1 (J1), 10/1 (J6)	6/1 (J1)
Support Plate	8/1	6/1(J4)	6/1	6/1	4/1(J2), 7/1 (J5)	4/1(J2), 7/1 (J4)
Switch Box	8/1	-	4/1	4/1	-	-
Torque Tube	8/1	5/1(J6)	5/1	5/1	-	-
Safety Cover 300	-	-	-	5/1	-	-
Flanged Bushing	-	-	-	6/1	-	-
Axle Casing	-	-	-	8/1	-	-

Table 6-3: Due dates in each order set, J(X) representing job(X)

The job set for experiments 5NSF and 5aNSF			
No Special Features	Job Set For Experiment 5NSF including Quantity	Job Set For Experiment 5aNSF including Quantity	
	Splined Shaft, 20	Splined Shaft, 10, 10	
	Gearbox Mounting, 30	Gearbox Mounting, 15, 15	
	Safety Cover 200, 50	Safety Cover 200, 15, 20, 15	
	Support Plate, 25	Support Plate, 12, 13	
	Gearbox Mounting, 45	Gearbox Mounting, 15, 15, 15	
	Torque Tube, 30	Torque Tube, 15, 15	
The job set for experiment 5aSF			
Special Features	Initial Job Set Quantity	Job Set For Experiment 5aSF including Quantity	
		3, 8- Resource Scenario	*6- Resource Scenario*
	Safety Cover 200, 50	15, 15, 20	15, 15, 20
	Support Plate, 25	10, 10, 5	10, 10, 5
	Splined Shaft, 20	10, 10	10, 10
	Gearbox Mounting, 30	-	10, 10, 10
	Support Plate, 25	10, 10, 5	10, 10, 5
The job set for experiment 5bSF			
Special Features	Initial Job Set Quantity	Job Set For Experiment 5bSF including Quantity	
		3, 8- Resource Scenario	*6- Resource Scenario*
	Safety Cover 200, 50	10, 10, 10, 10, 10	10, 10, 10, 10, 10
	Support Plate, 25	5, 5, 5, 5, 5	5, 5, 5, 5, 5
	Splined Shaft, 20	5, 5, 5, 5	5, 5, 5, 5
	Gearbox Mounting, 30	-	5, 5, 5, 5, 5, 5
	Support Plate, 25	5, 5, 5, 5, 5	5, 5, 5, 5, 5

Table 6-4: The job set for Experiments 5NSF and 5aNSF: 5aSF and 5bSF

[3] Experiments in italics were only demonstrated.

6.2 THE CONSIDERATION OF SPECIAL FEATURES

Experiment 1SF[4] considered the case study order set, varying due dates and the restrictive shift patterns as shown in Tables 6-2 and 6-3 and secondary resources as shown in Table A2-6 in Appendix 2. Results of these experiments are presented in Tables A3-41 to A3-43. Experiments 2SF and 3SF repeated Experiment 1SF on order sets 1 and 3 respectively. Results of these experiments are presented in Tables A3-44 to A3-49.

Experiments 4SF, 5SF and 6SF considered operation/resource flexibility on order sets 1, 3 and the case study order set respectively in addition to the consideration of secondary resources. Results of the experiments are as shown in Tables A3-50 to A3-58. Experiments 4aSF[5], 5aSF and 6aSF repeated these experiments respectively but split up the job order for a more effective evaluation of the OpRes rules. Results of the experiments are shown in Tables A3-59 to A3-67.

Experiment 7SF considered machine breakdowns and planned maintenance in addition to all the other considerations of experiment 1SF. Results of the experiments are presented in Tables A3-68 to A3-70.

Experiment 8SF attempted reducing the degree of lateness and/or the number of late orders by exploring the routing flexibility options in a disturbed manufacturing system.

The graphical definitions of these experiments are shown in Figure 6-1.

6.3 CONSIDERATION OF TOOL SELECTION RULES

The experiments carried out in this category considered varying due dates and restrictive shift patterns in addition to tool selection rules in 2 resource scenarios (3 and 6). Similar scheduling rules to those used in the previous experiments were

[4] SF represents experiments that do require secondary resources.

[5] a and b in the jobs splits is just a way of demarcating one set of splits from another. As an example, where there are 5aSF and5bSF, both jobs are split from 5SF but 5bSF are smaller splits than 5aSF.

applied in these experiments. In addition to these however, 4 scheduling rules[6], were used.

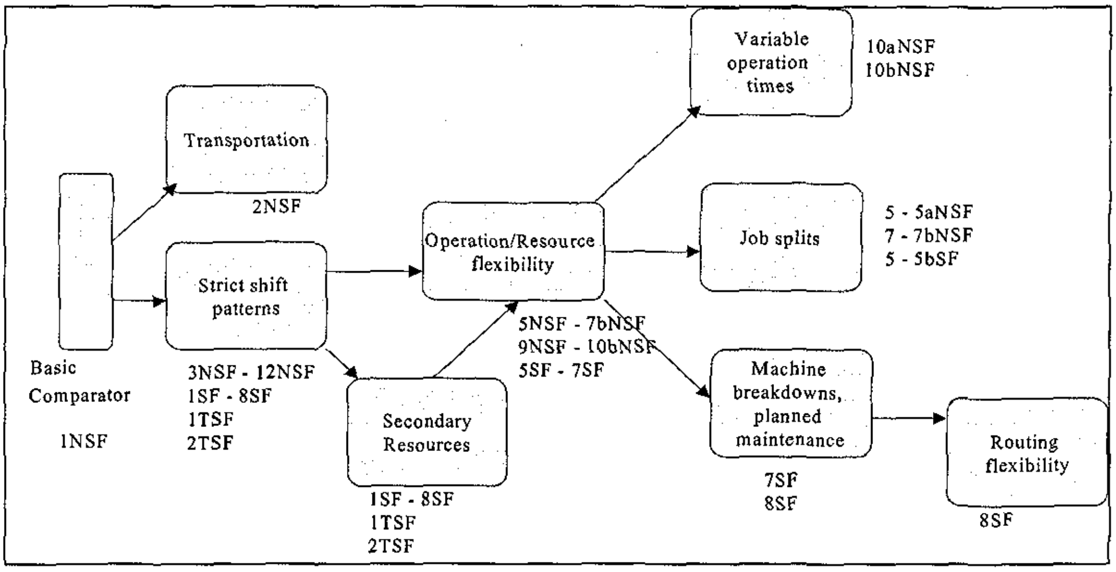

Figure 6-1: Graphical labelling of conducted experiments

These experiments gave an opportunity to further compare all the developed rules and to evaluate the tool utilisation percentages associated with the different tool selection rules.

Experiments 1TSF[7] and 2TSF considered tool selection rules in addition to secondary resources using order sets A and B respectively, the product data of which is amended as shown in Table 6-5. Results are shown in Tables A3-71 to A3-73.

	A		B	
Products	Qty	Due Dates	Qty	Due Dates
Splined Shaft	20	4/1	20(J1)	4/1
Gearbox Mounting	-	-	30(J2), (J6)	7/1, 8/1
Safety Cover 200	25	5/1	50(J3)	5/1
Support Plate	25	6/1	25(J4)	6/1
Torque Tube	30	5/1	-	-
Switch Box	20	7/1	20(J5)	7/1

Table 6-5: The order sets used in tool consideration experiments

[6] LOpFlex and HOpFlex that consider operation/tool flexibility, and MaxToolIndex and MinToolIndex, that consider the values of tool index (refer to section 5.1.2)
[7] TSF represents experiments that consider tool selection rules.

CHAPTER 7

DISCUSSION

Scheduling rules were tested primarily to see if novel scheduling rules could be developed to give better schedule performances than the conventional ones. This chapter deals with the results of the schedules generated and analyses these considering the scheduling conditions. The results showed that although it was possible to have better schedule performance with the custom-made rules, they were not always as good as predicted nor were they always as good as the conventional scheduling rules. The following sub-sections first identify the effect of the different scheduling environments and then, some scheduling approaches that utilise certain scheduling optimisation strategies are presented with a view to further improving schedule performances. Eventually, the best scheduling rules are presented. Based on these results, attempts are made to justify the deviation in schedule performance from that expected.

The chapter is divided into analysis of results (section 7.2), presentation of other scheduling approaches (section 7.3) and the plausible reasons for schedule behaviours (section 7.4).

7.1 FOREWORD TO THE ANALYSIS OF RESULTS

In the presentation of results, the use of minimum, average, maximum and total values for the job completion data (lead and late times) could have been considered. For resource data (working, idle and utilisation), the options that could have been considered were minimum, average and maximum. However, to adequately represent the schedule performances while also allowing ease of evaluation, the total option was used for late and lead times, and the average option for the resource data.

While the total option more accurately represents the overall job completion data, the average values were used for the resource data. This is primarily because they provide a more commonly used measure of central tendency[1] for a set of data (Aczel,

[1] 3 commonly used measures of central tendency are mean, median and mode, values which are equal only if the data set is symmetric. The mean is usually favoured because it is based on information contained in *all* the data in the data set.

1993). Often, this value gave a poor indication of the central tendency of the data because one or more of the resources most often gave unusually small data values (nil for resource minimum utilisation % for instance when at least one resource was not used at all). This significantly influences the value of the mean but the application of trimmed mean which eliminates or trims the percents of unusually small data values from the data values would result in more biased results. This is because some of the other experiments had more balanced workload and hence no unusually small data values that required trimming. Hence, where it seems that resource average utilisation or working percentages are so low or resource average idle % so high, this is not necessarily a true indication of the data. Only as comparative data[2] are the values appropriate.

In the analysis of results of the generated schedules, for each category of experiments (Table 6-1), for each schedule performance measures (and overall)[3] and for each resource scenario, the best 7 scheduling rules are identified. For each schedule performance (and overall), these rules were compared across the 3 resource scenarios and the common scheduling rules were taken as the resulting best rules for the particular schedule performance measure (and overall).

To evaluate the methodology for determining the scheduling rules required for a given system objective, similar experiments were grouped together and their results compared, for the effect of that similarity. As an example, to determine the effect of batch-splitting for problems considering the variable operation/resource flexibility, experiments 5NSF[4] and 5aNSF; 7NSF, 7aNSF and 7bNSF, and 5SF, 5aSF and 5bSF were compared for a consistent pattern. At the end of the analysis, it should be possible to establish the effect of batch-splitting and to tell whether this effect is the same when secondary resources are considered.

[2] when scheduling rules' results are being compared

[3] The overall best scheduling rules are those that perform well in the most number of schedule performance measures considering that the best scheduling rules for a schedule performance measure are those that are the best in ***all*** 3 resource scenarios.

[4] a, b are just letters that denote job splits. b denotes a further split from that of a. NSF represents experiments that do not need secondary resources. SF experiments do need secondary resources.

7.2 ANALYSIS OF RESULTS

This section deals with the schedule performances that have been obtained by carrying out the experiments in Table 6-1 (brought forward to this section for easy referral to the experiments and referred to as Table 7-1).

To adequately analyse the results, several tables were drawn up (section 7.2.2) to more easily bring out the best scheduling rules, either overall or with regards to the schedule performance measures, across the 3 resource scenarios and for all category of experiments. This led to the performance of each scheduling rule being analysed in summary (section 7.4.2).

7.2.1 SCHEDULING ENVIRONMENTS

This section deals with each scheduling environment and highlights the findings from the experiments. Figures 7-1 and 7-2 show the general results of the experiments and in later sections, these are discussed in detail.

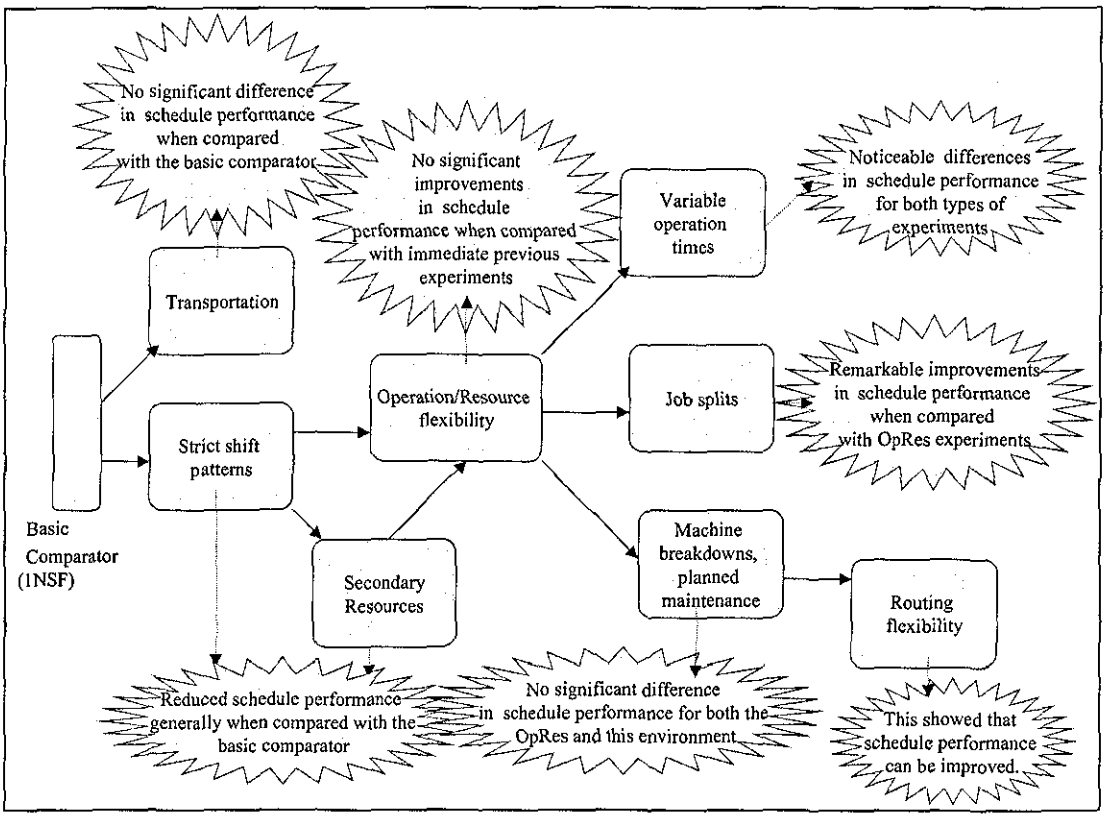

Figure 7-1: Graphical presentation of the general results

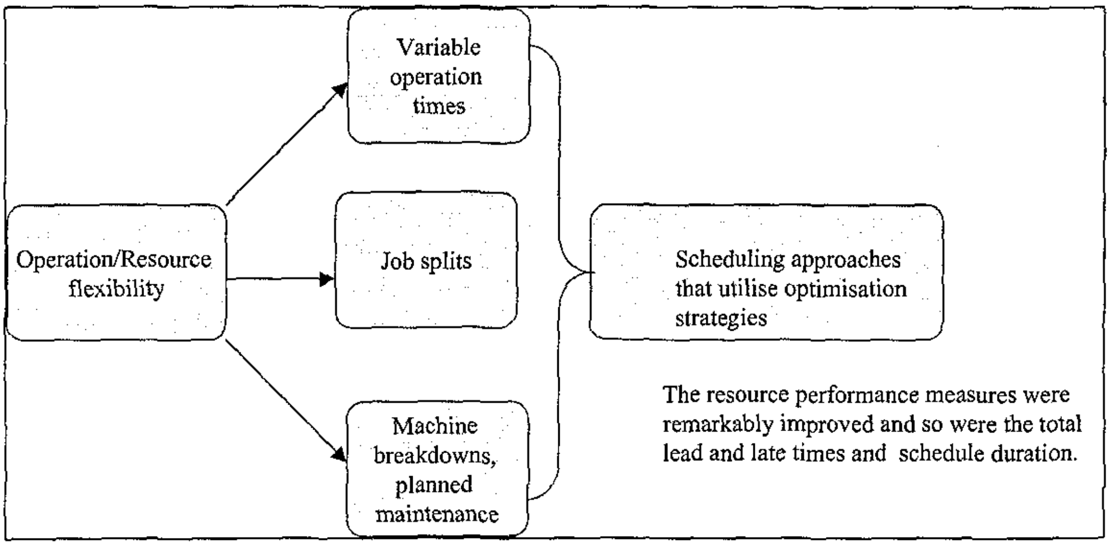

Figure 7-2: Graphical presentation of the general results 2

EFFECT OF TRANSPORTATION: Experiment 2NSF (compared to 1NSF)

SIGNIFICANT PERFORMANCE MEASURES: In the 3-resource scenario,

- Resource idle % and resource idle range[5] increased with transportation.
- There was also a large range in the results of resource utilisation and working % with transportation.
- Total lead time, average added value % and schedule duration values were similar for both experiments.
- In the 6 and 8-resource scenarios, similar results were obtained for both sets of experiments (1NSF and 2NSF).

EFFECT OF SECONDARY RESOURCES: Experiments 1SF (compared to 4NSF) and 2SF (compared to 3NSF)

SIGNIFICANT PERFORMANCE MEASURES:

- There was generally an increase in degree of lateness (% late orders), total lead and late times, resource idle %, and schedule duration.
- There was also a marked decrease in resource working %, resource utilisation % and the added value %.

EFFECT OF A STRICTER SHIFT PATTERN: Experiment 3NSF (compared to 1NSF)

SIGNIFICANT PERFORMANCE MEASURES:

[5] difference between the highest and lowest value

- In the 3-resource scenario, there was an increase in degree of lateness (% late orders), total lead time and schedule duration,
  - a decrease in resource working %, idle % and
  - similar resource utilisation % and average added value % when compared with 1NSF.

In the 6 and 8-resource scenarios, the results were similar to the 1NSF results but higher resource average utilisation % and average idle % ranges were obtained.

EFFECT OF OPERATION/RESOURCE FLEXIBILITY: Experiments 5NSF (compared to 4NSF); 4SF (compared to 2SF); 5SF (compared to 3SF)

SIGNIFICANT PERFORMANCE MEASURES:

- There was not much difference in % late orders although there was generally an increase in total lead and late time.
- There were no other clear-cut patterns.
  - As an example, in comparing experiments 3SF and 5SF, it was discovered that for the 3-resource scenario, there was a lower resource working % range as opposed to a higher range with the 6-resource scenario.
  - Also, while schedule duration was reduced in the 3-resource scenario, it was increased in the 6 and 8-resource scenario.

EFFECT OF OPERATION/RESOURCE FLEXIBILITY JOB SPLITS: Experiments 5NSF, 5aNSF; 7NSF, 7aNSF, 7bNSF; 5SF, 5aSF, 5bSF

SIGNIFICANT PERFORMANCE MEASURES: There was a reduction in % late orders but increases in total lead time and total late time[6].

- There were increases in resource working %, utilisation % and decreases in schedule duration, average added value % and idle %.

EFFECT OF ROUTING FLEXIBILITY: Experiment 8SF

SIGNIFICANT PERFORMANCE MEASURES: The flexibility of the system was dependent on the eventual operation time. With routing flexibility, more than one route was possible and for each route, there may be a different total production time (summation of the operation time for all of the operations).

[6] total late time reduced when % late orders was remarkably small or nil.

Category	Experiments	Considerations
No Special Features	1NSF	Order set 1, Same Due Date, 23 Hours a Day
	2NSF	Order set 1, Same Due Date, 23 Hours a Day, Transportation
	3NSF	Order set 1, Different Due Dates, 9 Hours a Day
	4NSF	Case Study order set, Different Due Dates, 9 Hours a Day
	5NSF	Case Study order set, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility
	5aNSF	Case Study order set, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility – Split job set as shown in Table 7-4
	6NSF	Order set 3, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility (order set of Table 6-2)
	7NSF	Order set 3, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility (order set of Table 6-3)
	7aNSF	Order set 3, Different Due Dates, 9 Hours a Day, Operation/Resource *Flexibility- Split job set as shown in Table 7-4a*
	7bNSF	Order set 3, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility- Split job set as shown in Table 7-4b
	8NSF	Order set 1, Different Due Dates, 9 Hours a Day, Scheduling optimisation strategies
	9NSF	Case Study order set, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility, Scheduling Optimisation Strategies
	10aNSF	Case Study order set, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility – Operation times independent of resources used
	10bNSF	Case Study order set, Different Due Dates, 9 Hours a Day, Operation/Resource Flexibility – Resource-dependent operation times
	11NSF[7]	*Case Study order set, Different Due Dates, 9 Hours a Day, Dynamic Insertion of Orders*
	12NSF	*Case Study order set, Different Due Dates, 9 Hours a Day, Dynamic Deletion of Orders*
Special Features	1SF	Case Study order set, Different Due Dates, 9 Hours a Day, Secondary Resources
	2SF	Order set 1, Different Due Dates, 9 Hours a Day, Secondary Resources
	3SF	Order set 3, Different Due Dates, 9 Hours a Day, Secondary Resources
	4SF	Order set 1, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility
	5SF	Order set 3, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility
	5aSF	Order set 3, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility– Split job set as shown *in* Table 7-4a
	5bSF	Order set 3, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility– Split job set as shown in Table 7-4b
	6SF	Case Study Order Set, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility
	7SF	Case Study order set, Different Due Dates, 9 Hours a Day, Secondary Resources, Operation/Resource Flexibility, Machine Breakdowns, Planned Maintenance
	8SF	*Case Study order set, Different Due Dates, 9 Hours a Day, Secondary Resources, Machine Breakdowns, Planned Maintenance, exploration of Routing Flexibility*
Tool Considerations	1TSF	Order set A, Different Due Dates, 9 Hours a Day, Secondary Resources, Tool Selection Rules
	2TSF	Order set B, Different Due Dates, 9 Hours a Day, Secondary Resources, Tool Selection Rules

Table 7-1: Table 6-1 referred to Chapter 7

[7] Experiments in italics are only demonstrative in this research.

- Better schedules were obtained for routes with the smallest total production time because this ensured that the jobs finished earlier thus resulting in lower schedule duration.
- Resource schedule performances are only better when the operations are done on different resources. If most of the operations dictated by the route are done on the same resource, then while resource utilisation for some may be high, other resources may have nil utilisation % resulting in low resource average utilisation %. This is also true for resource working and idle %.

In an operation/resource flexibility environment, this may not be strictly true because an operation may be manually forced to be done on another resource hence balancing workload on the resources. This would ordinarily lead to better resource average utilisation and working % and to a lower resource average idle % than if the resources were allowed to pick their operations.

EFFECT OF OPERATION TIME DEPENDENT ON RESOURCE: Experiment 10bNSF (compared to 10aNSF)

SIGNIFICANT PERFORMANCE MEASURES:

- There was generally a decrease in % late orders, total lead time and total late time.
- There was very little difference in added value %, resource idle %, utilisation %, and working %.
- There was some improvement, however little, in schedule duration.

EFFECT OF SYSTEM DISTURBANCE: MACHINE BREAKDOWNS AND PLANNED MAINTENANCE: Experiment 7SF (compared to 6SF)

SIGNIFICANT PERFORMANCE MEASURES:

- There was a reduction in % late orders for most jobs and unpredictable total late times.
- There was a higher total lead time but the other results were similar to when there were no disturbances.

EFFECT OF TOOL SELECTION RULES: Experiments 1TSF and 2TSF

SIGNIFICANT PERFORMANCE MEASURES:

- Although the selected tool rule had no effect on schedule performance[8], it had on tool utilisation rates.
- Also, although this depended greatly on the tool requirements for the operations, it appeared that the tool life rule almost always required lesser tools and consequently, for that rule, the tool kits had a lesser number of partially worn out tools.

<u>EFFECT OF THE SCHEDULING APPROACHES THAT UTILISE SCHEDULING OPTIMISATION STRATEGIES</u>: Experiments 8NSF and 9NSF

<u>SIGNIFICANT PERFORMANCE MEASURES</u>:

- This produced an all-round better schedule performance. Tables 7-2 and 7-3 show that the scheduling approaches perform very well especially when backward sequencing is not involved.
- Compared with the best rules either in terms of % late orders or schedule duration, the scheduling approaches generally perform better (Tables 7-2 and 7-3).
- The FF1/2 approach seems to consistently be the best when % late orders is considered.
- When the best rule in schedule duration is considered, 2 or 3 of the scheduling approaches seem able to give better schedule duration for any given resource scenario and condition and the % late order value is almost always improved.
- While the schedule duration may improve when BF3/4 is considered, % late orders and total late and lead times are almost always worse. BF1/2 behaves almost as well as FF1/2 and FF3.
- Outstanding results were achieved by combining Approach 1 (also known as A1) with the other scheduling rules and the results are as presented in Tables A3-26 to A3-27. This is however understandable considering that using the approach re-defines the problem by balancing workload.

The raw results of applying the scheduling approaches can be seen in Tables A3-22 to A3-29 in Appendix 3.

[8] For different tool selection rules, the schedule performances were the same. As an example, the LPos results (with respect to schedule performance measures) were identical when the minimum tool life rule and the minimum tool flexibility rule were used.

Application of Scheduling Approaches that utilise Optimisation Strategies to Experiment 8NSF						
3-Resource Scenario						
Schedule Performance	Best Schedule Rule		Scheduling Approaches			
	% Late Orders	Schedule Duration	FF1/2	FF3	BF1/2	BF3/4
% Late Orders	33.33	83.33	33.33	33.33	33.33	66.67
Total Late Time	13D 7:15	10D 1:10	8D 6:04	9D 7:03	7D 3:45	11D 1:14
Total Lead Time	30D 7:45	32D 14:01	25D 6:34	31D 8:08	26D 19:28	37D 14:26
Average Added Value	50.88	50.91	48.88	45.5	36.4	42.39
Resource Avg. Working %	22.28	34.17	29.85	26.4	24.36	24.76
Resource Avg. Idle %	14.68	0.73	6.09	10.91	8.64	9.31
Resource Avg. Utils %	60.05	96.81	82.52	70.39	66.23	68.56
Schedule Duration	12D 6:54	8D 0:17	9D 4:07	10D 8:50	11D 5:41	11D 1:19
6-Resource Scenario						
Schedule Performance	Best Schedule Rule		Scheduling Approaches			
	% Late Orders	Schedule Duration	FF1/2	FF3	BF1/2	BF3/4
% Late Orders	50	66.67	16.67	16.67	33.33	50
Total Late Time	6D 18:57	14D 3:58	1D 14:16	1D 14:16	4D 20:14	5D 13:17
Total Lead Time	30D 7:36	32D 17:08	23D 18:22	22D 11:35	28D 18:30	30D 18:14
Average Added Value	54.12	48.83	69.03	63.03	46.47	51.87
Resource Avg. Working %	13.43	13.58	16.65	16.65	15.19	14.87
Resource Avg. Idle %	22.89	22.46	19.82	19.62	20.17	21.39
Resource Avg. Utils %	36.89	37.59	45.77	45.77	42.83	40.89
Schedule Duration	10D 4:32	10D 1:53	8D 5:16	8D 5:16	9D 0:11	9D 4:50
8-Resource Scenario						
Schedule Performance	Best Schedule Rule		Scheduling Approaches			
	% Late Orders	Schedule Duration	FF1/2	FF3	BF1/2	BF3/4
% Late Orders	44.44	66.67	44.44	22.22	22.22	33.33
Total Late Time	15D 9:07	7D 15:20	9D 23:09	7D 20:51	5D 1:53	10D 6:12
Total Lead Time	47D 17:25	40D 2:27	37D 10:24	34D 15:46	36D 18:56	40D 13:30
Average Added Value	48.77	54.8	53.02	55.6	45.64	44.89
Resource Avg. Working %	12.85	14.11	17.91	14.36	15.55	12.09
Resource Avg. Idle %	30.71	38.09	18.02	21.92	20.11	22.61
Resource Avg. Utils %	34.64	22.87	49.73	39.51	41.7	33.62
Schedule Duration	11D 7:06	10D 6:59	8D 2:34	10D 2:42	9D 8:03	12D 0:08

Table 7-2: Best performances compared with scheduling approaches in 8NSF

7.2.2 SCHEDULING RULES

Tables 7-4, 7-5 and 7-6 identify the best scheduling rules for each set of experiments across the 3 resource scenarios for each schedule performance measure. Table 7-7 presents the overall best scheduling rules for each experiment. This was evaluated by determining the scheduling rules that appeared most often when all the schedule performance measures were considered. A rule had to have been consistently good across the 3 resource scenarios for a schedule performance measure to have been rated one of the best for that schedule performance measure.

In Tables 7-8 to 7-14, the best scheduling rules across some sets of experiments and the 3 resource scenarios are presented. These were obtained from Tables 7-4 and 7-5. As an example, from experiments 5NSF to 10bNSF, there are 8 experiments from which scheduling rule performances can be evaluated. Of the 8 experiments, 7 experiments reported the LNoOfOps rule as one of the best in % late orders. Therefore, 87.5% of the experiments in this category (see Table 7-8) report this rule as one of the best.

Application of Scheduling Approaches that utilise Optimisation Strategies to Experiment 9NSF						
3-Resource Scenario						
Schedule Performance	Best Schedule Rule		Scheduling Approaches			
	% Late Orders	Schedule Duration	FF1/2	FF3	BF1/2	BF3/4
% Late Orders	50	100	50	16.67	50	50
Total Late Time	10D 20:00	20D 4:00	7D 16:01	6D 10:29	7D 16:33	8D 18:13
Total Lead Time	35D 9:27	47D 11:18	27D 17:28	24D 14:47	31D 17:59	33D 23:39
Average Added Value	55.58	45.57	58.99	42.43	47.81	46.45
Resource Avg. Working %	29.27	35.05	34.51	28.38	30.37	32
Resource Avg. Idle %	6.58	0.97	1.17	5.86	3.67	3.31
Resource Avg. Utils %	81.35	96.92	96.31	78.51	78.99	81.38
Schedule Duration	10D 1:20	9D 2:31	9D 1:24	11D 1:29	9D 8:01	9D 7:10
6-Resource Scenario						
Schedule Performance	Best Schedule Rule		Scheduling Approaches			
	% Late Orders	Schedule Duration	FF1/2	FF3	BF1/2	BF3/4
% Late Orders	16.67	16.67	0	0	0	16.67
Total Late Time	9H 6M	9H 6M	0	0	0	14H 10M
Total Lead Time	21D 17:32	21D 17:32	20D 23:34	20D 23:34	14D 12:38	16D 2:56
Average Added Value	70.9	70.9	74.74	74.74	42.36	49.61
Resource Avg. Working %	22.9	22.9	35.12	35.12	18.37	23.91
Resource Avg. Idle %	16.71	16.71	3.94	3.94	18.49	17.05
Resource Avg. Utils %	57.63	57.63	39.55	39.55	49.68	58.2
Schedule Duration	5D 6:06	5D 6:06	4D 4:22	4D 4:22	6D 7:33	5D 0:00
8-Resource Scenario						
Schedule Performance	Best Schedule Rule		Scheduling Approaches			
	% Late Orders	Schedule Duration	FF1/2	FF3	BF1/2	BF3/4
% Late Orders	16.67	16.67	0	0	0	0
Total Late Time	9H 6M	9H 6M	0	0	0	0
Total Lead Time	21D 22:10	21D 22:10	22D 0:08	22D 0:08	16D 0:50	16D 0:50
Average Added Value	71.62	71.62	61.74	61.74	42.23	42.23
Resource Avg. Working %	17.12	17.12	21.04	21.04	12.75	12.75
Resource Avg. Idle %	22.52	22.52	16.56	16.56	22.54	22.54
Resource Avg. Utils %	43.08	43.08	53.55	53.55	36.04	36.04
Schedule Duration	5D 6:06	5D 6:06	5D 2:22	5D 2:22	6D 2:16	6D 2:16

Table 7-3: Best performances compared with scheduling approaches in 9NSF

Based on these tables, the scheduling rules are analysed individually as follows.

<u>EDD</u>

Over 60% of the experiments in the SF category reported EDD as one of the best rules in resource performance measures and in schedule duration. In the operation/resource flexibility (SF category) experiments, 83.3% and 66.6% of the experiments showed that EDD was one of the best in total late and lead times respectively. It was one of the best scheduling rules in experiments 7NSF, 7bNSF, 2SF, 4SF, 5SF, 5aSF and 6SF.

<u>FCFS</u>

Approximately 50% of the operation/resource flexibility experiments showed that FCFS was amongst the best in % late orders, total lead time, total late time and average added value %. 80% of the experiments in the SF category showed that the rule was good in resource performance measures and in schedule duration. It was one of the best scheduling rules in experiments 7NSF, 1SF - 5aSF, 6SF and 7SF.

LRem

It was consistently good in % late orders, total late time, total lead time and added value % regardless of the category of experiments. It was one of the best overall scheduling rules in experiments7NSF, 7aNSF, 10aNSF, 3SF-6SF and 2TSF.

HRem

50% of the experiments in the operation/resource flexibility experiments and also in both SF and NSF categories of experiments show that HRem was consistently good in resource performance measures and in schedule duration. It was one of the overall best in experiments 1NSF, 5aNSF, 7aNSF, 10aNSF and 5aSF.

Category	Experiment	Schedule Performance	Schedule Rules
No Special Features	1NSF	Total Lead Time	EDD/FCFS, LRem, LNoOfOps, Cost
		Average Added Value	EDD/FCFS, LPT, LRem, LNoOfOps, Cost
		Resource Avg. Working %	CR, HST, HRem, Cost
		Resource Avg. Idle %	CR, HST, HRem, Cost
		Resource Avg. Utils %	CR, HST, HRem, Cost
		Schedule Duration	CR, HRem, Cost
	2NSF	Total Late Time	HPos, LNoOfOps, HNoOfOps, Cost
		Total Lead Time	HPos, LRem, LNoOfOps, Cost
		Average Added Value	CR, HST, HRem, Cost
		Resource Avg. Working %	CR, HST, HRem, Cost
		Resource Avg. Idle %	CR, HST, HRem, Cost
		Resource Avg. Utils %	CR, HRem, Cost
		Schedule Duration	CR, HRem, Cost
	3NSF	% Late Orders	HPos, LRem, LNoOfOps
		Total Late Time	CR
		Total Lead Time	FCFS, LNoOfOps
		Average Added Value	CR, LPT, HPos, Cost
		Resource Avg. Working %	HST, LPos, HRem, Cost
		Resource Avg. Idle %	HST, LPos, HRem, Cost
		Resource Avg. Utils %	HST, LPos, HRem, Cost, HNoOfOps
		Schedule Duration	HST, LPos, HRem, Cost
	4NSF	% Late Orders	HPos, LRem, LNoOfOps, HST, LPT
		Total Late Time	CR, LRem, LNoOfOps,
		Total Lead Time	LST, HPos, LRem, LNoOfOps
		Average Added Value	HPos, LRem, LNoOfOps
		Resource Avg. Working %	CR, LPos, HRem, SPT, HST
		Resource Avg. Idle %	CR, HST, SPT, LPos, HRem
		Resource Avg. Utils %	HST, SPT, LPos, HPos, HRem
		Schedule Duration	LPos, HRem, CR, SPT, HST
	5NSF	% Late Orders	SPT, LST, FCFS, HPos, LNoOfOps, Cost, LOpRes
		Total Late Time	EDD, SPT
		Total Lead Time	SPT, LOpRes, LNoOfOps, LRem
		Average Added Value	LST, SPT, LRem, LNoOfOps
		Resource Avg. Working %	None
		Resource Avg. Idle %	LST, LPos
		Resource Avg. Utils %	LST, Cost
		Schedule Duration	SPT, LPos
	5aNSF	% Late Orders	EDD, FCFS, LOpRes
		Total Late Time	Cost, CR, EDD, FCFS, LOpRes
		Total Lead Time	HPos, LRem, LNoOfOps, FCFS, LOpRes
		Average Added Value	HPos, LRem, HNoOfOps, FCFS, LOpRes
		Resource Avg. Working %	LPos, HRem, HNoOfOps, Cost, CR, LOpRes
		Resource Avg. Idle %	LPos, HRem, HNoOfOps, Cost, CR, LOpRes
		Resource Avg. Utils %	LPos, HRem, HNoOfOps, Cost, CR, LOpRes
		Schedule Duration	LPos, Cost, CR, FCFS, LOpRes
	6NSF	% Late Orders	EDD, FCFS, LST, SPT, LRem, LNoOfOps
		Total Late Time	EDD, FCFS, CR, LRem, LOpRes
		Total Lead Time	EDD, FCFS, SPT, LRem, LNoOfOps
		Average Added Value	SPT, LRem, LOpRes
		Resource Avg. Working %	LST, Cost
		Resource Avg. Idle %	Cost
		Resource Avg. Utils %	LST, Cost
		Schedule Duration	HRem

Table 7-4: The best rules for each performance measure (NSF category)

Category	Experiment	Schedule Performance	Schedule Rules
	7NSF	% Late Orders	HPos, LRem, LNoOfOps, EDD
		Total Late Time	HPos, LRem, LOpRes, EDD
		Total Lead Time	LRem, LNoOfOps, EDD
		Average Added Value	LRem, LNoOfOps, EDD
		Resource Avg. Working %	LOpRes, FCFS
		Resource Avg. Idle %	LPos, Cost
		Resource Avg. Utils %	LOpRes, FCFS
		Schedule Duration	LOpRes, FCFS
	7aNSF	% Late Orders	LRem, LNoOfOps, HNoOfOps, EDD
		Total Late Time	LRem, LNoOfOps, LOpRes, Cost, EDD
		Total Lead Time	HPos, LRem, LNoOfOps, EDD
		Average Added Value	HPos, LRem, LNoOfOps
		Resource Avg. Working %	LPos, HRem, Cost, LOpRes
		Resource Avg. Idle %	LPos, HRem, Cost
		Resource Avg. Utils %	LPos, HRem, Cost, LOpRes
		Schedule Duration	LPos, HRem, Cost, LOpRes
	7bNSF	% Late Orders	HPos, LRem, LNoOfOps, EDD
		Total Late Time	HPos, LRem, LNoOfOps, EDD, Cost, LOpRes
		Total Lead Time	HPos, LRem, LNoOfOps, EDD
		Average Added Value	HPos, LRem, LNoOfOps, EDD
		Resource Avg. Working %	Cost, LOpRes
		Resource Avg. Idle %	LNoOfOps, Cost, LOpRes
		Resource Avg. Utils %	HRem, HNoOfOps, Cost, LopRes
		Schedule Duration	LPos, HRem, HNoOfOps, Cost, LOpRes
	10aNSF	% Late Orders	HPos, LRem, LNoOfOps
		Total Late Time	No Pattern
		Total Lead Time	HPos, FCFS
		Average Added Value	Cost, FCFS
		Resource Avg. Working %	LPos, LRem, HRem, Cost
		Resource Avg. Idle %	LPos, LRem, HRem, Cost
		Resource Avg. Utils %	LPos, LRem, HRem, Cost
		Schedule Duration	LPos, LRem, HRem, Cost
	10bNSF	% Late Orders	LNoOfOps, Cost, LOpRes, HNoOfOps, FCFS, HPos
		Total Late Time	Cost, LOpRes, EDD
		Total Lead Time	LOpRes
		Average Added Value	HPos, LOpRes, LRem, Cost
		Resource Avg. Working %	LPos, HRem, Cost
		Resource Avg. Idle %	LPos, LOpRes, HRem, Cost
		Resource Avg. Utils %	LPos, HRem, Cost
		Schedule Duration	LPos, LOpRes, HRem, Cost, EDD

Table 7-4 (Contd.): The best rules for each performance measure (NSF category)

Experiment	Schedule Performance	Schedule Rules
1SF	% Late Orders	LST, LPT, FCFS, HPos, LRem, LNoOfOps, Cost
	Average Added Value	LST, FCFS, HPos, LRem
	Resource Avg. Working %	HST, LPos, FCFS
	Resource Avg. Idle %	FCFS
	Resource Avg. Utils %	HST, LPos, FCFS
	Schedule Duration	HST, FCFS
2SF	% Late Orders	HPos, LRem, LNoOfOps, Cost
	Total Late Time	HPos, LNoOfOps, Cost, EDD, HST
	Total Lead Time	HPos, LRem, LNoOfOps, FCFS, SPT
	Average Added Value	HPos, LRem, LST, HST, Cost
	Resource Avg. Working %	LNoOfOps, EDD, FCFS
	Resource Avg. Idle %	HNoOfOps, EDD, FCFS, HST
	Resource Avg. Utils %	LNoOfOps, EDD, FCFS
	Schedule Duration	LNoOfOps, EDD, FCFS
3SF	% Late Orders	HPos, LNoOfOps, LRem
	Total Late Time	HPos, LNoOfOps, LRem, CR
	Total Lead Time	HPos, LRem
	Average Added Value	HPos, LNoOfOps, LRem, CR
	Resource Avg. Working %	HRem, EDD, FCFS
	Resource Avg. Idle %	HRem, EDD, FCFS, CR, LST
	Resource Avg. Utils %	HRem, EDD, FCFS
	Schedule Duration	HRem, EDD, FCFS, HST+D43
4SF	% Late Orders	HPos, LNoOfOps, FCFS, LRem
	Total Late Time	HPos, LNoOfOps, FCFS, LRem, EDD
	Total Lead Time	HPos, FCFS, LRem, EDD
	Average Added Value	HPos, LNoOfOps, FCFS, LRem, EDD
	Resource Avg. Working %	EDD, FCFS
	Resource Avg. Idle %	EDD, FCFS
	Resource Avg. Utils %	LPos, EDD, FCFS
	Schedule Duration	LPos, EDD, FCFS
5SF	% Late Orders	LRem, LNoOfOps
	Total Late Time	LNoOfOps, EDD, FCFS
	Total Lead Time	LRem, EDD, FCFS
	Average Added Value	LRem, Cost, EDD, FCFS
	Resource Avg. Working %	LPos, EDD, FCFS
	Resource Avg. Idle %	EDD, FCFS
	Resource Avg. Utils %	LPos, EDD, FCFS
	Schedule Duration	LPos, EDD, FCFS
5aSF	% Late Orders	HPos, LRem, LNoOfOps, Cost
	Total Late Time	Cost, LRem, LNoOfOps, EDD
	Total Lead Time	LRem, LNoOfOps, EDD
	Average Added Value	Cost, LRem
	Resource Avg. Working %	HRem, EDD, FCFS
	Resource Avg. Idle %	HRem, EDD, FCFS, LPos
	Resource Avg. Utils %	HRem, EDD, FCFS
	Schedule Duration	HRem, EDD, FCFS, LPos
5bSF	% Late Orders	HPos, LRem, LNoOfOps, EDD
	Total Late Time	LOpRes, LRem, LNoOfOps, EDD
	Total Lead Time	EDD
	Average Added Value	HPos, Cost, LNoOfOps
	Resource Avg. Working %	LPos, HRem
	Resource Avg. Idle %	HNoOfOps, LOpRes
	Resource Avg. Utils %	HNoOfOps
	Schedule Duration	HNoOfOps, Cost

Table 7-5: The best rules for each performance measure (SF category)

Category	Experiment	Schedule Performance	Schedule Rules
	6SF	% Late Orders	HPos, LRem, HOpRes, FCFS
		Total Late Time	HPos, LRem, HOpRes, FCFS
		Total Lead Time	HPos, LRem, HOpRes, FCFS
		Average Added Value	LRem, EDD, FCFS
		Resource Avg. Working %	EDD, FCFS
		Resource Avg. Idle %	EDD, FCFS
		Resource Avg. Utils %	EDD, FCFS
		Schedule Duration	EDD, FCFS
	7SF	% Late Orders	HPos, LNoOfOps, FCFS, LST, SPT, LOpRes
		Total Late Time	EDD, FCFS, SPT
		Total Lead Time	FCFS, SPT
		Average Added Value	FCFS, SPT
		Resource Avg. Working %	FCFS, LPos, HRem
		Resource Avg. Idle %	FCFS, HRem
		Resource Avg. Utils %	FCFS, LPos, HRem
		Schedule Duration	FCFS, SPT

Table 7-5 (Contd.): The best rules for each performance measure (SF category)

Category	Experiment	Schedule Performance	Schedule Rules
Tool Consideration	1TSF	% Late Orders	HPos, LRem, MaxToolIndex, HOpFlex, Cost
		Total Late Time	HPos, LRem, MaxToolIndex
		Total Lead Time	HPos, MaxToolIndex
		Average Added Value	HPos, LRem, MaxToolIndex, LOpFlex, LPT
		Resource Avg. Working %	LOpFlex
		Resource Avg. Idle %	HPos, LOpFlex, HOpFlex, Cost, MaxToolIndex
		Resource Avg. Utils %	LOpFlex, LPT
		Schedule Duration	LOpFlex, LPT
	2TSF	% Late Orders	HPos, MaxToolIndex, MinToolIndex, HOpFlex, Cost, LPT
		Total Late Time	HOpFlex, SPT, MaxToolIndex, LRem
		Total Lead Time	LRem, HOpFlex, Cost
		Average Added Value	HOpFlex, SPT, MaxToolIndex, LRem
		Resource Avg. Working %	SPT, MaxToolIndex, Cost
		Resource Avg. Idle %	HRem, SPT, Cost
		Resource Avg. Utils %	SPT, Cost
		Schedule Duration	SPT, MaxToolIndex, Cost

Table 7-6: The best rules for each schedule performance measure (TSF Category)

		Scheduling Rules		
Category	Experiments	Rank1	Rank2	Rank3
No Special Features	1NSF	Cost	HRem, CR, HST	
	2NSF	CR		
	3NSF	HST, Cost		
	4NSF	CR		
	5NSF	LPos		
	5aNSF	LOpRes, HNoOfOps	Cost	CR, HRem, LPos
	6NSF	LNoOfOps	Cost	
	7NSF	LOpRes, EDD	FCFS, HPos	LRem
	7aNSF	Cost, LOpRes	HRem, LRem, LPos	LNoOfOps
	7bNSF	LNoOfOps, HNoOfOps, Cost, LOpRes	EDD	
	10aNSF	LPos	LRem, HRem	Cost, LOpRes
	10bNSF	LOpRes, Cost		
Special Features	1SF	FCFS		
	2SF	FCFS, EDD	LNoOfOps, Cost	HST
	3SF	HPos	LRem, FCFS	
	4SF	EDD, FCFS	LNoOfOps, HPos	LRem
	5SF	EDD, FCFS	LPos, LRem	
	5aSF	EDD	FCFS	HRem, LRem
	5bSF	HNoOfOps, LOpRes	Cost, LRem	
	6SF	FCFS	EDD, HPos	LRem
	7SF	FCFS	Cost	SPT
Tool Consideration	1TSF	LOpFlex	HPos, MaxToolIndex	
	2TSF	SPT, Cost	MaxToolIndex	HOpFlex, LRem

Table 7-7: The overall best rules for all experiments

Schedule Performance Measures	Scheduling Rules (% Ep[9])
% Late Orders	FCFS(50%), HPos (62.5%), LNoOfOps (87.5%), EDD (62.5%), LRem (62.5%)
Total Late Time	EDD (87.5%), Cost (50%), LOpRes (75%), LRem (50%)
Total Lead Time	HPos (50%), LNoOfOps (75%), EDD (50%), LRem (75%)
Average Added Value	HPos (50%), LNoOfOps (50%), LRem (87.5%)
Resource Average Working %	Cost (75%), LOpRes (50%), HRem (50%), LPos (50%)
Resource Average Idle %	Cost (87.5%), HRem (50%), LPos (75%)
Resource Average Utilisation %	Cost (87.5%), LOpRes (50%), HRem (62.5%), LPos (50%)
Schedule Duration	Cost (62.5%), LOpRes (62.5%), HRem (62.5%), LPos (75%)

Table 7-8: Comparing Experiments 5NSF to 10bNSF: Operation/Resource (NSF)

Schedule Performance Measures	Scheduling Rules (% Ep)
% Late Orders	HPos (83.3%), LNoOfOps (83.3%), LRem (83.3%)
Total Late Time	FCFS(66.6%), EDD (83.3%), LNoOfOps (66.6%), LRem (66.6%)
Total Lead Time	FCFS (83.3%), EDD (66.6%), LRem (66.6%)
Average Added Value	FCFS (66.6%), LRem (66.6%)
Resource Average Working %	FCFS(83.3%), EDD (66.6%), LPos (50%), HRem (50%)
Resource Average Idle %	FCFS(83.3%), EDD (66.6%)
Resource Average Utilisation %	FCFS(83.3%), EDD (66.6%), LPos (50%)
Schedule Duration	FCFS(83.3%), EDD (66.6%), LPos (50%)

Table 7-9: Comparing Experiments 4SF to 7SF: Operation/Resource (SF)

Schedule Performance Measures	Scheduling Rules (% Ep)
% Late Orders	FCFS(50%), HPos (71.4%), LNoOfOps (85.7%), LRem (71.4%)
Total Late Time	FCFS(57.1%), EDD (85.7%), LOpRes (50%), LRem (57.1%)
Total Lead Time	FCFS (57.1%), EDD (64.3%), LRem (57.1%)
Average Added Value	FCFS (50%), LRem (78.6%), HPos (50%)
Resource Average Working %	LPos (50%), HRem (50%),
Resource Average Idle %	LPos (57.1%), HRem (50%)
Resource Average Utilisation %	LPos (50%), HRem (50%)
Schedule Duration	LPos (64.3%)

Table 7-10: Comparing Operation/Resource experiments in the SF and NSF category

[9] % of experiments for which scheduling rule is one of the best

Schedule Performance Measures	Scheduling Rules (% Ep)
% Late Orders	HPos (88.9%), LNoOfOps (88.9%), LRem (88.9%)
Total Late Time	LNoOfOps (75%), LRem (62.5%), EDD (75%)
Total Lead Time	FCFS (62.5%), LRem (75%)
Average Added Value	FCFS (55.6%), LRem (77.8%)
Resource Average Working %	FCFS(88.9%), EDD (66.6%)
Resource Average Idle %	FCFS(88.9%), EDD (66.6%)
Resource Average Utilisation %	FCFS(88.9%), EDD (66.6%)
Schedule Duration	FCFS(88.9%), EDD (77.8%)

Table 7-11: Comparing Experiments 1SF to 7SF: All SF Experiments

% Late Orders	HPos (70%), LNoOfOps (90%), EDD (50%), LRem (70%)
Total Late Time	LOpRes (75%), LRem (45.5%)
Total Lead Time	HPos (50%), LNoOfOps (83.3%), LRem (75%)
Average Added Value	HPos (50%), LNoOfOps (50%), LRem (75%)
Resource Average Working %	Cost (75%), LOpRes (50%), HRem (66.6%), LPos (50%)
Resource Average Idle %	Cost (83.3%), HRem (66.6%), LPos (66.6%)
Resource Average Utilisation %	Cost (83.3%), LOpRes (50%), HRem (75%), LPos (50%)
Schedule Duration	Cost (66.6%), LOpRes (62.5%), HRem (75%), LPos (66.6%)

Table 7-12: Comparing Experiments 1NSF to 10NSF (minus 8 and 9NSF): NSF Experiments

% Late Orders	MaxToolIndex (100%), HOpFlex (100%), Cost (100%), HPos (100%)
Total Late Time	LRem (100%), MaxToolIndex (100%)
Total Lead Time	No Pattern
Average Added Value	LRem (100%), MaxToolIndex (100%)
Resource Average Working %	No Pattern
Resource Average Idle %	Cost (100%)
Resource Average Utilisation %	No Pattern
Schedule Duration	No Pattern

Table 7-13: Comparing experiments in the TSF category

% Late Orders	HPos (78.95%), LNoOfOps (89.47%), LRem (78.95%)
Total Late Time	LRem (52.63%)
Total Lead Time	LNoOfOps (55%), LRem (75%)
Average Added Value	LRem (76.19%), HPos (52.38%)
Resource Average Working %	HRem (57.14%), LPos (47.62%)
Resource Average Idle %	HRem (52.38%)
Resource Average Utilisation %	HRem (57.14%), LPos (47.62%)
Schedule Duration	HRem (52.38%), LPos (52.38%)

Table 7-14: Comparing all experiments in the SF and NSF category

LST, HST, SPT, LST

About 57% of the experiments in the NSF category (that considered HST) showed that HST was one of the best in the resource performance measures. It was also one of the overall best scheduling rules in experiments 1NSF, 3NSF and 2SF. SPT was one of the best overall scheduling rules in experiment 7SF and 2TSF.

Cost

About 80% of the experiments in the NSF category show that cost was good in resource performance measures and schedule duration. The same result was recorded in 2TSF. It was consistently one of the best in each of the schedule performance measures in experiments 1NSF and 2NSF. It was one of the overall best in 3NSF, 5aNSF, 6NSF, 7aNSF, 10aNSF, 10bNSF, 2SF, 5bSF, 7SF and 2TSF.

CR

It was one of the overall best scheduling rules in experiments 1NSF, 2NSF, 4NSF, and 5aNSF. It was not particularly noticeable in any schedule performance measures.

LNoOfOps

This was outstanding by proving to be consistently one of the best in %late orders, regardless of category of experiments. 75% of the SF experiments showed LNoOfOps to be one of the best in total late time and 83.3% of the NSF experiments show it to be one of the best in total lead time. 55% of all experiments in both the NSF and SF category show the rule to be one of the best in total lead time. It was noticeably the overall best in experiment 6NSF and 7bNSF and one of the overall best scheduling rules in 7aNSF, 2SF and 4SF.

HNoOfOps

It was good in resource performance measures and schedule duration for experiments 5aNSF and 5bNSF. It was noticeably one of the overall best in experiments 5aNSF, 7bNSF and 5bSF.

HOpRes

It had no outstanding performance until experiment 6SF where it was good in % late orders, total late time and total lead time.

LOpRes

50% of operation/resource flexibility experiments (SF + NSF) and 75% of operation/resource flexibility experiments in the NSF category showed that LOpRes was one of the best in total late time. Also, about 50% of the NSF experiments showed that LOpRes was one of the best in resource performance measures and schedule duration. It was hardly noticeable in the SF experiments. And until the jobs of experiment 5NSF were broken into smaller batches of experiment 5aNSF, its performance was below expectation. After the job splits, it was clearly the overall best. It was one of the best rules in experiments 5aNSF, 7NSF, 7aNSF, 7bNSF, 10aNSF, 10bNSF and 5bSF which shows that it is favoured in job splits especially where secondary resources are not considered.

LPos

Over 50% of the experiments in the operation/resource flexibility experiments (SF + NSF) showed that LPos was consistently good in resource performance measures and in schedule duration. This was also the case with the NSF experiments. It was the overall best in experiments 5NSF, 5aNSF, 7aNSF, 10aNSF, 5SF.

HPos

Over 70% of all category of experiments showed HPos to be consistently good in %late orders. 50% of the NSF experiments showed that it was one of the best in total lead time and average added value %. Also, 50% of the experiments in the operation/resource flexibility experiments (SF + NSF) showed that it was one of the best in average added value %. It was one of the overall best scheduling rules in 7NSF, 3SF, 4SF, 6SF and 1TSF.

MinToolIndex

It had no outstanding performance.

MaxToolIndex

It was consistently good in %late orders, total late time and added value % for the tool consideration experiments. It was one of the overall best scheduling rules in 1TSF and 2TSF.

LOpFlex

In tool consideration experiments, it was consistently good in %late orders and one of the overall best scheduling rules in 1TSF.

HOpFlex

In tool consideration experiments, it was one of the overall best scheduling rules in 2TSF.

A point to note is that for some of the experiments, when both secondary resources and the restrictive shift patterns were considered, some of the rules led to incomplete allocation of some jobs. This is because the Preactor package used was in Training/Evaluation Mode and as such could not schedule beyond 3 weeks. However, it was necessary to have a variety of product orders to establish true schedule rule performances. To make a fair judgement of these rules, new % late order values were evaluated for all rules with uncompleted operations, all of which were destined to be late. Also, because some other rules allowed complete allocation, it was necessary to re-evaluate the schedule duration. This was possible by considering the 9-hour shift (8am to 6pm, 1-hour break) and by assuming that since the most number of jobs uncompleted was 2, secondary constraints could not have been restrictive. The shift pattern for the primary resources on Sunday was 50% but since some of the jobs could not be completed after a certain period, one can assume that after that certain period, this value became 100% for easy evaluation. An example of the evaluation of schedule duration can be found in Appendix 5.

7.3 SOLUTION REASONING

In this section, some approaches are presented, approaches that give better schedule performance most especially with regards to minimising late orders and improving resource utilisation. The performance of these approaches have been compared with those of the custom-made scheduling rules described in Chapter 5 which have been analysed in detail in section 7.2. This section gives an overview of how the scheduling approaches work and the rationale behind applying them to the proposed scheduling problem.

7.3.1 INTRODUCTION TO THE APPROACHES

When more than one job needs to be scheduled, there are almost always times when some of the resources are idle. This is caused by a number of reasons, some of which are outlined as follows:

It is possible that the spare times between operations are too small for whole operations especially if the operations are "batched" together. As an example, suppose op20 of a certain job needs to be done on M3 on which there is available time of 44 minutes. If op20 requires 45 minutes then the operation will be unloadable.

It is possible that some of the free resource spaces are not those required.

It is possible that operation precedent constraints may limit the loading of operations. As an example, in Fig 7-3 below, the available resource spaces are on M1, M2 and M3 as shown and job 200 awaiting processing has requirements as shown in Table 7-15.

Operation	Resource Requirement
Op10	M2
Op20	M3
Op30	M1
Op40	M1
Op50	M1
Op60	M1

Table 7-15: Resource requirements for unscheduled job

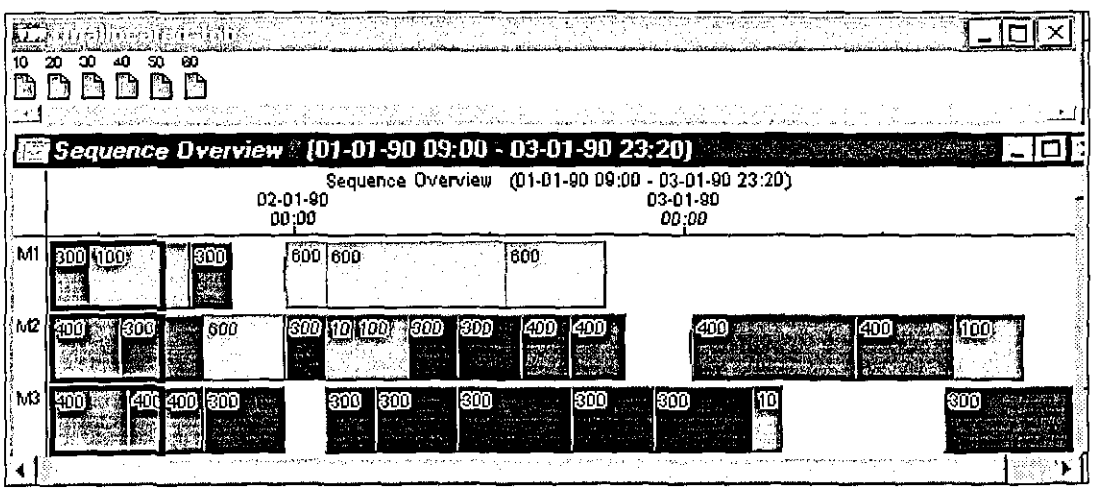

Figure 7-3: Illustration of schedule spaces

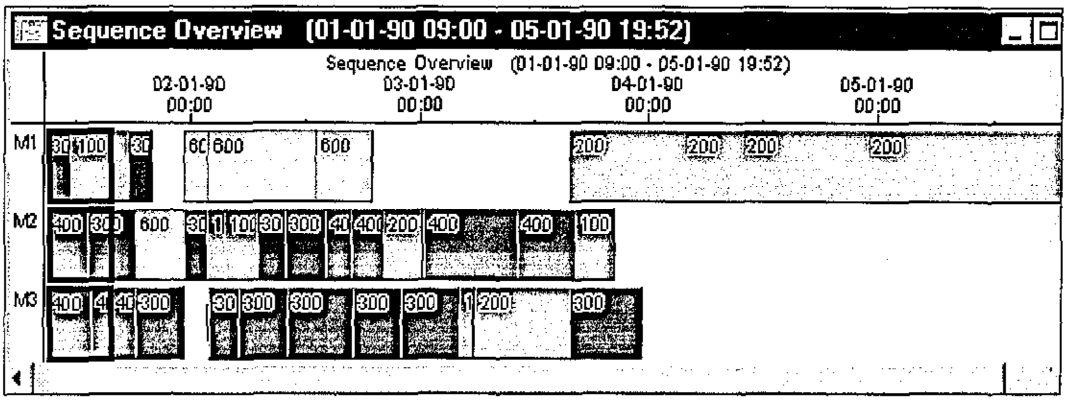

Figure 7-4: Illustration of scheduling not using up the space

Fig 7-4 shows that by forward sequencing, using the "highest-cost-first" criterion, two of the spaces were not used. This is because of an operational constraint that required that the first resource used be M2. When the available space on M2 is used, the spaces on M1 and M3 are not taken advantage of. When as in Fig 7-5, the first operation was made to use M1 (the first available resource space), contrary to expectation, the job was started later apparently because the operation required more time than was available on M1 at that spare time.

One of the best ways to get round this problem is by batch splitting (Figure 7-6). Also, the number of resources that can perform certain operations can be increased (Figure 7-7).

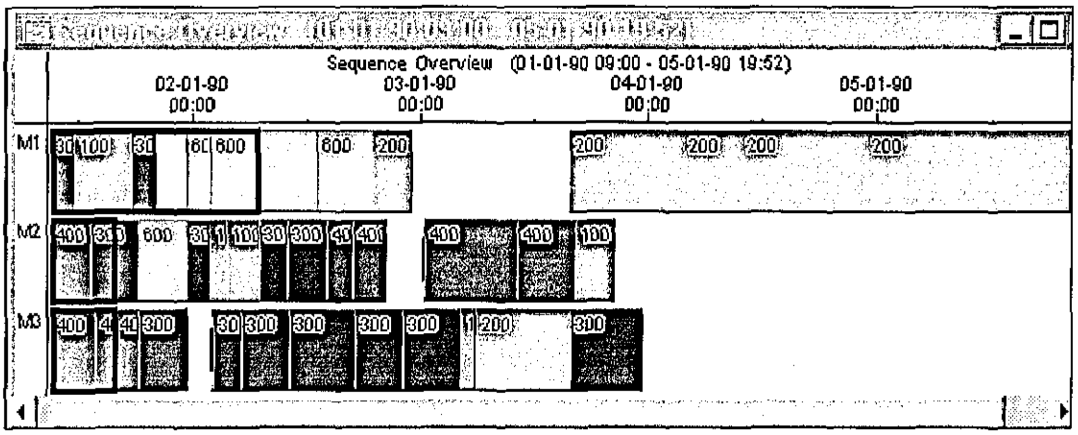

Figure 7-5: Illustration of an attempt at using up the space

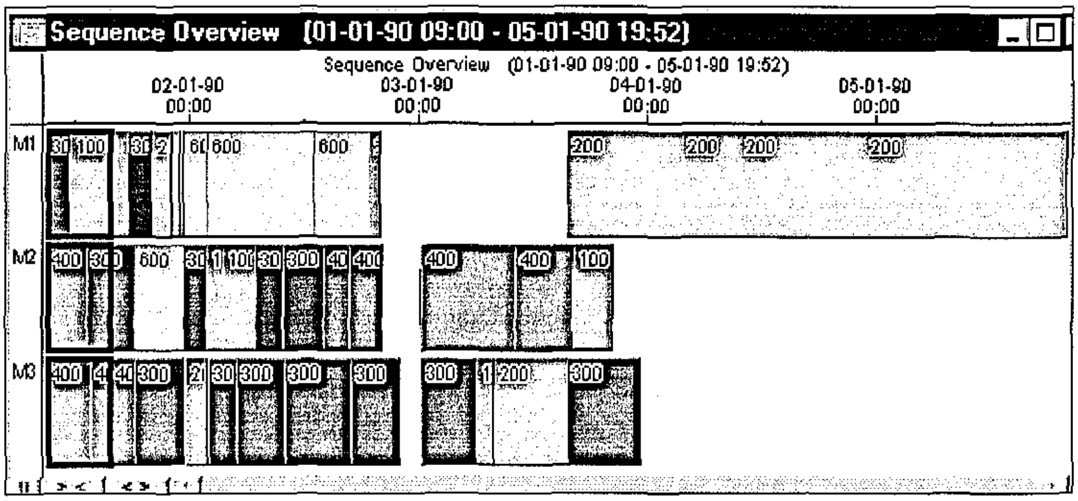

Figure 7-6: Illustration of using up the space

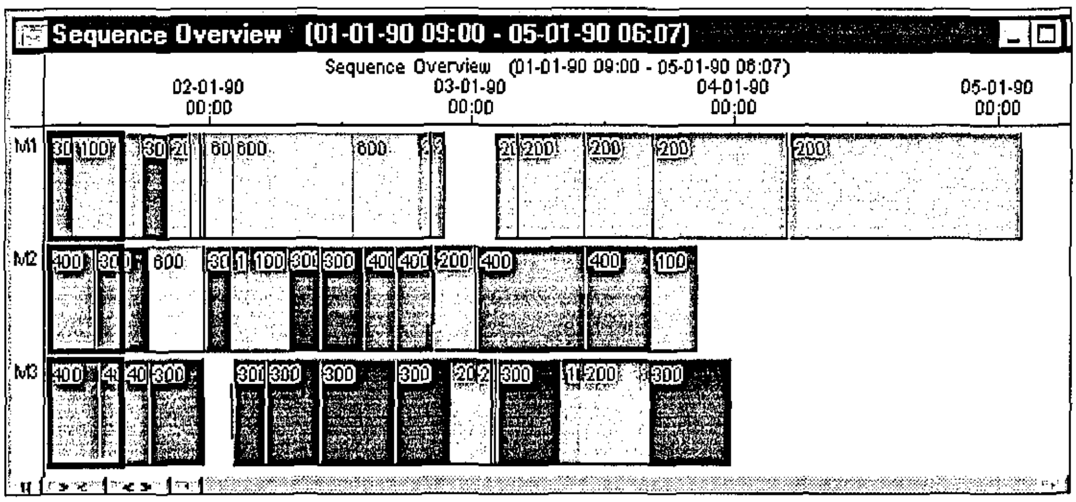

Figure 7-7: Illustration of effectively using up the space

In this research, the main scheduling optimisation strategies that have been employed are batch splitting, increasing operation flexibility, concurrent operations and backward sequencing. Table 7-16 shows some of the effects of these scheduling optimisation strategies on schedule performance.

7.3.2 PRESENTED SOLUTIONS

For different scheduling conditions, different scheduling rules performed differently such that a rule that was the best in a particular situation was not necessarily good in another. However, it was discovered that regardless of the best rule for each set of experiments, the existing schedule performance could be improved by relaxing some of the constraints of the jobs. This is by applying some of the schedule optimisation strategies with the custom-made rule [10] that performed the best in that situation.

[10] Listed in Chapter 5

Eight approaches have been presented, all of which can be applied to both static and dynamic scheduling problems. In a static case, the approaches are used just as stated. However, in a case where there is already an existing job set and an existing schedule (the best for the situation), for the new jobs that have just arrived, all started jobs are locked and all other jobs (including the new jobs) are unallocated.

Scheduling Optimisation Strategies	Effects
Batch Splitting	This tends to break up the jobs into manageable batch sizes that allow the operations to be more easily loadable on the planning board with the net effect of shortening schedule duration and lead time.
Increasing Operation Flexibility	This allows the operations to be possible on more than one resource such that if a resource is busy, another can be used. However, this must be effectively done so that it does not lead to just shifting the load on one resource to another. This should have an overall effect of increasing resource utilisation and could lead to the shortening of schedule duration and lead time.
Allowing Concurrent Operations	This is particularly useful after operation flexibility has been increased. This is because operation precedent constraints cannot allow certain operations to be done concurrently and as such, more often than not, it is similar operations that are done concurrently in this work. After batch splitting, if operational flexibility has been increased, it is possible to process the splits simultaneously on different resources thereby cutting down on schedule duration and lead time.
Backward Sequencing	This involves attempting to meet due dates by pushing work back from the due date to the starting operation. If it is possible to backward sequence (that is, if it is still possible to do all the operations by the due date), then the net effect would be to increase the percentage of early jobs.

Table 7-16: The effect of some Scheduling Optimisation Strategies

For a scheduling situation, the overall best scheduling rule is determined by comparing the schedule performance for each of the scheduling rules used. Most of the approaches start off by applying the best scheduling rule for the given situation. All early jobs are locked on the planning board and the rest are unallocated and re-scheduled using one of some scheduling rules depending on the approach in question.

In all (except Approach 1) of the approaches, it is required to re-schedule job-by-job but because of the way Preactor works, all the jobs are scheduled and the first job that needs to be re-scheduled is left on the planning board while all the others are unallocated. Then by using any of the scheduling optimisation strategies, an effort is made to slot all of the job's operations in existing resource spaces to ensure that resource utilisation and the degree of lateness are improved.

While these approaches have the advantage of combining the advantages of the best scheduling rule in that situation with those of the applied scheduling optimisation strategies, there is the need for resources to be flexible. Also, by choosing any one of the rules in the approaches, other considerations such as cost or job priority may be lost. Below are details of the approaches that have been used and the result of using them are as shown in Chapter 8.

I. APPROACH 1

This is unlike the other approaches. It looks at the possibility that jobs are late because of the uneven allocation of jobs to resources and as such focuses primarily on balancing workload. If after balancing workload, schedule performance is still not satisfactory, then any of the following approaches can be used.

Fig. 7-8 shows the result of allocating operations to resources using the "lowest-position-of-operations first" rule for the order set 1. From the figure, it is evident that resource M4 is relatively over-utilised but if the last few operations on this resource can be distributed between resources M6 and M7, schedule duration may be remarkably reduced and workload may be more evenly balanced (Figure 7-9).

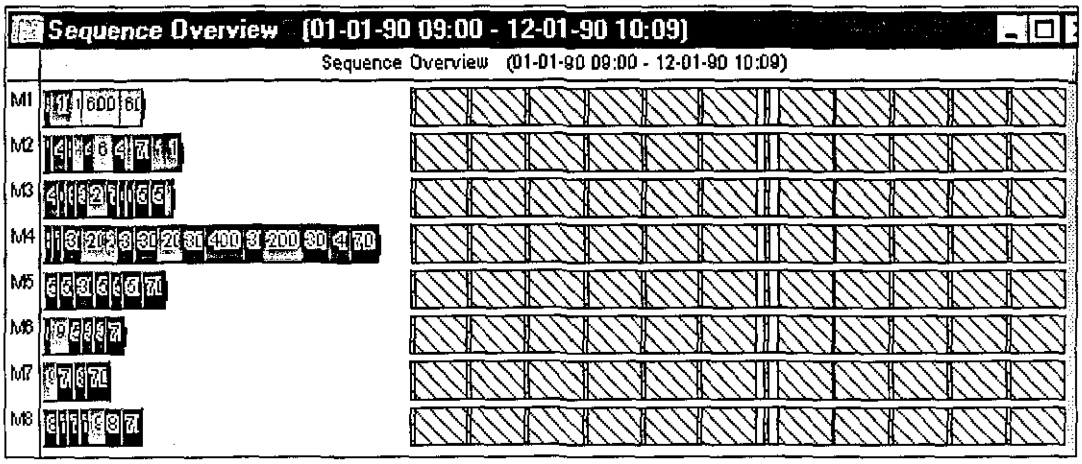

Figure 7-8: Illustration of uneven workload[11]

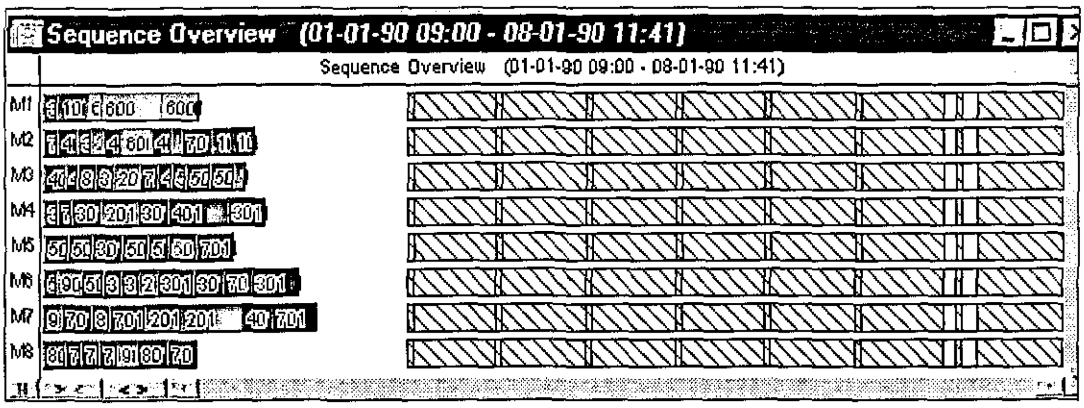

Figure 7-9: Illustration of evened-out workload

II. THE FF1 APPROACH

CRITERION FOR SELECTING NEXT JOB TO LOAD: The highest-number-of-operations-first rule

RATIONALE: By considering first the job with the highest number of operations, schedule duration should be reduced. This is because if at the end of all manual loading it is discovered that it is not possible for some of the jobs to be early, these jobs have lower numbers of operations compared with those that have been loaded. Chances are that the total remaining duration of work (which would be late) would also be lower.

ANTICIPATED EFFECT: Improvement in resource utilisation[12], lead time and schedule duration

III. THE FF2 APPROACH

[11] The hatched blocks are a function of Preactor in evaluating utilization percents

[12] brought about by the application of scheduling optimisation strategies

CRITERION FOR SELECTING NEXT JOB TO LOAD: The highest-duration-of-operations-jobs-first rule

RATIONALE: Same as FF1 but here, emphasis is on total work to be done rather than number of operations.

ANTICIPATED EFFECT: Same as FF1

IV. THE FF3 APPROACH

CRITERION FOR SELECTING NEXT JOB TO LOAD: The fewest-number-of-unallocated-operations-first rule

RATIONALE: Jobs that have the tendency to be early need not be late!

ANTICIPATED EFFECT: Fewer number of late jobs and improvement in resource utilisation

In the BF_X approaches, the first stage was to backward sequence all the operations of all the jobs. All the early jobs are locked on the planning board while the other jobs are unallocated. Based on the approach in use, the unallocated jobs are forward sequenced using some scheduling rule (criterion for selecting next job to load) and some scheduling optimisation strategies are applied.

V. THE BF1APPROACH

CRITERION FOR SELECTING NEXT JOB TO LOAD: Forward sequence using the lowest-number-of-operations-first rule

RATIONALE: To increase the number of jobs that will be early. By backward sequencing, very few resources spaces are created and to successfully slot in all operations of a job, the number of operations need to be few.

ANTICIPATED EFFECT: Fewer number of late jobs and improvement in resource utilisation

VI. THE BF2 APPROACH

CRITERION FOR SELECTING NEXT JOB TO LOAD: Forward sequence using the lowest-duration-of-operations-first rule

RATIONALE: Same as BF1 but here, emphasis is on total work to be done rather than number of operations

ANTICIPATED EFFECT: Same as BF1

VII. THE BF3 APPROACH

CRITERION FOR SELECTING NEXT JOB TO LOAD: Forward sequence using the highest-number-of-operations-first rule.

RATIONALE: By considering first the job with the highest number of operations, schedule duration should be reduced. This is because if at the end of all manual loading it is discovered that it is not possible to load the other jobs, these jobs have lower numbers of operations and chances are that the total remaining duration of work is lower. The worst case scenario is if these operations have to start at the end of all the previous operations and if all late. Even then, they should have a lowering effect on the schedule duration than if the lowest number of operations had been loaded first.

ANTICIPATED EFFECT: Improvement in resource utilisation, lead time and schedule duration

VIII. THE BF4 APPROACH

CRITERION FOR SELECTING NEXT JOB TO LOAD: Forward sequence using the highest-duration-of-operations-first rule.

RATIONALE: Same as BF3 but here, emphasis is on total work to be done rather than number of operations

ANTICIPATED EFFECT: Same as BF3

7.4 DISCUSSION

The previous sections dealt with the results of the experiments carried out. In this section, an attempt is made to explain why the schedules behaved the way they did and to give plausible reasons for any deviation in schedule performance whether negative or positive. This section approaches the task by analysing first the scheduling environment and later the scheduling rules.

7.4.1 SCHEDULING ENVIRONMENTS

The effects of the scheduling environments are presented as follows.

EFFECT OF TRANSPORTATION

- Transportation did not make significant difference to the total lead time and schedule duration possibly because transportation times were relatively much lower compared to other operation times.
- No significant effect was obtained for both the 6- and 8-resource scenarios, possibly because 1 or 2 of the resources were already not being used so maximum resource idle % could not have been higher nor could minimum resource working or utilisation % have been lower.
- As expected, resource utilisation % dropped and resource idle % rose and this can be attributed to the fact that AGVs were treated as resources and could only be used on the few occasions that there was demand for them.

  For few transportation operations, the utilisation % on an AGV would be remarkably small (hence the large range values) and this would ordinarily contribute to a fall in resource average utilisation %. This would also be the case with resource idle %.
- The utilization % for the other resources did not change when evaluated in exclusion of transportation (that is, compared with experiment 1NSF).

EFFECT OF SECONDARY RESOURCES

Results were as expected, with an increase in % late orders, total lead time, schedule duration and a reduction in working and utilisation %. This can be attributed to the fact that when secondary resources are considered, in addition to the primary resources being available, other supporting (secondary) resources also need to be available and this is not always possible. This results in operations waiting until the other supporting resources are available.

EFFECT OF A STRICTER SHIFT PATTERN

As expected, % late orders, total lead time and schedule duration increased. This was primarily because such a shift pattern meant fewer machine-hours available for the same amount of processing.

EFFECT OF OPERATION/RESOURCE FLEXIBILITY AND ASSOCIATED JOB SPLITS

- With operation/resource flexibility increased from 1, there was, contrary to expectation, not much improvement in the schedule performance measures. This was attributed to the fact that the large batch sizes could not allow the flexibility factor to be taken advantage of.

- When the jobs were broken down into smaller batches, the flexibility advantage was more pronounced. The difference in results can be attributed to the inflexibility associated with large batch sizes in the previous experiments. Each operation (for a batch of 50, the effective operation time was operation time * 50) had to be finished before subsequent operations could start. Unless there is human intervention, even if the other applicable resources are idle, all of the operation will have to be done on the resource on which the operations were started. By breaking down the batches, it was possible for that operation (for the batch size of 50) to be done concurrently on different resources hence shortening schedule duration, reducing % late orders, resource idle % and total late time, and making full use of the resources. The effect of the latter was an increase in resource working and utilisation %.
- It was observed that with further splits in addition to the consideration of secondary resources, very little improvement in schedule performance was achieved. This was primarily because there is a limit to the reduction in the number of secondary resources that can be used in job splits. In this work, for instance, there were 18 fixtures and with the concurrent use of resources, and the assumption that there is no de-fixturing until the whole job is finished, then there is a greater demand for unavailable fixtures. And the number of fixtures per job cannot be cut down to one if the work is to be held firmly in place. Yet, this is not the only secondary resource being considered. All these secondary resources need to be synchronised hence putting more strain on the scheduling problem.

EFFECT OF OPERATION TIME DEPENDENT ON RESOURCE

Considering operation/resource flexibility in relation to operation times being either dependent or independent of the selected resources, it was expected that regardless of whether or not secondary resources were considered, better performance would be recorded for resource-dependent operation times. This is because it is expected that the resource with the lower operation time will most likely be selected each time there is an option of selecting a resource. This should therefore lead to a reduction in total operation time and hence in schedule duration and in % late orders. With shorter operation times, it may also be easier for some operations to squeeze in between available resource spaces.

- Results showed that the schedule performance was generally better with the resource-dependent operation times.
- There was little difference in resource idle, utilisation and working % and this is most probably because the difference in both experiments was not in resource availability but in operation time. Therefore, a resource was always used in both cases and only operation times varied. This can only significantly affect time-dependent schedule performance measures such as % late orders, total late time, total lead time and schedule duration.

EFFECT OF SYSTEM DISTURBANCE: MACHINE BREAKDOWNS AND PLANNED MAINTENANCE

- Although there was a higher total lead time, contrary to expectation, there was a reduction in % late orders and the other results were similar to when there were no disturbances.
  - It was expected that the disturbance would result in fewer machine-hours available for the same amount of processing but this appeared not to be the case. The schedule performance can be attributed to the operation/resource flexibility factor which meant that for as long as another resource could perform the operation, there was no apparent disturbance.
  - A better value of % late orders could mean that the resources that the operations were forced to use were in fact available earlier than it would have been if the other resources had been available.

EFFECT OF TOOL SELECTION RULES

- With the consideration of tools, it was fairly difficult to determine the best tool selection rule because several determining factors had to be considered – tool life of the tools being considered, the tool sets for the operations and the operation times, to mention a few.
  - Any of the 3 tool selection rules could have been the best in terms of tool utilisation rates depending on the scheduling environment.

- If tool cost is considered, depending on the tools being considered for a particular operation, one tool continues to be selected for as long as its tool life is greater than the operation time, if that same set of tools is applicable to several other operations. The net effect is that that tool is well utilised.
- On the other hand, if different sets of tools are applicable to several operations, then the tools are often partially worn out leading to tool wastes. This is also the case with the tool flexibility rule.
- With the tool life rule, the scenario is slightly different because after a tool has been used for an operation, there is a higher chance of it being used for another operation for as long as it is one of a set of tools for another operation. This implies that using this rule, more tools are likely to be well-utilised and fewer tools are likely to be used.

- With the tool consideration experiments, it was observed that the schedule performance was the same regardless of the tool selection rule used and this was due to the fact that the operation times were not dependent on the tools selected.
- Also, the tool utilisation percentages were slightly different for some of the scheduling rules given the same scheduling environment and tool selection rule. This was primarily because different rules required most times a different sequence of operations. Therefore, sometimes, after certain operations had been done, other tools had to be considered for subsequent operations because of insufficient tool life.

EFFECT OF THE SCHEDULING APPROACHES UTILISING SCHEDULING OPTIMISATION STRATEGIES

- The scheduling optimisation strategies introduced in section 8.3 produced very good results as expected, better than those obtained from using the conventional and the custom-made scheduling rules. This is primarily because the operational constraints were relaxed. In applying these strategies, it was ensured that workload was not just transferred from one resource to another and that other resources were used only when they were idle with the net effect of fully utilising the resources. It was therefore no surprise that utilisation % was very good. And by allowing concurrent operations and batch splitting, schedule duration, % late orders and total late time were reduced.

- The scheduling optimisation strategies can be applied to a manufacturing system considering secondary resources although this was not done in this work because of the way the scheduling problem was modelled in Preactor. Although the application of the scheduling optimisation strategies to such a system is possible, it would not be so easy. This is because batch-splitting and concurrent operations have to be synchronised with the availability of secondary resources and there is a limit to the number of secondary resources that can be used for a job.

7.4.2 SCHEDULING RULES

When Preactor is given the option of selecting between two or more operations because they have the same value of an operational parameter (for example cost of operation) which is being considered by the operating rule, it chooses the operation that arrived first. If different resources can be used, then if possible, the operations are done concurrently on separate resources.

Operation parameters that are not constant throughout the job (dynamic) make the jobs that arrive first have a higher chance of finishing first if the operation parameter being considered is the same for the final operations. This is always the case with LPos and HPos whose final positional factor (PF) value is always 1. The advantage of these 2 rules is that the total late time is remarkably lower if all jobs have the same due date since most of the operations are started almost at the same time unless there are some jobs that have larger disparity in their total number of operations. If varying due dates exist, then the total late time may not necessarily be lower because while some jobs may start far too early because of the favour of the operational parameter being considered, others may start far too late and only the late jobs count with this parameter. It would seem ideal therefore to choose a rule that considers due dates. The Earliest Due Date rule would not consider other operational parameters such as cost and in most cases, as shown in the results, is not concerned about utilisation.

Backward sequencing often causes relatively low resource utilisation % and although total late orders may be low, often this rule alone is not sufficient because it does not allow complete allocation of some other jobs that may have needed to be started earlier. With LRem, HRem and Cost, it is not common to have to choose operations based on arrival times although it is possible for some of the operations to have the same value of "remwork" and/or "cost of operation" respectively.

This section attempts to explain the schedule behaviours and the possible reasons for this by treating the custom-made scheduling rules individually.

LRem

First, because the jobs have different numbers of operations and the operations have different operation time values, it is very unlikely that operations in the jobs have the same value of "remwork". This being so, there is very little fear of the scheduling depending on arrival time which is usually the case if operations share the same operational value being considered. There is also a higher chance of the job with the lowest total processing time (total operation time for all its operations) being that which is finished first. This is because once an operation is finished, the "remwork" value decreases by that operation time and thus the new "remwork" value becomes even lower than that of the other jobs which were initially higher and which have not been decreased. This ensures therefore that the first job started is finished before the others are started.

% late orders was good as expected and primarily because it was expected that more of the shorter duration jobs would be finished first. Although total lead and late time were good, this was not expected. This is because it was thought that the jobs left for later with the chance of being late had a higher total duration. Hence, it was expected that at least the total late time would be high unless the due dates were far out.

HRem

Unlike LRem, a job that is started first would not necessarily be the first to finish. This is because it is possible that after the operation time is deducted from the first highest "remwork" value, depending on the operation time value and the difference between the previous highest and the next highest "remwork", the next "remwork" value may be higher, equal or lower than one or more of the other jobs. If it is lower than any one of the other jobs, then the first operation of the job with the highest value is scheduled next. This should promote a more even spread of the jobs for processing such that the total late time is considerably reduced. This is because most if not all the jobs are then nearer completion than if only one job had been started because then, that would have been the only one nearer completion.

By having a more even spread of the operations, and on different resources as dictated by resource requirements, it was expected that resource performance measures would be good. Results were as expected.

LPos

This rule is similar to LRem although more operations are likely to have the same value of PF. This being so, more of the operations' scheduling would depend on arrival time. The job with the highest number of operations is started first although there is very little chance of it finishing first. Since the scheduling power could fluctuate between the jobs depending on which presently has the lowest value of PF which would depend on the range of numbers of operations, the jobs may all start early on. In the case where there is a large disparity between the jobs in terms of the number of operations, there may be a great difference in the starting times of the operations. For example, a job with 2 operations has PFs of 0.5 and 1.0 and in comparison to a job of 20 operations will have to wait a relatively long time for its first operation to be started. With very little disparity however, the total late time can be considerably reduced since most if not all the jobs would have been started and as such would be nearer completion than if they had not been started.

Since most of the jobs could be started, then depending on the resources required by each operation, resource performance measures could be good. Results were as expected.

HPos

This rule is similar to LPos except that the job with the lowest number of operations is started first.

It was expected that being similar to LPos, resource performance measures would be good. However, the results were not as good. Instead, the rule was good in % late orders, total late time, total lead time and average added value %. On further investigation, it can be seen that if the lowest number of operations are started first, they can more easily be finished hence resulting in lower % late orders. If a larger proportion of the job set is finished, then lower late and lead times may result, depending on how late the late jobs are. Also, once resource waiting and/or idle times and setup times are minimised, average added value % is expected to improve. This must have been the case with HPos since the rule ensured that most jobs started about the same time and the use of different resources (and this was improved where operation/resource flexibility was considered) ensured that unless secondary constraints played actively in the scheduling process, idle and/or waiting time were not high.

HNoOfOps

With the application of this rule, it was expected that fewer but jobs with higher numbers of operations would be finished first regardless of the due dates. The ru ensures that the job that starts first is finished first because the "Number of Operations" value is static for the job. This may be good in the evaluation of total late time since the jobs that are scheduled first have a higher chance of being early and in this case may be the bulk of the order set in terms of total operation time. The jobs that may be late are those scheduled later on and this have lesser numbers of operations and perhaps, lesser total operation time which may imply that even with the worst case scenario being that all other jobs are late, their total late time should be considerably low. This argument should however not be valid if the operation times for the jobs with lower numbers of operations are remarkably higher.

As expected, schedule duration was lower. Resource performance measures can be high if one considers that once a job is started and it requires different resources, the operations are spread over the resources. However, this was not expected to be high because it was expected that once the operations are started randomly on the resources, it may be difficult to squeeze in other operations as a result of which resource utilisation and working % may not be so good. It may be easier for these operations to just start from where the preceding operations stopped, unless the total operation times are remarkably lower than the available resource spaces.

LNoOfOps

Like the HNoOfOps rule, LNoOfOps ensures that the job that starts first is finished first because the "Number of Operations" value is static for the job. It also ensures that jobs with fewer numbers of operations are scheduled first and most likely finished before their due dates if it is assumed that they do not arrive too close to their due dates and that the total processing times are small enough. This could mean good % late orders although high total late and lead times since the jobs that are likely to be late are those of higher numbers of operations and possibly with higher total processing time.

As expected, % late orders was low but contrary to expectation, so also were the total late and lead times. The deviation from expected could be either because the total operation time for the remaining operations were very small or because the due dates were far out.

LOpRes

This rule favours the operations that can be done by the fewest number of resources. Also, because it is dynamic (that is, changes with every operation), it behaves very much like HRem, LRem and HPos in that the scheduling power fluctuates and as such the job started first is not necessarily that which finishes first. Nevertheless, for the reasons given with those other rules, the total late time may be considerably reduced. Another issue in this rule's favour is that by allowing operations with lower flexibility to be scheduled first, the system flexibility is greatly increased and this should therefore have the net effect of generally providing all-round good schedules.

Just like HRem, it was good in resource performance measures. This could be because of the improved flexibility of the system which resulted from leaving more flexible operations for later. However, contrary to expectation, LOpRes was not outstanding. This may be because the optimum job splits was not determined before scheduling.

HOpRes

This rule favours the operations that can be done by the highest number of resources, which means that there is very little limitation for the first few jobs to be scheduled. These jobs have higher chances of finishing on time and as such total late time should be reasonably low. Also, because it is dynamic (that is, changes with every operation), it behaves very much like HRem, LRem and HPos in that the scheduling power fluctuates and as such the job started first is not necessarily that which finishes first. Nevertheless, for the reasons given with those other rules, the total late time may be considerably reduced.

Only one set of experiments (6SF) reported well of this scheduling rule. Although this was not as expected, it is only reasonable to assume that the reduced flexibility that results after the first few operations played a major role. This is because the first few operations do not normally need much flexibility to commence considering that at this stage of scheduling most resources (and supporting) are available.

Cost

This rule is similar to LRem. The operation with the lowest cost is started first and there is no certainty of finishing first because there is no correlation between the cost of the operations. This depends only on the operation precision required and on the number of resources needed. Because the cost of the operations are most likely haphazard, there may be a spread of the jobs for processing such that the total late time is considerably reduced. This is because, most if not all, the jobs are then nearer completion than if only one job had been started because then, that would have been the only one nearer completion.

As observed with HRem, a spread of operations may very well mean an even utilisation of resources, hence expected good resource performance measures. This was indeed the case. Also, as expected, schedule duration was lower.

MaxToolIndex

This rule is associated with minimum tool changes and may favour operations nearer the end of the job. Because of this, it was expected to behave like HPos but in addition, to result in low total late and/or lead time and schedule duration and high average added value % since minimum tool changes may imply minimum associated setup times, idle and/or waiting times. Also, since the rule favours operations nearer completion, then it is expected that more jobs would be finished before due date, hence leading to good % late orders. As expected, % late orders and total late time was consistently good in both sets of experiments carried out. The schedule duration value was however amongst the best only in 2TSF which means that the schedule performance fell below expectation.

MinToolIndex

This rule was supposed to be a comparator for MaxToolIndex and was not expected to perform so well. It performed as expected most probably because it favoured operations that had a higher number of tool changes. This would ordinarily increase total processing time and hence lead to a low average added value % and high % late orders, total late time and total lead time.

LOpFlex

This was expected to improve schedule performance since it was expected to increase the system flexibility, thus improving resource performance measures. This was not the case and is probably because the scheduling was such that no operation had to wait for a tool to be available. Once the resource was available, the tool was also. In the end, it was the availability of the resource that mattered and not that of the tool. If a tool on the resource could not be used, then another was selected from the tool kit. The research did not cater for the unavailability of tools from the tool kits. It is therefore no wonder that there was no definite pattern in the rule's behaviour (Table 8-12).

HOpFlex

The same argument in LOpFlex holds in this case.

SUMMARY

Multiple resource constraints and multiple criteria have been successfully handled in a dynamic FMS environment. Fixtures, tools, AGVs and finite buffer capacity and machine breakdowns, planned maintenance, tool wears, and impromptu withdrawal or insertion of orders have been considered. Several custom-made scheduling rules have been tested against conventional rules and some scheduling approaches have also been presented.

By treating fixtures, tools and buffers as secondary resources and AGVs and machines as primary resources, it is possible to synchronise the availability of both classes of resources. And although the multiple criteria objectives are not used to model the scheduling problem in Preactor, they are considered in the development of the scheduling rules. As such, the criteria objectives are built into the system.

The FMS scheduling problem is simplified by having one or two system disturbances at a time although the scheduling problem can be modelled to have more system disturbances provided there is adequate system flexibility. Otherwise the system may lock. Having machine breakdowns and planned maintenance may take care of tool wears that may be inherent in the broken down machine.

Results showed that the custom-made scheduling rules performed favourably in comparison to the conventional rules. Although not always as good as expected, results also showed that there is great potential for rules that consider not only operational data but also operational time factors such as due date, operation time and setup time. Otherwise, as with EDD that ensures that certain jobs are early, this may be at the expense of cost. More of the late jobs may be more expensive to the customer hence resulting in customer dissatisfaction.

Results also showed that the scheduling environment plays significant role in schedule performance. Although most of the rules are consistent in their performance regardless of the environment, there was an effect in schedule performance in terms of data values. With job splits for instance, there was better resource utilisation percent (%) although the rules still behaved as they did without the splits.

The use of the scheduling approaches showed that taking full advantage of an FMS can result in great schedule performances and make it easier to justify FMS use. Although it can be argued that this depends on how good the scheduling rules employed are, it can be seen that the scheduling optimisation strategies make more significant contribution to the improvement in resource utilisation. The scheduling rules however ensure that the scheduling approach performance is better than when only the scheduling rules are used, in terms of % late orders. A right mix of these two factors accounts for the overall success of the presented scheduling approaches.

CHAPTER 8

CASE STUDY

This chapter extends the experiments presented in Section 7.3.2 by combining the best scheduling rules in a particular situation with scheduling optimisation strategies. Focus is on the 3-resource scenario using the case study order set. The associated procedures for each approach are enumerated and schedule performances evaluated.

Table 7-16[1] illustrates the effects of the scheduling optimisation strategies that have been applied to the approaches presented. Changing an operation's resource requirement (equivalent to increasing operation flexibility) is made possible by assuming that the resources are flexible. An operation would not ordinarily be put on a resource incapable of performing it. However, to ensure that the workload is not just transferred from one resource to another, the number of operation/resource changes is limited to six (section 5.4)[2].

There is also a limit to the batch sizes after batch splitting. Theoretically, this can be as low as 1although this would further increase the scheduling problem size. In this study, and especially in the case study where the 3-resource scenario is being used, the batch size is limited to a third (1/3) of the order size. This would mean that often, approximately the same amount of work of the same order could be done concurrently on the three resources.

Table 8-1 shows the case study order set to which the approaches have been applied.

[1] In section 7.3.2
[2] This means that for the whole loading process for all the operations, only 6 operations can be loaded on separate resources from those initially allocated in the process plans.

Products	Quantity	Due Dates
Splined Shaft	20	4/1
Gearbox Mounting	30	7/1
Safety Cover 200	50	5/1
Support Plate	25	6/1
Gearbox Mounting	45	6/1
Torque Tube	30	5/1

Table 8-1: The case study order set

THE FF1 APPROACH

From results of experiment 4NSF, it can be seen that amongst the best scheduling rules in % late orders are HPos, LRem, and LNoOfOps. Any of these rules could therefore have been selected but in this case, HPos was selected. The resulting schedule performance with 2 late orders, order 300 and 500, is as shown in Table 8-2. These 2 orders were then unloaded while the rest were locked on the planning board. The products database in Appendix 2 shows that order 300 (Safety Cover 200) has 13 operations while order 500 (Gearbox Mounting) has 6. Therefore based on procedures of FF1 (section 7.3.2), order 300 was loaded first.

Following the first loading after the unloading and locking processes, the first optimisation strategy to be applied is dependent on the existing situation. In this case, it can be seen from Figure 8-1that there are some available resource spaces which if used up could improve resource utilisation and reduce schedule duration and possibly % late orders, total late and lead times. The only open options were to either change the resource requirement of the first late operation of order 300 or to split batch. Batch splitting would not have had as good as effect on improving schedule performance because the resource spaces on the different resources are not concurrent as a result of which concurrent operations would have been impossible. By changing the resource requirements of Weld SubB to M3, the operation and its preceding operations were made to start earlier and the break in M3 usage (Figure 8-1) was used up leading to a full utilisation of resources. The operations of order 300 were done earlier and because these operations determined schedule duration (Order 300's last operation was the overall last operation in Figure 8-1), the schedule duration was lowered (comparing Figures 8-1 and 8-2 and Tables 8-2 and 8-3).

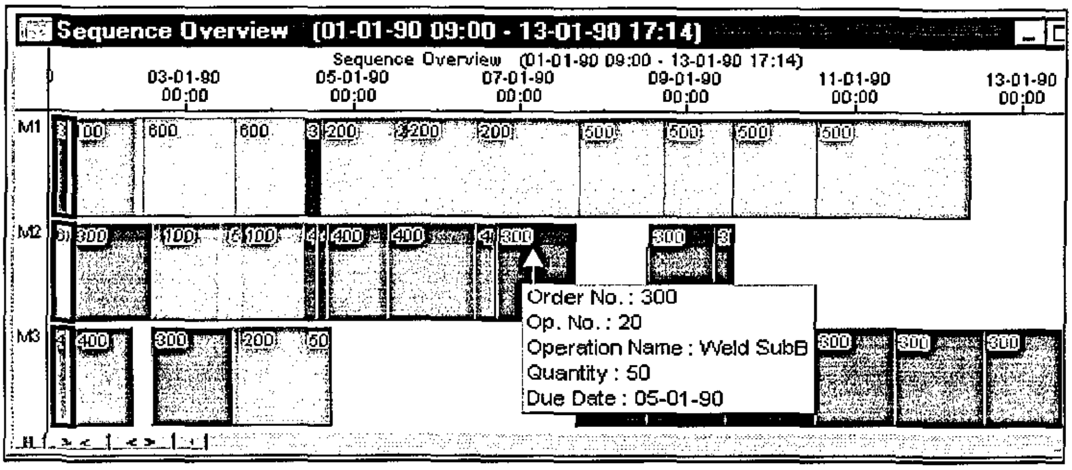

Figure 8-1: The effect of loading the case study order set

Form No. : P000-000 30-04-00 18:17

Schedule Performance Metrics

Job Count Data	Early	Late	Incomplete	Started
Absolute	4	2	0	0
Percentage	66.67	33.33	0.00	0.00

Job Completion Data	Total	Minimum	Average	Maximum
Early Time	2 Days 18:24	6 Hours 45 Mins	16 Hours 36 Mins	1 Day 14:14
Late Time	10 Days 2:17	5 Days 9:00	6 Days 10:09	7 Days 17:14
Setup Time	0 Hours 56 Mins	0 Hours 04 Mins	0 Hours 09 Mins	0 Hours 22 Mins
Lead Time	36 Days 17:47	2 Days 19:20	6 Days 2:59	12 Days 8:14
Added Value Percentage		49.97	57.22	84.60

Resource Data	Minimum	Average	Maximum
Working Percentage	22.31	27.47	31.84
Setup Percentage	0.08	0.11	0.14
Unavailable Percentage	62.62	62.62	62.62
Idle Percentage	5.45	9.79	14.90
Utilization Percentage	59.68	73.50	85.19

Schedule Span 01-01-90 09:00 to 13-01-90 17:14 Schedule Duration 12 Days 8:14

Table 8-2: The resulting schedule performance

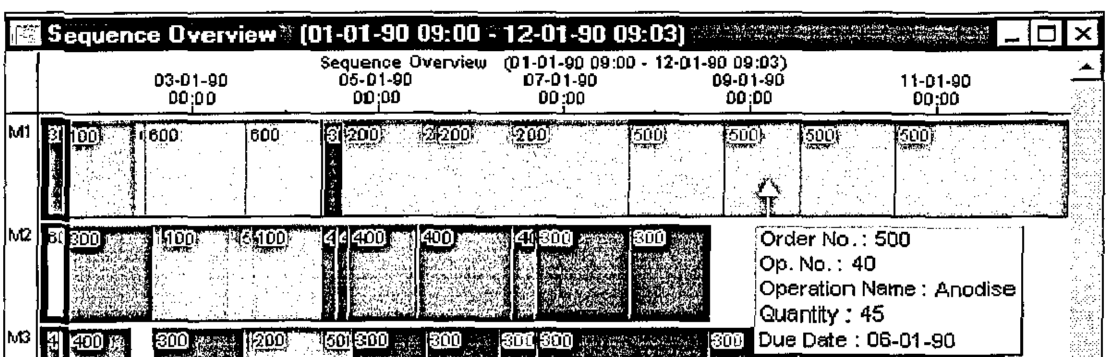

Figure 8-2: The effect of changing resource requirements of Weld SubB

Loading of orders 300 and 500 resulted in a schedule that showed that M2 was not used after the loading of order 300. To fully utilise resources however, some operations of order 500 needed to be loaded on M2. This was done by first determining the operations that could be loaded on M2. It would not have improved schedule performance to load the first operation, drill plate on M2 because it would then have had to start later than it did. The earliest operation that could be loaded on M2 was the next operation, "anodise". Therefore, by batch splitting and by allowing concurrent operations (loading the split operations on M1 and M2 concurrently), it was possible to further reduce schedule duration and to increase utilisation % of M2 (Figure 8-3, Table 8-3, Table 8-4).

Form No.: P000-000 — 30-04-00 16:21

Schedule Performance Metrics

Job Count Data	Early	Late	Incomplete	Started
Absolute	4	2	0	0
Percentage	66.67	33.33	0.00	0.00

Job Completion Data	Total	Minimum	Average	Maximum
Early Time	2 Days 18:24	6 Hours 45 Mins	16 Hours 38 Mins	1 Day 14:14
Late Time	11 Days 2:51	5 Days 9:00	5 Days 13:26	5 Days 17:48
Setup Time	0 Hours 56 Mins	0 Hours 04 Mins	0 Hours 09 Mins	0 Hours 22 Mins
Lead Time	34 Days 18:21	2 Days 19:20	5 Days 19:04	10 Days 8:48
Added Value Percentage		49.97	59.66	84.60

Resource Data	Minimum	Average	Maximum
Working Percentage	20.45	30.82	35.73
Setup Percentage	0.09	0.12	0.14
Unavailable Percentage	64.19	64.19	64.19
Idle Percentage	0.00	4.87	12.22
Utilization Percentage	65.49	86.07	99.74

Schedule Span 01-01-90 09:00 to 12-01-90 09:00 — Schedule Duration 11 Days 0:00

Table 8-3: The effect of altering resource requirement

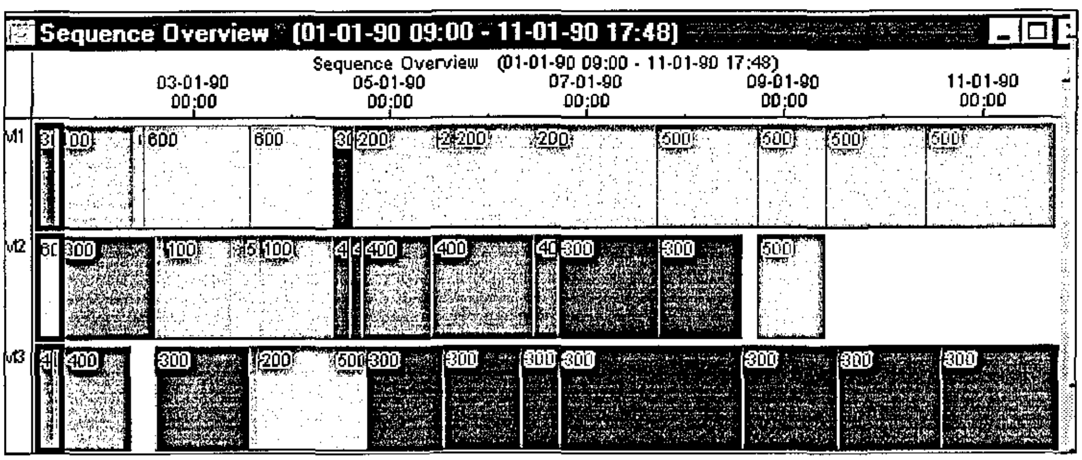

Figure 8-3: Final effect of effectively using the FFI Approach

Form No. : P000-000 | 30-04-00 18:40

Schedule Performance Metrics

Job Count Data	Early	Late	Incomplete	Started
Absolute	4	2	0	0
Percentage	66.67	33.33	0.00	0.00

Job Completion Data	Total	Minimum	Average	Maximum
Early Time	2 Days 18:24	6 Hours 45 Mins	16 Hours 36 Mins	1 Day 14:14
Late Time	10 Days 10:51	4 Days 17:00	5 Days 5:26	5 Days 17:48
Setup Time	0 Hours 58 Mins	0 Hours 04 Mins	0 Hours 09 Mins	0 Hours 22 Mins
Lead Time	34 Days 2:21	2 Days 19:20	5 Days 18:24	10 Days 8:48
Added Value Percentage		49.97	59.68	84.80

Resource Data	Minimum	Average	Maximum
Working Percentage	25.69	32.71	37.11
Setup Percentage	0.10	0.13	0.15
Unavailable Percentage	62.50	62.50	62.50
Idle Percentage	0.29	4.86	11.88
Utilization Percentage	69.51	87.20	98.98

Schedule Span 01-01-90 09:00 to 11-01-90 17:48 | Schedule Duration 10 Days 8:48

Table 8-4: The final schedule performance after using the FF1 Approach

THE FF2 APPROACH

The same procedures of the FF1 approach were required here. However, the FF2 approach required that instead of loading first the order with the highest number of operations, that with the highest duration of operations was required. Incidentally, for this order set, these 2 orders were the same. The final schedule performance was therefore the same as that of FF1.

THE FF3 APPROACH

After unloading orders 300 and 500, the order with the lowest number of remaining operations was loaded first. Because of this, order 500 was loaded. Scheduling techniques such as batch-splitting, increasing resource flexibility and allowing concurrent operations were applied as was appropriate. After satisfactorily loading order 500, order 300 was loaded. The resulting schedule performance is as shown in Table 8-5.

Form No.: P000-000 30-04-00 18:42

Schedule Performance Metrics

Job Count Data	Early	Late	Incomplete	Started
Absolute	4	2	0	0
Percentage	66.67	33.33	0.00	0.00

Job Completion Data	Total	Minimum	Average	Maximum
Early Time	2 Days 18:24	6 Hours 45 Mins	16 Hours 36 Mins	1 Day 14:14
Late Time	11 Days 22:30	5 Days 9:00	5 Days 23:15	6 Days 13:27
Setup Time	0 Hours 58 Mins	0 Hours 04 Mins	0 Hours 09 Mins	0 Hours 22 Mins
Lead Time	37 Days 10:25	2 Days 19:20	6 Days 5:44	11 Days 4:27
Added Value Percentage		49.45	58.80	84.83

Resource Data	Minimum	Average	Maximum
Working Percentage	22.82	30.32	34.30
Setup Percentage	0.09	0.12	0.14
Unavailable Percentage	60.51	60.51	60.51
Idle Percentage	2.06	6.05	10.53
Utilization Percentage	62.53	80.09	94.01

Schedule Span 01-01-90 09:00 to 12-01-90 10:27 Schedule Duration 11 Days 4:27

Table 8-5: The final schedule performance after using the FF3 Approach

THE BF1 APPROACH

The first procedure of the BF_X approaches is to backward sequence *all* operations for *all* orders. This results most often in some late and some incomplete orders. Only the early orders are locked on the planning board. If there are no such orders, then the locking process is by-passed. All other orders are unallocated.

Backward sequencing the case study order set results in the schedule of Table 8-6 and Figure 8-4. Two orders (100 and 600) were early and the rest uncompleted. Therefore these orders, 100 and 600, were locked on the planning board while the rest were unallocated. The next stage, unique to the approach, was to load the order with the lowest number of operations. Orders 200 and 500 were thus loaded leading to the schedule of Figure 8-5.

Both orders, though completed, were late. Schedule performance could be improved by employing scheduling optimisation strategies that would ensure that the available resource spaces are used up thus improving resource utilisation and reducing schedule duration and possibly % late orders, total late and lead times. Orders could be made to start earlier by changing resource requirements or simply by shifting operations forward thus taking up the spaces that were originally taken up by other operations when the "load operations with the minimum number of operations first" rule was first used[3]. Figure 8-6 shows the effect of making some operations start earlier and of batch splitting and the allowing of concurrent operations. By using the scheduling strategies, schedule performance was remarkably improved. The resources were more utilised and schedule duration was reduced.

Form No. : P000-000 22-07-00 05:58

Schedule Performance Metrics

Job Count Data	Early	Late	Incomplete	Started
Absolute	2	0	4	0
Percentage	33.33	0.00	66.67	0.00

Job Completion Data	Total	Minimum	Average	Maximum
Early Time	12 Hours 00 Mins	6 Hours 00 Mins	6 Hours 00 Mins	6 Hours 00 Mins
Late Time	0 Hours 00 Mins	0 Hours 00 Mins	0 Hours 00 Mins	0 Hours 00 Mins
Setup Time	0 Hours 10 Mins	0 Hours 04 Mins	0 Hours 05 Mins	0 Hours 06 Mins
Lead Time	3 Days 15:01	1 Day 7:44	1 Day 19:46	2 Days 7:47
Added Value Percentage		44.76	49.59	50.41

Resource Data	Minimum	Average	Maximum
Working Percentage	18.97	28.34	31.72
Setup Percentage	0.02	0.05	0.11
Unavailable Percentage	62.46	62.46	62.46
Idle Percentage	5.79	11.14	18.47
Utilization Percentage	50.52	70.17	84.49

Schedule Span 01-01-90 09:06 to 07-01-90 18:00 Schedule Duration 6 Days 8:54

Table 8-6: The effect of backward sequencing the case study order set

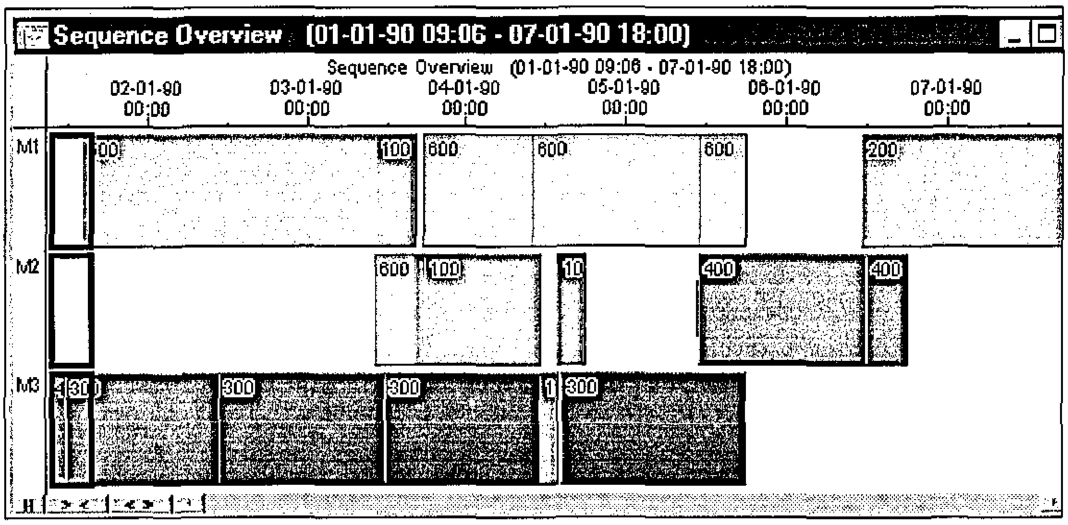

Figure 8-4: The effect of backward sequencing the case study order set

[3] With the way Preactor works, one has to load all operations based on the LNoOfOps rule first and then unallocate all the other operations while leaving that with the lowest number of operations for the application of the scheduling optimisation strategies.

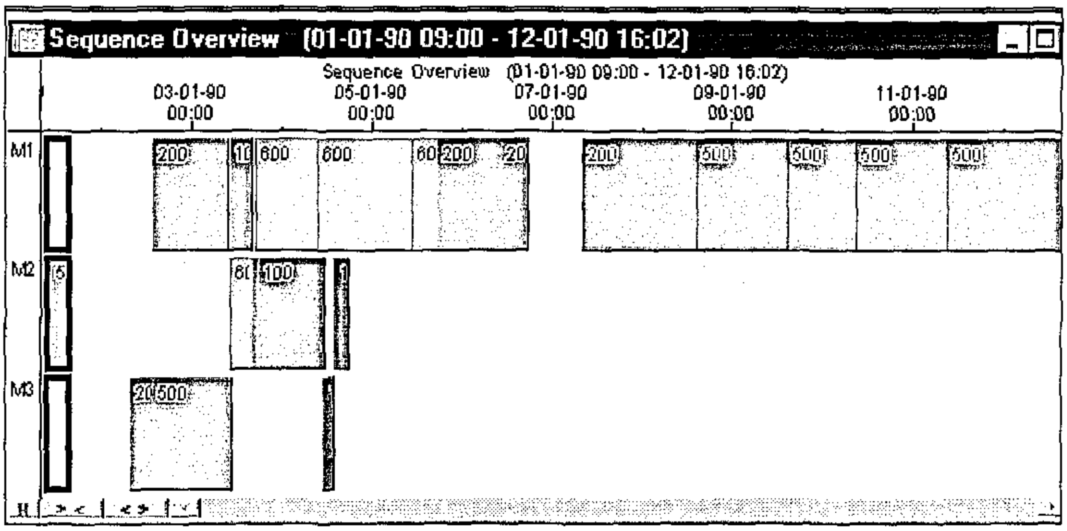

Figure 8-5: The effect of loading the orders 200 and 500

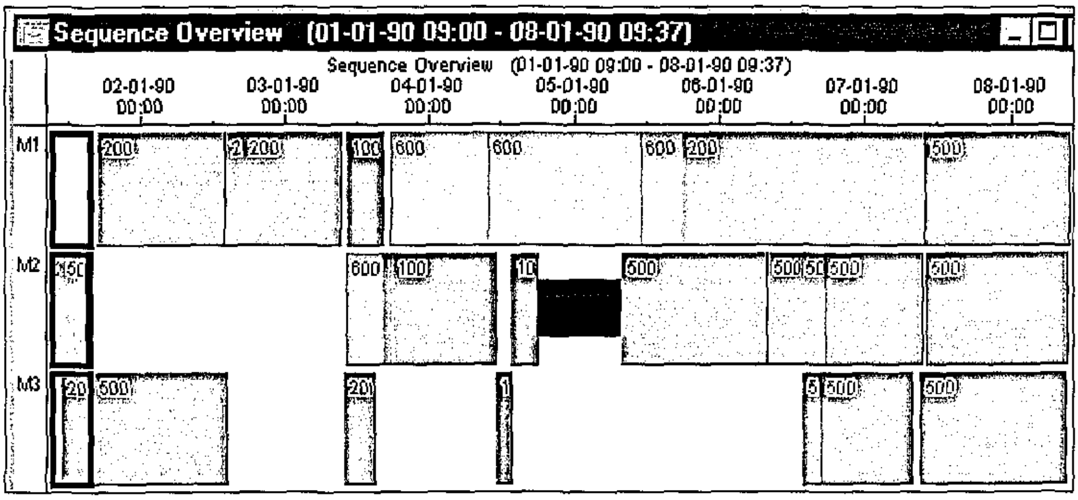

Figure 8-6: The effect of utilising some of the optimisation strategies

This was repeated for subsequent jobs. The final schedule is as shown in Figure 8-7.

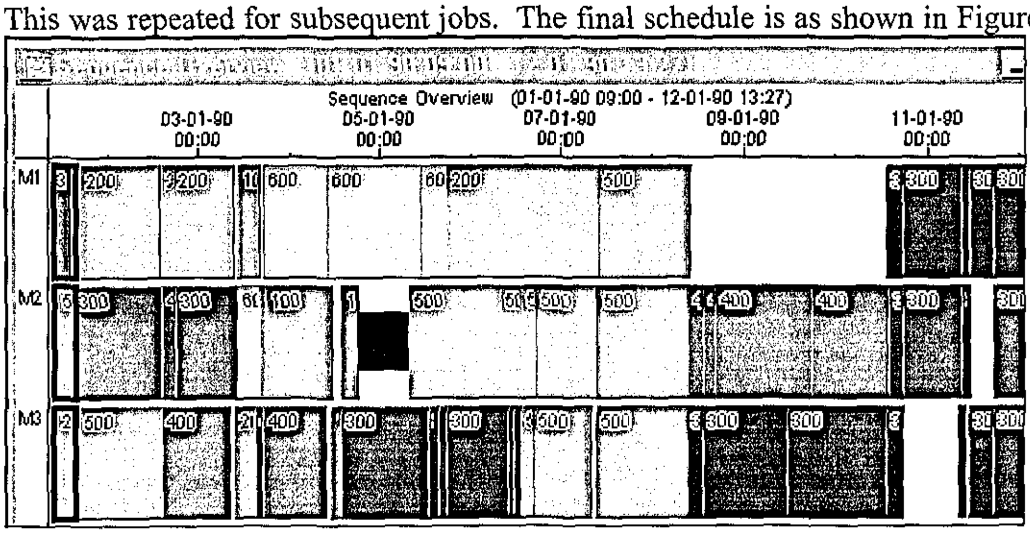

Figure 8-7: The final effect of applying the BF1 Approach

Results show better performance to that obtained in Table 8-6 and Figure 8-4. Although the results are not as good as when the FF_x approaches were considered, they were nevertheless better than when the best scheduling rules were used (Table 9-2), in all regard but % late orders and average added value %.

Form No.: P300-000 — 22-07-00 08:47

Schedule Performance Metrics

Job Count Data	Early	Late	Incomplete	Started
Absolute	3	3	0	0
Percentage	50.00	50.00	0.00	0.00

Job Completion Data	Total	Minimum	Average	Maximum
Early Time	1 Day 2:00	8 Hours 00 Mins	8 Hours 40 Mins	14 Hours 00 Mins
Late Time	11 Days 12:57	1 Day 9:37	3 Days 20:19	6 Days 10:28
Setup Time	1 Hours 15 Mins	0 Hours 04 Mins	0 Hours 12 Mins	0 Hours 41 Mins
Lead Time	35 Days 19:00	1 Day 7:44	5 Days 23:11	11 Days 4:28
Added Value Percentage		30.47	42.48	58.48

Resource Data	Minimum	Average	Maximum
Working Percentage	25.88	30.32	32.72
Setup Percentage	0.08	1.89	5.09
Unavailable Percentage	60.51	60.51	60.51
Idle Percentage	0.00	4.77	10.75
Utilization Percentage	70.32	81.92	89.88

Schedule Span 01-01-90 09:00 to 12-01-90 10:27 — Schedule Duration 11 Days 4:28

Table 8-7: The final schedule performance from applying the BF1 Approach

THE BF2 APPROACH

The same procedures of the BF1 approach were required here. However, the BF2 approach required that instead of first loading the order with the lowest number of operations, that with the lowest duration of operations was required. Incidentally, for this order set, these 2 orders were the same. The final schedule performance was therefore be the same as that of BF1.

THE BF3 APPROACH

Following the procedures of BF1 up to the unloading stage, the late order with the highest number of operations was re-loaded first. This was order 300 (Safety Cover 200). By applying some of the scheduling techniques of Table 7-12, it was possible to improve schedule performance of Table 8-6 as shown in Figure 8-8 and Table 8-8.

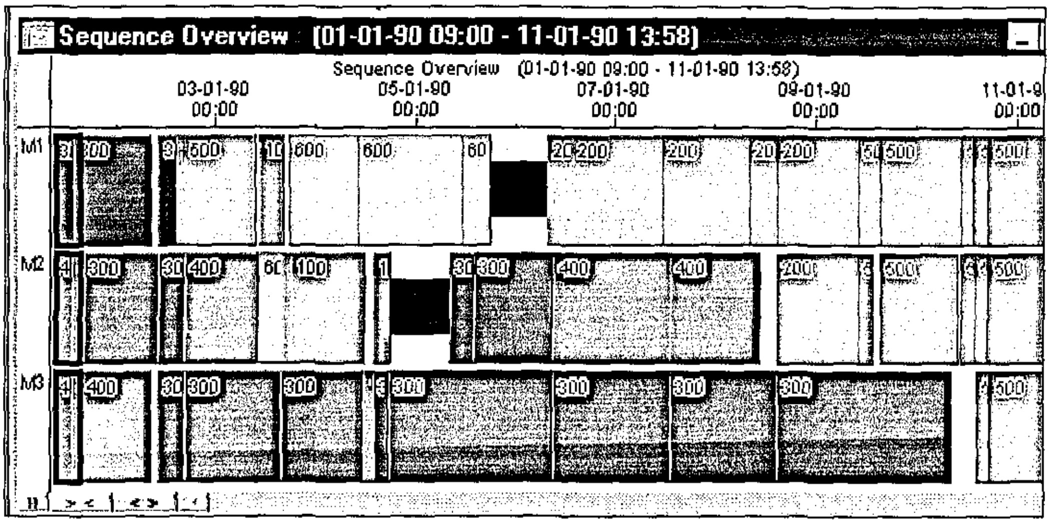

Figure 8-8: The final effect of applying the BF3 Approach

Form No. : P300-000 22-07-00 07:00

Schedule Performance Metrics

Job Count Data

	Early	Late	Incomplete	Started
Absolute	2	4	0	0
Percentage	33.33	66.67	0.00	0.00

Job Completion Data

	Total	Minimum	Average	Maximum
Early Time	12 Hours 00 Mins	6 Hours 00 Mins	6 Hours 00 Mins	6 Hours 00 Mins
Late Time	11 Days 19:04	1 Day 10:04	2 Days 22:48	4 Days 13:59
Setup Time	1 Hours 02 Mins	0 Hours 04 Mins	0 Hours 10 Mins	0 Hours 24 Mins
Lead Time	35 Days 9:25	1 Day 7:44	5 Days 21:04	8 Days 20:25
Added Value Percentage		28.85	47.17	70.01

Resource Data

	Minimum	Average	Maximum
Working Percentage	32.41	33.22	34.40
Setup Percentage	0.10	3.95	5.89
Unavailable Percentage	63.48	63.48	63.48
Idle Percentage	0.00	1.19	3.57
Utilization Percentage	84.88	88.88	89.97

Schedule Span 01-01-90 09:00 to 11-01-90 13:58 Schedule Duration 10 Days 4:58

Table 8-8: The final schedule performance from applying the BF3 Approach

THE BF4 APPROACH

The same procedures of the BF3 approach were required here. However, the BF4 approach required that instead of first loading the order with the highest number of operations, that with the highest duration of operations was required. Incidentally, for this order set, these 2 orders were the same. The final schedule performance was therefore be the same as that of BF3.

SUMMARY

In this chapter, results of the approaches show that better results than the custom-made or the conventional scheduling rules can be achieved. The resource performance measures were considerably improved and so also were the total late and lead times. It was almost impossible to improve % late orders primarily because in an attempt to fully utilise resource spaces, no spaces were left for the later jobs/operations.

The BF_x approaches involve attempting to meet due dates by pushing work back from the due date to the starting operation. This ensures that work that can be done by the due date are so done although such a strategy can only promise few early orders unless it is possible to backward sequence all the orders. This would then lead to an increase in the percentage of early jobs. Nevertheless, both the BF_x and the FF_x approaches allow the flexibility of an FMS to be taken advantage of and the final results show that the FF_x approaches have the greater potential for improving system performance in a flexible manufacturing system.

CHAPTER 9

METHODOLOGY FOR SELECTING SCHEDULING RULES

Results of the various experiments show that scheduling rules behave in an indefinite way dictated by the scheduling environments. This chapter presents a methodology for the determination of the scheduling rule appropriate for a given system objective given the scheduling environment. This is as stated below:

1. For the system objectives, determine the appropriate performance measure from the report sheets of the simulator used. The various performance measures in Preactor and the equivalent system objectives are shown in Table 9-1.
2. Identify the scheduling environment under scrutiny.
3. For the scheduling environment, identify the required system objective.
4. For the required system objective, identify the equivalent performance measure in the software in use. If this is PREACTOR, Table 9-1 can be useful.
5. For that scheduling environment, identify all the experiments.
6. For each of the experiments in that environment, identify the best scheduling rules in the performance measure determined in 4.
7. Across the experiments of 5, identify the scheduling rules that are common to ALL the experiments.

Following the procedures above, the best scheduling rules (in terms of the performance measures in PREACTOR) have been given for two types of scheduling environments, the SF and the NSF experiments.

Table 9-1 shows the associated system objectives for the schedule performance measures that were considered in this work. By identifying the associated system objectives for these schedule performance measures, it is possible to allocate scheduling rules that have been consistently good in these system objectives to these system objectives. As an example, by identifying that minimising % late orders is the same as having system objectives of minimising lateness and minimising the number of tardy jobs, then from the results of Chapter 8, one can expect that the LNoOfOps rule would be applicable to fulfilling the system objective.

Schedule Performance Measures	System Objectives
(Minimising) % late orders	Minimising number of tardy jobs, meeting due dates, minimising lateness
(Minimising) total late time	Minimising number of tardy jobs, meeting due dates, minimising lateness
(Minimising) total lead time	Minimising lead time
(Maximising) average added value %	Minimising unproductive time, setup times and tool changes, maximising production rate
(Maximising) resource average working %	Maximising FMS utilisation, maximising average machine utilisation
(Minimising) resource average idle %	Minimising unproductive time, minimising total number of part transfers
(Maximising) resource average utilisation %	Maximising FMS utilisation, maximising average machine utilisation
(Minimising) schedule duration	Minimising total production time, minimising makespan, minimising throughput

Table 9-1: Performance measures and associated system objectives

In a similar manner, the scheduling rules for other system objectives in similar scheduling problems have been derived and presented in Table 9-2.

System Objectives	Scheduling Rules
Minimising total throughput time/makespan	HRem, LPos
Maximising FMS utilisation	HRem
Maximising average machine utilisation	HRem
Minimising unproductive time	LRem
Minimising total number of part transfers	HRem
Minimising total production time	HRem, LPos
Minimising lateness	LRem, LNoOfOps, HPos
Minimising number of tardy jobs	LRem, LNoOfOps, HPos
Meeting due dates	LRem, LNoOfOps, HPos
Minimising setup times and tool changes	LRem
Maximising production rate	LRem
Balancing machine usage	HRem
Minimising lead time	LRem

Table 9-2: System objectives and associated scheduling rules

The results (Chapter 7) derived from using secondary resources was slightly different from the others. For the resource performance measures for instance, the conventional rules, EDD and FCFS were consistently outstanding. On that note, Table 9-3 presents another list of associated scheduling rules for the system objectives.

System Objectives	Scheduling Rules
Minimising total throughput time/makespan	HRem, LPos
Maximising FMS utilisation	FCFS, EDD
Maximising average machine utilisation	FCFS, EDD
Minimising unproductive time	LRem
Minimising total number of part transfers	HRem
Minimising total production time	HRem, LPos
Minimising lateness	LRem, LNoOfOps, HPos
Minimising number of tardy jobs	LRem, LNoOfOps, HPos
Meeting due dates	LRem, LNoOfOps, HPos
Minimising setup times and tool changes	LRem, FCFS, EDD
Maximising production rate	LRem
Balancing machine usage	HRem
Minimising lead time	LRem, FCFS, EDD

Table 9-3: System objectives and associated scheduling rules 2

CHAPTER 10

CONCLUSIONS

Several research issues on FMS scheduling have been addressed. This chapter presents some of the most significant conclusions drawn from the experiments carried out. The conclusions are as follows.

1. The design of a planning module that considered the simultaneous scheduling of workpieces, machines, cutting tools, fixtures, buffers and material handling devices has been successfully done by modelling the machines and AGVs as primary resources and the others as secondary resources.
2. The consideration for a dynamic scheduling problem has been successfully modelled using Preactor. This allowed machine breakdowns and planned maintenance. In addition, by modelling tool wear (via the consideration for tool life in selecting tools), allowing the impromptu insertion or deletion of orders and by allowing impromptu machine breakdown by temporarily removing the resource from the planning board, dynamic scheduling problems were more accurately modelled.
3. Planning strategies that aimed to minimise % late orders and/or force the order to conform to due dates were successfully generated. This was achieved by presenting scheduling approaches that allowed more flexibility within the system by allowing batch-splitting, increased operation/resource flexibility and concurrent operations.
4. Planning strategies that aimed to fully utilise resources in a bid to improve resource performance measures were successfully generated. This was achieved by presenting scheduling approaches as this allowed batch-splitting, increased operation/resource flexibility and concurrent operations with the net effect of spreading work over the available resources.
5. Custom-made scheduling rules that utilised more functional operational parameters were successfully developed and applied to hypothetical scheduling problems. While the EDD rule was very good in minimising % late orders, the fact that it does not consider any operational parameters means that some costlier jobs for instance could be very late while those that bring lesser income may be far too early.

6. The generated custom-made scheduling rules were successfully compared with the conventional scheduling rules and while these were not always as good as the conventional scheduling rules, they showed that there was potential in developing scheduling rules that considered more functional operational parameters. The LNoOfOps rule for instance was consistently better than the EDD rule in % late orders which was not expected considering that EDD's only considered parameter is due date which is the main determinant for % late orders.
7. Scheduling approaches that successfully produced better schedules than either conventional or custom-made scheduling rules were generated. These approaches utilised scheduling optimisation strategies such as batch-splitting, increasing system flexibility and allowing concurrent operations thus combining the advantages of each. Also, by ensuring that jobs that had the tendency to be late were made more flexible, it was easier to cut down on % late orders and/or total late time. The net effect of applying these approaches was the full utilisation of the resources and the reduction in % late orders, total late time and schedule duration.
8. The research was able to successfully present a methodology for selecting scheduling rules for given system objectives. This was achieved by comparing the results of all the experiments for definite patterns for each schedule performance which could then be associated with some system objective. As an example, LNoOfOps was consistently very good in % late orders such that it can be assumed that within reason, this rule would perform well if used for a system which aims to minimise tardiness.
9. The effect of scheduling environments on schedule performance and the mechanics of the scheduling rules in determining schedule performance have been successfully presented. For instance, it was observed that while an operation/resource flexibility environment may represent a flexible system, it does not guarantee good schedule performances and effects such as job splitting may be needed for optimum performance and to allow for a complete utilisation of the flexibility of the system.
10. An attempt has been made to reduce the number of partially worn-out tools and the experiments have successfully shown that this would involve more than just applying simple tool selection rules. It could involve re-designing tool requirements for each operation such that more of the same tool sets are used for

various operations while restricting the number of similar tools on the tool kit to a minimum. This would ensure that if tool cost is being used for instance, the same tool in a tool set for an operation continues to be selected for the operations until its tool life is lesser than the required operation time. The same would typically apply for most other tool selection rules if the tool parameter value is static. For a dynamic tool parameter such as tool life, since the tool had a minimum tool life and as such was used, then, it would always continue to have the minimum tool life. However, if a maximum value of this dynamic tool parameter were required, the argument would most certainly not be valid and a different approach may be required.

CHAPTER 11

FURTHER WORK

1. The generation of planning strategies that aim to reduce the overall manufacturing cost by considering penalty cost as a dynamic operational parameter could be addressed.

   If a job is late by D days and the cost of late jobs per day is G, then Penalty cost, PC would be GD. Further work could aim to reduce this value because what it really means is that although to do the job should cost the customer £ X, it will cost the manufacturer GD as a result of which he will eventually receive X-GD for his services. The scheduling problem could be modelled in such a way that the program knows by how long the jobs will be late and re-evaluates the penalty cost and based on this, re-schedules the jobs until a satisfactory schedule is obtained. Such an operational parameter does not consider only the due dates but also the cost of the job to the supplier and customer. More of such operational parameters could be considered in future work or study to ensure that the early jobs are just as urgent.

2. Further work could also look at more tool selection rules and look at the option of switching between tool kits if the required tool (resident on the tool kit of the machine being considered) for an operation has insufficient tool life. This current study assumed that there is always an applicable tool with sufficient tool life on the tool kit but this is not always so. There may be the need to bring in another tool from the tool store if the required tool cannot be found on another tool kit on the shop floor or if the required tool is busy.

   The generation of several other tool selection rules may show that tool utilisation rates may be very varied and combined with the tool switches allowed, there would most likely be differences in schedule performances as a result of using different operation scheduling rules.

3. The effect of using more AGV selection rules may be investigated. This research used the SPT rule which was directly related to the distance between where the AGV was and where it had to visit. It could be possible to program the system such that an AGV is used at least a certain number of times such that utilisation rate will not be unusually low for any of the AGVs, hence decreasing the average utilisation rate.

4. Cost and tool index were the only parameters that had to be evaluated in the current study. Therefore, it may be argued that their performance was biased since this research did not test other rankings but the first which it proposed. Therefore, future work in this area may look at varying the parameters that have been ranked to arrive at the final values of "cost of operation" and "tool index".

5. A demonstrative class of experiments involving dynamic scheduling of FMS was carried out in this study (Chapter 5). However, this could not be fully investigated primarily because of the difficulty of comparing the results fairly. No two scheduling conditions could be modelled exactly alike. This area has thus been suggested as a feasible area for further research work.

6. In view of the work that has been done in this reported research, Preactor can be developed to more easily handle the scheduling environments and the scheduling rules that have been developed.

The suggested Preactor development could involve:

I. The ability to select a main system objective (for example, minimising tardiness) that would force Preactor to select for use the appropriate scheduling rule (in this example case, the LNoOfOps rule).

II. The allowance for rules for one or more resources (such as tool selection rules) as well as operation sequencing rules.

III. The ability to compare schedule performances for more than a test bed (different number of resources, - primary and secondary, and product orders) on the same gantt chart to ensure that the other scheduling conditions are constant.

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APPENDIX 1

CA-Scheduler Agent supports cross-platform scheduling by initiating and tracking units of work - such as jobs, tasks, and processes - on non-mainframe platforms. CA-Scheduler Agent extends the power and flexibility of CA-Scheduler throughout the enterprise, while allowing job and schedule definitions and administration to remain centralized. CA-Scheduler Agent facilitates the administration, management, and realtime monitoring of CA-Scheduler workloads that are processed on distributed, heterogeneous platforms.

Operating Environment

CA90s Services 9712 or higher; IBM or Interlink TCP/IP; CA-Scheduler 7.4 or higher; Microsoft Windows NT (Intel) 4.0 SP3 or higher; HP-UX 10.2 or higher, or Sun Solaris 2.5 or higher, or AIX 4.2 or higher

Highlights:

- Simplifies the administration and monitoring of multiplatform workload scheduling
- Allows clients to use CA-Scheduler on OS/390 or MVS to manage workload scheduling across the enterprise
- Enables CA-Scheduler to function as a centralized scheduling hub for the enterprise
- Utilizes advanced Unicenter TNG event and communication facilities
- Provides a robust, remote scheduling agent environment
- Allows clients to leverage existing CA-Scheduler knowledge
- Extends the superior workload tracking functions of CA-Scheduler to non-mainframe platforms

CA-Scheduler Agent Release 1.0

Currently Availabile - General Availability Status

Major Features:

- **Centralized Workload Management**
  With CA-Scheduler Agent, CA-Scheduler on OS/390 or MVS remains the central workload manager which maintains all job/task and schedule information, and performs all scheduling and status monitoring functions. CA-Scheduler Agent automatically performs specific tasks on target platforms at the request of CA-Scheduler. This seamless integration allows CA-Scheduler functionality to be extended to non-mainframe platforms without requiring users to learn new panels or functions.

- **Remote Job/Task Initiation**
  CA-Scheduler is the repository for all information about jobs or tasks that execute on a target machine. At the scheduled time, when all predecessor requirements are met, CA-Scheduler requests initiation of the job or task (script, program, .bat file, etc.). The

CA-Scheduler Agent receives the initiation request and starts the job, task or process.

- **Job/Task Status Information**
  As work starts, executes, and ends on target platforms, the CA-Scheduler Agent collects this event information and sends it to CA-Scheduler on the mainframe. In this way, CA-Scheduler can monitor the status of tasks on target platforms.

- **CA-Scheduler Agent Messages**
  As the CA-Scheduler Agent processes requests and monitors jobs, it produces messages that are recorded in the Unicenter TNG Event Log. These messages are accessible using the Unicenter TNG Event Manager GUI on Windows NT.

APPENDIX 2: MANUFACTURING DATABASES USED IN PREACTOR

Products	Operation Names	Operation No.	Level	Key
Splined Shaft	Op1	10	1	1
	Op2	20	1	1
	Op3	30	1	1
	Op4	40	1	1
	Op5	50	1	1
Gearbox Mounting	Op1	10	1	1
	Op2	20	1	1
	Op3	30	1	1
	Op4	40	1	1
	Op5	50	1	1
	Op6	60	1	1
Axle Casing	Op1	10	1	1
	Op2	20	1	1
	Op3	30	1	1
Safety Cover 200	Op1_SubA	10	1	2
	Op2_SubA	20	1	2
	Op3_SubA	30	1	2
	Op1_SubB	10	1	4
	Op2_SubB	20	1	4
	Op3_SubB	30	1	4
	Op1_SubC	40	2	1
	Op2_SubC	50	2	1
	Op3_SubC	60	2	1
	Op4	40	2	3
	Op5	50	2	3
	Op6	60	2	3
	Op7	70	3	5
Safety Cover 300	Op1_SubA	10	2	2
	Op2_SubA	20	2	1
	Op3_SubA	30	2	1
	Op1_SubB	40	1	2
	Op2_SubB	50	1	2
	Op3_SubB	60	1	2
	Op1_SubC	40	1	4
	Op2_SubC	50	1	4
	Op3_SubC	60	1	4
	Op4	70	2	3
	Op5	80	2	3
	Op6	90	2	3
	Op7	100	3	5
Support Plate	Op1_SubA	10	1	1
	Op2_SubA	20	1	1
	Op3_SubA	30	1	1
	Op1_SubB	10	1	3
	Op2_SubB	20	1	3
	Op3_SubB	30	1	3
	Op4	40	2	2
	Op5	50	2	2

Table A2-1: Products Database

Products	Operation Names	Operation No.	Level	Key
Switch Box	Op1	10	1	2
	Op2	20	1	2
	Op3	30	2	1
	Op4	40	2	1
	Op5	50	2	1
	Op6	30	2	3
	Op7	40	2	3
	Op8	50	2	3
	Op9	60	3	2
	Op10	70	3	2
Torque Tube	Op1	10	1	1
	Op2	20	1	1
	Op3	30	1	1
	Op4	40	1	1
Flanged Bushing	Op1	10	1	1
	Op2	20	1	1
	Op3	30	1	1
	Op4	40	1	1

Table A2-1 (Contd.): Products Database

Products	Operation Names	Applicable Resource
Splined Shaft	Op1	M1
	Op2	M2
	Op3	M2
	Op4	M3
	Op5	M2
Gearbox Mounting	Op1	M2
	Op2	M3
	Op3	M1
	Op4	M1
	Op5	M1
	Op6	M1
Safety Cover 200	Op1_SubA	M1
	Op2_SubA	M2
	Op3_SubA	M3
	Op1_SubB	M1
	Op2_SubB	M2
	Op3_SubB	M3
	Op1_SubC	M2
	Op2_SubC	M2
	Op3_SubC	M3
	Op4	M3
	Op5	M3
	Op6	M3
	Op7	M3
Support Plate	Op1_SubA	M2
	Op2_SubA	M2
	Op3_SubA	M2
	Op1_SubB	M3
	Op2_SubB	M3
	Op3_SubB	M3
	Op4	M2
	Op5	M2
Switch Box	Op1	M1
	Op2	M1
	Op3	M2
	Op4	M3
	Op5	M2
	Op6	M1
	Op7	M3
	Op8	M3
	Op9	M3
	Op10	M2
Torque Tube	Op1	M2
	Op2	M1
	Op3	M1
	Op4	M1

Table A2-2: Products-Operations-Resource Information for a 3-Resource scenario

Products	Operation Names	Applicable Resource	Applicable Resource for SecRes (Order set 3)
Splined Shaft	Op1	M1	M1
	Op2	M2	M2
	Op3	M2	M2
	Op4	M3	M3
	Op5	M2	M2
Gearbox Mounting	Op1	M2	M2
	Op2	M3	M3
	Op3	M4	M5
	Op4	M4	M5
	Op5	M4	M4
	Op6	M4	M5
Safety Cover 200	Op1_SubA	M1	M1
	Op2_SubA	M2	M2
	Op3_SubA	M3	M3
	Op1_SubB	M4	M4
	Op2_SubB	M5	M5
	Op3_SubB	M4	M4
	Op1_SubC	M6	M6
	Op2_SubC	M6	M6
	Op3_SubC	M4	M4
	Op4	M4	M5
	Op5	M4	M5
	Op6	M4	M6
	Op7	M4	M6
Support Plate	Op1_SubA	M2	M2
	Op2_SubA	M2	M2
	Op3_SubA	M2	M2
	Op1_SubB	M3	M3
	Op2_SubB	M3	M3
	Op3_SubB	M3	M3
	Op4	M4	M4
	Op5	M4	M4
Switch Box	Op1	M5	M5
	Op2	M5	M5
	Op3	M6	M6
	Op4	M5	M5
	Op5	M6	M6
	Op6	M5	M5
	Op7	M3	M3
	Op8	M3	M3
	Op9	M3	M3
	Op10	M4	M4
Torque Tube	Op1	M2	M2
	Op2	M1	M1
	Op3	M1	M1
	Op4	M1	M1

Table A2-3: Products-Operations-Resource Information for a 6-Resource scenario

Products	Operation Names	Applicable Resource
Splined Shaft	Op1	M1
	Op2	M2
	Op3	M2
	Op4	M3
	Op5	M2
Gearbox Mounting	Op1	M2
	Op2	M3
	Op3	M4
	Op4	M4
	Op5	M4
	Op6	M4
Axle Casing	Op1	M7
	Op2	M8
	Op3	M6
Safety Cover 200	Op1_SubA	M1
	Op2_SubA	M2
	Op3_SubA	M3
	Op1_SubB	M4
	Op2_SubB	M5
	Op3_SubB	M4
	Op1_SubC	M6
	Op2_SubC	M6
	Op3_SubC	M4
	Op4	M4
	Op5	M4
	Op6	M4
	Op7	M4
Safety Cover 300	Op1_SubA	M2
	Op2_SubA	M4
	Op3_SubA	M8
	Op1_SubB	M8
	Op2_SubB	M7
	Op3_SubB	M2
	Op1_SubC	M8
	Op2_SubC	M3
	Op3_SubC	M7
	Op4	M8
	Op5	M5
	Op6	M6
	Op7	M4
Support Plate	Op1_SubA	M2
	Op2_SubA	M2
	Op3_SubA	M2
	Op1_SubB	M3
	Op2_SubB	M3
	Op3_SubB	M3
	Op4	M4
	Op5	M4

Table A2-4: Products-Operations-Resource Information for an 8-Resource scenario

Products	Operation Names	Applicable Resource
Switch Box	Op1	M5
	Op2	M5
	Op3	M6
	Op4	M5
	Op5	M6
	Op6	M5
	Op7	M3
	Op8	M6
	Op9	M6
	Op10	M4
Torque Tube	Op1	M2
	Op2	M1
	Op3	M1
	Op4	M1
Flanged Bushing	Op1	M8
	Op2	M3
	Op3	M7
	Op4	M8

Table A2-4 (Contd.): Products-Operations-Resource Information for an 8-Resource scenario

Products	Operation Names	Applicable Resource	Applicable Tools
Splined Shaft	Op1	M1	T101, 102, 103
	Op2	M2	T111, 112
	Op3	M2	T114, 116, 117
	Op4	M3	T121, 122, 123
	Op5	M2	T113, 115
Gearbox Mounting	Op1	M2	T113, 118
	Op2	M3	T124
	Op3	M4	T131, 132, 133
	Op4	M4	T134, 135, 136
	Op5	M4	T137, 138
	Op6	M4	T139, 140
Axle Casing	Op1	M7	T161, 162, 163
	Op2	M8	T171, 172, 173
	Op3	M6	T151, 152
Safety Cover 200	Op1_SubA	M1	T108, 109, 110
	Op2_SubA	M2	T115, 118, 119
	Op3_SubA	M3	T124, 125
	Op1_SubB	M4	T132, 133, 134
	Op2_SubB	M5	T144, 145
	Op3_SubB	M4	T138, 139
	Op1_SubC	M6	T158, 159
	Op2_SubC	M6	T160
	Op3_SubC	M4	T136, 137
	Op4	M4	T133, 134
	Op5	M4	T131, 132, 133
	Op6	M4	T134, 135
	Op7	M4	T136, 137, 138
Safety Cover 300	Op1_SubA	M2	T111, 112, 114
	Op2_SubA	M4	T139, 140
	Op3_SubA	M8	T171, 172, 173
	Op1_SubB	M8	T174, 175, 176
	Op2_SubB	M7	T163, 164, 165
	Op3_SubB	M2	T112, 113, 114
	Op1_SubC	M8	T177, 178, 180
	Op2_SubC	M3	T123, 124, 125
	Op3_SubC	M7	T164, 167, 168
	Op4	M8	T171, 174
	Op5	M5	T141, 142
	Op6	M6	T154
	Op7	M4	T135
Support Plate	Op1_SubA	M2	T119, 120
	Op2_SubA	M2	T114
	Op3_SubA	M2	T116
	Op1_SubB	M3	T126, 127, 128
	Op2_SubB	M3	T129, 130
	Op3_SubB	M3	T125, 128
	Op4	M4	T133
	Op5	M4	T133, 134

Table A2-5: Products-Operations-Tools-Resource Information for a 6/8-Resource scenario

Products	Operation Names	Applicable Resource	Applicable Tools
Switch Box	Op1	M5	T141, 142
	Op2	M5	T143, 144
	Op3	M6	T153, 154
	Op4	M5	T146, 147, 148
	Op5	M6	T155, 156, 157
	Op6	M5	T148, 149, 150
	Op7	M3	T122
	Op8	M6	T154, 157
	Op9	M6	T155, 160
	Op10	M4	T136, 139, 140
Torque Tube	Op1	M2	T113, 114, 115
	Op2	M1	T106, 107
	Op3	M1	T108, 109, 110
	Op4	M1	T104, 105
Flanged Bushing	Op1	M8	T177, 180
	Op2	M3	T127, 128
	Op3	M7	T167, 169, 170
	Op4	M8	T171, 179

Table A2-5 (Contd.): Products-Operations-Tools-Resource Information for a 6/8-Resource scenario

Products	Operation Names	Applicable Resource	Applicable Tools
Splined Shaft	Op1	M1	T101, 102, 103
	Op2	M2	T111, 112
	Op3	M2	T114, 116, 117
	Op4	M3	T121, 122, 123
	Op5	M2	T113, 115
Gearbox Mounting	Op1	M2	T113, 118
	Op2	M3	T124
	Op3	M1	T102, 103, 109
	Op4	M1	T107, 108, 109
	Op5	M1	T101, 110
	Op6	M1	T102, 103
Safety Cover 200	Op1_SubA	M1	T108, 109, 110
	Op2_SubA	M2	T115, 118, 119
	Op3_SubA	M3	T124, 125
	Op1_SubB	M1	T103, 104, 105
	Op2_SubB	M2	T114, 115
	Op3_SubB	M3	T128, 129
	Op1_SubC	M2	T118, 119
	Op2_SubC	M2	T120
	Op3_SubC	M3	T126, 127
	Op4	M3	T123, 124
	Op5	M3	T121, 122, 123
	Op6	M3	T124, 125
	Op7	M3	T126, 127, 128
Support Plate	Op1_SubA	M2	T119, 120
	Op2_SubA	M2	T114
	Op3_SubA	M2	T116
	Op1_SubB	M3	T126, 127, 128
	Op2_SubB	M3	T129, 130
	Op3_SubB	M3	T125, 128
	Op4	M2	T114
	Op5	M2	T113, 114
Switch Box	Op1	M1	T105, 106
	Op2	M1	T105, 108
	Op3	M2	T113, 114
	Op4	M3	T146, 147, 148
	Op5	M2	T126, 127, 130
	Op6	M1	T115, 116, 117
	Op7	M3	T122
	Op8	M3	T124, 127
	Op9	M3	T125, 130
	Op10	M2	T116, 119, 120
Torque Tube	Op1	M2	T113, 114, 115
	Op2	M1	T106, 107
	Op3	M1	T108, 109, 110
	Op4	M1	T104, 105

Table A2-6: Products-Operations-Tools-Resource Information for a 3-Resource scenario

Products	Operation Names	Applicable Route	Applicable Setup Groups
Splined Shaft	Op1	Standard, Alternate	F1
	Op2	All	F1
	Op3	All	F1
	Op4	All	F2
	Op5	All	F1
Gearbox Mounting	Op1	Standard, Alternate	F1
	Op2	Standard	F1
	Op3	All	F1
	Op4	Alternate	F2
	Op5	All	F3
	Op6	All	F3
Axle Casing	Op1	Standard, Alternate	F1
	Op2	All	F1
	Op3	All	F1
Safety Cover 200	Op1_SubA	Standard, Alternate	F1
	Op2_SubA	All	F2
	Op3_SubA	Standard	F3
	Op1_SubB	All	F2
	Op2_SubB	Standard	F3
	Op3_SubB	All	F5
	Op1_SubC	Alternate	F3
	Op2_SubC	All	F1
	Op3_SubC	Alternate	F3
	Op4	All	F5
	Op5	Standard	F3
	Op6	Standard	F3
	Op7	All	F5
Safety Cover 300	Op1_SubA	Standard, Alternate	F1
	Op2_SubA	All	F2
	Op3_SubA	Standard	F3
	Op1_SubB	All	F2
	Op2_SubB	Standard	F3
	Op3_SubB	All	F5
	Op1_SubC	Alternate	F3
	Op2_SubC	All	F1
	Op3_SubC	Alternate	F3
	Op4	All	F5
	Op5	Standard	F3
	Op6	Standard	F3
	Op7	All	F5
Support Plate	Op1_SubA	Standard, Alternate	F3
	Op2_SubA	All	F3
	Op3_SubA	Standard	F4
	Op1_SubB	Alternate	F3
	Op2_SubB	All	F3
	Op3_SubB	Standard	F4
	Op4	All	F5
	Op5	All	F5

Table A2-7: Products-Route-Setup Group Information

Products	Operation Names	Applicable Route	Applicable Setup Groups
Switch Box	Op1	Standard, Alternate	F1
	Op2	Standard	F1
	Op3	All	F1
	Op4	All	F3
	Op5	All	F3
	Op6	Standard	F3
	Op7	All	F3
	Op8	Standard	F3
	Op9	All	F3
	Op10	All	F4
Torque Tube	Op1	Standard	F1
	Op2	All	F1
	Op3	All	F1
	Op4	All	F1

Table A2-7 (Contd.): Products-Route-Setup Group Information

Setup Times/Setup Groups	FI	F2	F3	F4	F5
F1	0	15	10	10	20
F2	15	0	15	15	15
F3	10	10	0	5	15
F4	10	10	5	0	15
F5	20	15	15	10	0

Table A2-8: Setup Group related setup times

Products	Operation Names	Operation Time (Minutes)	Secondary Resources	
			Fixtures	Others
Splined Shaft	Op1	15	4	
	Op2	5		
	Op3	10		
	Op4	5		Operators
	Op5	12		Operators
Gearbox Mounting	Op1	4	3	
	Op2	9		
	Op3	12		Operators
	Op4	6		Operators
	Op5	12		Operators
	Op6	20		
Axle Casing	Op1	5	3	
	Op2	5		
	Op3	6		Operators
Safety Cover 200	Op1_SubA	5	5	Operators
	Op2_SubA	6		
	Op3_SubA	5		
	Op1_SubB	10		Operators
	Op2_SubB	10		
	Op3_SubB	6		Operators
	Op1_SubC	6		
	Op2_SubC	12		Operators
	Op3_SubC	10		
	Op4	12		Supervisor
	Op5	10		Supervisor
	Op6	15		Supervisor
	Op7	15		Supervisor
Safety Cover 300	Op1_SubA	5	5	
	Op2_SubA	5		Operators
	Op3_SubA	5		Operators
	Op1_SubB	10		Operators
	Op2_SubB	10		
	Op3_SubB	6		Operators
	Op1_SubC	6		
	Op2_SubC	12		Operators
	Op3_SubC	12		
	Op4	10		Operators
	Op5	15		Supervisor
	Op6	15		Supervisor
	Op7	15		Supervisor
Support Plate	Op1_SubA	8	3	
	Op2_SubA	7		Operators
	Op3_SubA	8		
	Op1_SubB	9		
	Op2_SubB	5		Operators
	Op3_SubB	6		
	Op4	24		Supervisor
	Op5	12		Supervisor

Table A2-9: Products-Operations-Operation Times-Secondary Resource Information

Products	Operation Names	Operation Time	Applicable Setup Groups	
Switch Box	Op1	10	4	
	Op2	10		Operators
	Op3	6		Operators
	Op4	10		
	Op5	9		Operators
	Op6	8		Operators
	Op7	5		Operators
	Op8	10		
	Op9	10		Supervisor
	Op10	12		Supervisor
Torque Tube	Op1	10	4	
	Op2	5		Operators
	Op3	20		Operators
	Op4	12		Operators
Flanged Bushing	Op1	8	4	
	Op2	6		
	Op3	6		Operators
	Op4	10		Operators

Table A2-9 (Contd.): Products-Operations-Operation Times-Secondary Resource Information

To consider the tool changes necessary before some operations can be done, and to give preference to some products that have few operations left, the parameter Tool Index (TI) has been defined to encompass both. TI has been taken as PI*PF where an operation requiring tool change has a PI = 2 and that no requiring tool change has a PI = 4. Tool change is assumed if a different tool kit is used for a following operation.

Products	Operation Names	PF	PI	Tool Index
Splined Shaft	Op1	0.2	0	0
	Op2	0.4	2	0.8
	Op3	0.6	4	2.4
	Op4	0.8	2	1.6
	Op5	1	2	2
Gearbox Mounting	Op1	0.17	0	0
	Op2	0.33	2	0.66
	Op3	0.5	2	1
	Op4	0.67	4	2.68
	Op5	0.83	4	3.32
	Op6	1	4	4
Axle Casing	Op1	0.33	0	0
	Op2	0.66	2	1.32
	Op3	1	2	2
Safety Cover 200	Op1_SubA	0.077	0	0
	Op2_SubA	0.154	2	0.308
	Op3_SubA	0.231	2	0.462
	Op1_SubB	0.308	2	0.616
	Op2_SubB	0.385	2	0.77
	Op3_SubB	0.462	2	0.924
	Op1_SubC	0.538	2	1.076
	Op2_SubC	0.615	4	2.46
	Op3_SubC	0.692	2	1.384
	Op4	0.769	4	3.076
	Op5	0.846	4	3.384
	Op6	0.923	4	3.692
	Op7	1	4	4
Safety Cover 300	Op1_SubA	0.077	0	0
	Op2_SubA	0.154	2	0.308
	Op3_SubA	0.231	2	0.462
	Op1_SubB	0.308	4	1.232
	Op2_SubB	0.385	2	0.77
	Op3_SubB	0.462	2	0.924
	Op1_SubC	0.538	2	1.076
	Op2_SubC	0.615	2	1.23
	Op3_SubC	0.692	2	1.384
	Op4	0.769	2	1.538
	Op5	0.846	2	1.692
	Op6	0.923	2	1.846
	Op7	1	2	2
Support Plate	Op1_SubA	0.125	0	0
	Op2_SubA	0.25	4	1
	Op3_SubA	0.375	4	1.5
	Op1_SubB	0.5	2	1
	Op2_SubB	0.625	4	2.5
	Op3_SubB	0.75	4	3
	Op4	0.875	2	1.75
	Op5	1	4	4

Table A2-10: Products-Operation-Tool Index Information

Products	Operation Names	PF	PI	Tool Index
Switch Box	Op1	0.1	0	0
	Op2	0.2	4	0.8
	Op3	0.3	2	0.6
	Op4	0.4	2	0.8
	Op5	0.5	2	1
	Op6	0.6	2	1.2
	Op7	0.7	2	1.4
	Op8	0.8	2	1.6
	Op9	0.9	4	3.6
	Op10	1	2	2
Torque Tube	Op1	0.25	0	0
	Op2	0.5	4	2
	Op3	0.75	4	3
	Op4	1	4	4
Flanged Bushing	Op1	0.25	0	0
	Op2	0.5	2	1
	Op3	0.75	2	1.5
	Op4	1	2	2

Table A2-10 (Contd.): Products-Operation-Tool Index Information

Tool Kits	Resources	Tools
TK1	M1	T101-110
TK2	M2	T111-120
TK3	M3	T121-130
TK4	M4	T131-140
TK5	M5	T141-150
TK6	M6	T151-160
TK7	M7	T161-170
TK8	M8	T171-180

Table A2-11: Tool Information (1) for the resource scenarios

Tools	Tool Life (Mins.)	Tool Cost (£)	Tool Flexibility (%)
T101	640	140	6.52
T102	600	140	8.7
T103	500	180	8.7
T104	520	210	4.35
T105	580	180	8.7
T106	400	200	4.35
T107	800	150	4.35
T108	450	180	8.7
T109	600	180	10.87
T110	530	160	6.52
T111	450	190	2.17
T112	800	190	2.17
T113	850	140	10.87
T114	600	150	15.22
T115	680	130	10.87
T116	800	180	8.7
T117	830	200	4.35
T118	850	210	6.52
T119	950	200	8.7
T120	980	180	6.52
T121	400	160	4.35
T122	600	170	6.52
T123	680	220	6.52
T124	860	120	10.87
T125	450	60	8.7
T126	480	100	8.7
T127	680	110	10.87
T128	860	130	8.7
T129	680	100	4.35
T130	800	120	6.52

Table A2-12: Tool Information (2) for the 3 Resource scenario

Tools	Tool Life (Mins.)	Tool Cost (£)	Tool Flexibility (%)
T101	640	140	1.52
T102	600	140	1.52
T103	500	180	1.52
T104	520	210	3.04
T105	580	180	3.04
T106	400	200	1.52
T107	800	150	1.52
T108	450	180	3.04
T109	600	180	3.04
T110	530	160	3.04
T111	450	190	3.04
T112	800	190	3.04
T113	850	140	4.55
T114	600	150	6.08
T115	680	130	3.04
T116	800	180	3.04
T117	830	200	4.35
T118	850	210	6.52
T119	950	200	8.7
T120	980	180	1.52
T121	400	160	1.52
T122	600	170	3.04
T123	680	220	3.04
T124	860	120	4.55
T125	450	60	4.55
T126	480	100	1.52
T127	680	110	3.04
T128	860	130	4.55
T129	680	100	1.52
T130	800	120	1.52
T131	640	140	3.04
T132	600	140	4.55
T133	500	180	9.1
T134	520	210	7.6
T135	580	180	4.55
T136	400	200	6.08
T137	800	150	4.55
T138	450	180	4.55
T139	600	180	6.08
T140	530	160	4.55
T141	450	190	3.04
T142	800	190	3.04
T143	850	140	1.52
T144	600	150	3.04
T145	680	130	1.52

Table A2-13: Tool Information (3) for the 6/8 Resource scenario

Tools	Tool Life (Mins.)	Tool Cost (£)	Tool Flexibility (%)
T146	800	180	1.52
T147	830	200	1.52
T148	850	210	3.04
T149	950	200	1.52
T150	980	180	1.52
T151	400	160	1.52
T152	600	170	1.52
T153	680	220	1.52
T154	860	120	4.55
T155	450	60	3.04
T156	480	100	1.52
T157	680	110	3.04
T158	860	130	1.52
T159	680	100	1.52
T160	800	120	3.04
T161	640	140	1.52
T162	600	140	1.52
T163	500	180	3.04
T164	520	210	3.04
T165	580	180	1.52
T166	400	200	0
T167	800	150	3.04
T168	450	180	1.52
T169	600	180	1.52
T170	530	160	3.04
T171	450	190	6.08
T172	800	190	3.04
T173	850	140	3.04
T174	600	150	3.04
T175	680	130	1.52
T176	800	180	1.52
T177	830	200	3.04
T178	850	210	1.52
T179	950	200	1.52
T180	980	180	3.04

Table A2-13 (Contd.): Tool Information (3) for the 6/8 Resource scenario

For the case study order set, 10 hours was added to the tool life of each of the tools.

Transportation Times	M1	M2	M3	M4	M5	M6	M7	M8
M1	0	6	8	8	4	3	10	5
M2	6	0	10	8	3	5	8	2
M3	8	10	0	2	8	6	3	7
M4	8	8	2	0	3	9	4	5
M5	4	3	8	3	0	5	8	3
M6	3	5	6	9	5	0	7	8
M7	10	8	3	4	8	7	0	10
M8	5	2	7	5	3	8	10	0

Table A2-14: Transportation Times

Products	Operation Names	Applicable Resource		
		3-Resource	6-Resource	8-Resource
Splined Shaft	Op1	M1,2	M1, 4, 6	M1, 2, 3
	Op2	M2	M2	M2
	Op3	M2	M2, 3	M2, 3
	Op4	M3	M3	M3
	Op5	M1, 2, 3	M1-6	M1-8
Gearbox Mounting	Op1	M1, 2, 3	M1-6	M1-8
	Op2	M3	M3	M3
	Op3	M1, 2, 3	M1-6	M1-8
	Op4	M1, 2	M5, 6	M5-8
	Op5	M1, 2, 3	M2, 3, 5	M2, 6, 8
	Op6	M1, 2, 3	M1-6	M1-8
Safety Cover 200	Op1_SubA	M1, 2, 3	M1-4	M1-4
	Op2_SubA	M2	M2	M2
	Op3_SubA	M2, 3	M3, 4	M3, 4
	Op1_SubB	M1	M4	M4
	Op2_SubB	M2, 3	M1, 3, 5, 6	M2, 4, 6, 8
	Op3_SubB	M2, 3	M5, 6	M7, 8
	Op1_SubC	M1, 2, 3	M2, 3, 4, 6	M5-8
	Op2_SubC	M3	M1-6	M1-8
	Op3_SubC	M2, 3	M4	M7, 8
	Op4	M1, 2, 3	M4, 5, 6	M4, 5, 6
	Op5	M2, 3	M1, 3, 5, 6	M1,4, 5, 7+J491
	Op6	M1, 2, 3	M1-6	M1-8
	Op7	M3	M4	M8
Support Plate	Op1_SubA	M1, 2, 3	M2-6	M2, 3, 5, 6, 8
	Op2_SubA	M2, 3	M1-6	M2, 3, 5, 6, 7, 8
	Op3_SubA	M2	M2	M8
	Op1_SubB	M1, 2	M1-4	M1, 3, 5, 6
	Op2_SubB	M1, 2, 3	M1-6	M1, 3, 5, 6, 7, 8
	Op3_SubB	M3	M3	M3
	Op4	M1, 2, 3	M4, 5, 6	M4, 7, 8
	Op5	M2	M4	M7
Switch Box	Op1	M1, 2, 3	M1-6	M1, 3, 4, 5, 6, 7, 8
	Op2	M1, 2	M2, 3, 5, 6	M1, 3, 5, 7
	Op3	M1, 2, 3	M1-6	M1-8
	Op4	M3	M5	M5
	Op5	M2	M6	M7
	Op6	M1	M5	M8
	Op7	M2, 3	M1-6	M1-5
	Op8	M2, 3	M1-6	M1-8
	Op9	M3	M3	M6
	Op10	M2	M4	M7, 8
Torque Tube	Op1	M1, 2, 3	M2, 3, 6	M2, 3, 5, 6
	Op2	M1, 2, 3	M1, 2, 3, 5, 6	M1-8
	Op3	M1, 2, 3	M1-4	M1-8
	Op4	M1	M1	M7, 8

Table A2-15: Operation/Resource Flexibility Information for all resource scenarios

Products	Operation Names	Material Cost	Labour Cost	S	P
Splined Shaft	Op1	13.33	0	0.2	0.5
	Op2	16.66	0	0.5	0.5
	Op3	16.66	0	0.5	0.5
	Op4	10	5	0.2	0.5
	Op5	26.66	5	0.8	0.75
Gearbox Mounting	Op1	15	0	0.6	0.75
	Op2	12.5	0	0.5	0.5
	Op3	20	5	0.8	0.75
	Op4	7.5	5	0.2	0.5
	Op5	7.5	5	0.2	0.75
	Op6	7.5	0	0.1	0.25
Axle Casing	Op1	12.5	0	0.2	0.5
	Op2	12.5	0	0.2	0.5
	Op3	25	5	0.6	0.75
Safety Cover 200	Op1_SubA	10	5	0.6	0.75
	Op2_SubA	5	0	0.3	0.5
	Op3_SubA	5	0	0.2	0.5
	Op1_SubB	5	5	0.3	0.5
	Op2_SubB	5	0	0.2	0.5
	Op3_SubB	13.33	5	0.7	0.75
	Op1_SubC	5	0	0.4	0.5
	Op2_SubC	10	5	0.6	0.75
	Op3_SubC	5	0	0.2	0.5
	Op4	13.33	20	0.7	0.75
	Op5	5	20	0.2	0.75
	Op6	5	20	0.2	0.25
	Op7	13.33	20	0.7	0.75
Safety Cover 300	Op1_SubA	3.75	0	0.4	0.5
	Op2_SubA	7.5	5	0.6	0.75
	Op3_SubA	3.75	5	0.2	0.5
	Op1_SubB	7.5	5	0.6	0.75
	Op2_SubB	3.75	0	0.3	0.5
	Op3_SubB	3.75	5	0.2	0.5
	Op1_SubC	3.75	0	0.3	0.5
	Op2_SubC	3.75	5	0.2	0.5
	Op3_SubC	10	0	0.7	0.75
	Op4	10	5	0.7	0.75
	Op5	3.75	20	0.2	0.5
	Op6	3.75	20	0.2	0.25
	Op7	10	20	0.7	0.25
Support Plate	Op1_SubA	6	0	0.4	0.5
	Op2_SubA	12	5	0.6	0.75
	Op3_SubA	6	0	0.2	0.5
	Op1_SubB	6	0	0.4	0.5
	Op2_SubB	12	5	0.6	0.75
	Op3_SubB	6	0	0.2	0.5
	Op4	16	20	0.7	0.75
	Op5	6	20	0.2	0.5

Table A2-16: Calculation towards the cost of operation

Products	Operation Names	Material Cost	Labour Cost	S	P
Switch Box	Op1	3.75	0	0.4	0.75
	Op2	3.75	5	0.8	0.75
	Op3	7.5	5	0.6	0.75
	Op4	3.75	0	0.3	0.75
	Op5	3.75	5	0.3	0.75
	Op6	3.75	5	0.3	0.5
	Op7	7.5	5	0.6	0.75
	Op8	3.75	0	0.4	0.75
	Op9	3.75	20	0.3	0.75
	Op10	3.75	20	0.2	0.5
Torque Tube	Op1	10	0	0.4	0.5
	Op2	20	5	0.6	0.75
	Op3	26.66	5	0.8	0.75
	Op4	10	5	0.2	0.5

Table A2-16 (Contd.): Calculation towards the cost of operation

Most operation parameters have been defined in these tables taking into consideration cost of operation and assembling operations. Cost of operation is defined in terms of S, P, material and labour cost and TC. The S value is higher for operations requiring greater precision, and the P values, for operations requiring more secondary resources. Labour cost is dependent on whether or not the operations require operators and/or supervisors and material cost is dependent on tooling cost. The latter is assumed to be constant and equal to 10 for all transportation operations while the values of S and P are constant as 0 and 0.2 respectively. TC is the addition of labour and material cost and C, the addition of S and P.

Material cost constitutes the tooling cost and labour, the rate for supervisor or operator or both. Supervisor rate is £20 and operator, £5.

Tooling cost = TC/Qty

TC Drills, £300: TC Mills, £250: TC Grinds, £400

TC Rough Turns, £200: TC Assemblies, £400: TC others, £150

Cost of operation, C_o = C* Total Cost

C = S*P

Total Cost, TC = Labour cost + Tooling cost

S:

Operations prior to assembly, 7 to 10

Operations requiring finer grinding, 7 to 10

Operations requiring rough turning, 1 to 3

P:

Operations requiring tool change, 7 to 10

Operations requiring secondary resources in addition to Machines or AGVs, 7 to 10

Operations requiring only AGV or machine, 3

Operations requiring longer times, 7 to 10

Products	Operation Names	TC	C	Cost of Operation (£)
Splined Shaft	Op1	13.33	0.7	9.33
	Op2	16.66	1	16.66
	Op3	16.66	1	16.66
	Op4	15	0.7	10.50
	Op5	31.66	1.55	49.07
Gearbox Mounting	Op1	20	1.35	27.00
	Op2	12.5	1	12.50
	Op3	25	1.55	38.75
	Op4	12.5	0.7	8.75
	Op5	12.5	0.95	11.86
	Op6	7.5	0.35	2.63
Axle Casing	Op1	12.5	0.7	8.75
	Op2	12.5	0.7	8.75
	Op3	30	1.35	40.50
Safety Cover 200	Op1_SubA	15	1.35	20.25
	Op2_SubA	10	0.8	8.00
	Op3_SubA	5	0.7	3.50
	Op1_SubB	10	0.8	8.00
	Op2_SubB	5	0.7	3.50
	Op3_SubB	18.33	1.45	26.58
	Op1_SubC	5	0.9	4.50
	Op2_SubC	15	1.35	20.25
	Op3_SubC	5	0.7	3.50
	Op4	33.33	1.45	48.33
	Op5	10	0.95	9.50
	Op6	5	0.45	2.25
	Op7	33.33	1.45	48.33
Safety Cover 300	Op1_SubA	3.75	0.9	3.38
	Op2_SubA	12.5	1.35	16.88
	Op3_SubA	3.75	0.7	2.63
	Op1_SubB	12.5	1.35	16.88
	Op2_SubB	8.75	0.8	7.00
	Op3_SubB	3.75	0.7	2.63
	Op1_SubC	8.75	0.8	7.00
	Op2_SubC	3.75	0.7	2.63
	Op3_SubC	15	1.45	21.75
	Op4	15	1.45	21.75
	Op5	3.75	0.7	2.63
	Op6	3.75	0.45	1.69
	Op7	30	1.45	43.50
Support Plate	Op1_SubA	6	0.9	5.40
	Op2_SubA	10	1.35	13.50
	Op3_SubA	17	0.7	11.90
	Op1_SubB	6	0.9	5.40
	Op2_SubB	17	1.35	22.95
	Op3_SubB	6	0.7	4.20
	Op4	36	1.45	52.20
	Op5	6	0.2	1.20

Table A2-17: Calculation of cost of operation

Products	Operation Names	TC	C	Cost of Operation
Switch Box	Op1	8.75	1.15	10.06
	Op2	8.75	1.55	13.56
	Op3	12.5	1.35	16.88
	Op4	8.75	1.05	9.19
	Op5	8.75	1.05	9.19
	Op6	8.75	0.8	7.00
	Op7	12.5	1.35	16.88
	Op8	8.75	1.15	10.06
	Op9	23.75	1.05	24.94
	Op10	3.75	0.7	2.63
Torque Tube	Op1	10	0.9	9.00
	Op2	25	1.35	33.75
	Op3	31.66	1.55	49.07
	Op4	10	0.7	7.00

Table A2-17 (Contd.): Calculation of cost of operation

APPENDIX 3: THE SCHEDULING RESULTS

This appendix presents the results of the schedules generated.

3 Resources, INSF	Scheduling Rules						
Schedule Performance	Earliest Due Date/FCFS	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
Total Lead Time	10D 23:28	14D 7:10	12D 21:10	14D 13:43	12D 11:31	15D 4:04	15D 10:13
Minimum Added Value	27.29	23.44	30.78	31.69	35.89	16.59	28.06
Average Added Value	42.02	43.27	45.6	47.05	50.91	40.66	45.47
Maximum Added Value	99.63	53.75	84	75.15	63.66	86.32	55.35
Resource Min. Working %	63.81	89.76	74.19	78.78	92.06	66.22	84.82
Resource Avg. Working %	64.32	90.49	74.79	79.42	92.81	66.75	85.5
Resource Max. Working %	65.19	91.71	75.81	80.5	94.07	67.65	86.66
Resource Min. Utils %	67.09	93.63	77.73	82.79	96.14	69.02	89.47
Resource Avg. Utils %	67.63	94.39	78.36	83.46	96.92	69.58	90.2
Resource Max. Utils %	68.55	95.67	79.42	84.59	98.23	70.52	91.42
Resource Min. Idle %	29.54	3.63	19.2	14.21	1.15	27.89	7.64
Resource Avg. Idle %	30.37	4.81	20.18	15.24	2.36	28.76	8.75
Resource Max. Idle %	30.99	5.67	20.89	16	3.25	29.4	9.57
Schedule Duration	4D 6:08	3D 0:36	3D 15:50	3D 10:43	2D 22:47	4D 2:25	3D 4:50
Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	
Total Lead Time	11D 15:45	11D 6:23	14D 9:02	11D 1:25	13D 9:54	12D 12:13	
Minimum Added Value	39.82	27.58	23.78	27.15	21.07	30.84	
Average Added Value	50.88	44.15	42.7	44.4	39.52	49.69	
Maximum Added Value	90.04	97.11	58.44	97.11	75.15	64.1	
Resource Min. Working %	56.96	55.75	77.3	55.75	64.16	86.91	
Resource Avg. Working %	57.43	56.2	77.93	56.2	64.68	87.61	
Resource Max. Working %	58.2	56.96	78.98	56.96	65.56	88.8	
Resource Min. Utils %	59.57	58.24	81.15	58.24	67.48	90.53	
Resource Avg. Utils %	60.05	58.71	81.81	58.71	68.03	91.26	
Resource Max. Utils %	60.86	59.5	82.92	59.5	68.95	92.5	
Resource Min. Idle %	37.09	38.44	15.82	38.44	29.4	6.69	
Resource Avg. Idle %	37.84	39.17	16.83	39.17	29.99	7.83	
Resource Max. Idle %	38.39	39.71	17.58	39.71	30.6	8.67	
Schedule Duration	4D 18:24	4D 20:54	3D 12.18	4D 20:54	4D 5:34	3D 2:59	

Table A3-1

6 Resources, INSF	Scheduling Rules						
Schedule Performance	Earliest Due Date/FCFS	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
Total Lead Time	12D 13:38	16D 1:37	14D 9:07	14D 17:52	13D 21:44	12D 5:53	16D 12:52
Minimum Added Value	31	35.64	35.29	31.63	32.93	35.24	32.56
Average Added Value	48.83	44.43	46.13	47.18	47.86	55.91	43.58
Maximum Added Value	99.63	68.15	84	90.04	66.63	90.04	68.15
Resource Min. Working %	0	0	0	0	0	0	0
Resource Avg. Working %	26.96	26.48	25.35	26.75	24.48	26.38	26.16
Resource Max. Working %	89.73	88.14	84.36	89.03	81.47	87.81	87.06
Resource Min. Utils %	0	0	0	0	0	0	0
Resource Avg. Utils %	28.19	27.67	26.43	27.96	25.76	27.56	27.32
Resource Max. Utils %	93.84	92.1	87.98	93.08	85.73	91.74	90.93
Resource Min. Idle %	5.54	7.22	11.2	6.28	12.25	7.57	8.35
Resource Avg. Idle %	68.49	68.92	70.38	68.74	70.28	69.17	69.43
Resource Max. Idle %	95.62	95.7	95.88	95.06	95.03	95.72	95.75
Schedule Duration	3D 19:23	3D 21:02	4D 1:12	3D 20:06	4D 4:39	3D 21:23	3D 22:11

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
Total Lead Time	12D 6:19	13D 10:37	15D 20:11	12D 23:16	12D 3:36	13D 3:32
Minimum Added Value	34.86	35.5	35.64	38.18	35.38	33.79
Average Added Value	57.06	50.18	44.72	52.62	54.12	52.54
Maximum Added Value	94.19	97.11	62.14	97.11	77.4	87.14
Resource Min. Working %	0	0	0	0	0	0
Resource Avg. Working %	26.11	23.28	26.48	23.86	26.48	26.48
Resource Max. Working %	86.9	77.5	88.14	79.41	88.14	88.14
Resource Min. Utils %	0	0	0	0	0	0
Resource Avg. Utils %	27.26	24.44	27.67	25.07	27.67	27.67
Resource Max. Utils %	90.74	81.35	92.1	83.45	92.1	92.1
Resource Min. Idle %	8.53	17.47	7.22	15.45	6.14	7.22
Resource Avg. Idle %	69.49	71.84	69.05	71.15	68.92	69.05
Resource Max. Idle %	95.76	95.27	95.7	95.16	95.7	95.7
Schedule Duration	3D 22:22	4D 9:48	3D 21:02	4D 7:16	3D 21:02	3D 21:02

Table A3-2

8 Resources, INSF	Scheduling Rules						
Schedule Performance	Earliest Due Date/FCFS	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
Total Lead Time	17D 5:43	19D 23:58	16D 13:10	20D 5:19	19D 1:55	16D 17:23	20D 14:37
Minimum Added Value	31	31.08	36.22	32.7	31.31	34.59	29.95
Average Added Value	46.35	47.36	50.63	45.92	48.77	51.62	46.46
Maximum Added Value	99.63	75.1	78.47	90.04	81.34	94.12	72
Resource Min. Working %	0	0	0	0	0	0	0
Resource Avg. Working %	25.26	26.54	24.57	25.08	24	24.76	25.18
Resource Max. Working %	86.71	91.12	84.34	86.1	82.39	85.02	86.44
Resource Min. Utils %	0	0	0	0	0	0	0
Resource Avg. Utils %	26.58	27.7	25.82	26.38	25.19	26.04	26.49
Resource Max. Utils %	91.26	95.1	88.64	90.58	86.48	89.38	90.96
Resource Min. Idle %	8.04	4.42	10.55	8.69	12.63	9.84	8.33
Resource Avg. Idle %	69.65	69.15	70.48	69.86	71.16	70.24	69.74
Resource Max. Idle %	95.02	95.81	95.15	95.05	95.27	95.11	95.03
Schedule Duration	4D 4:20	3D 23:29	4D 7:09	4D 5:03	4D 9:36	4D 6:20	4D 4:39

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
Total Lead Time	17D 16:41	17D 13:55	19D 17:43	17D 9:34	16D 11:27	17D 8:29
Minimum Added Value	36.42	30.06	31.08	29.58	34.43	31.06
Average Added Value	50.61	47.41	47.99	46.9	54.6	54.45
Maximum Added Value	90.04	94.12	78.37	94.12	78.37	79.75
Resource Min. Working %	0	0	0	0	0	0
Resource Avg. Working %	23.4	22.7	26.54	23.13	26.54	25.7
Resource Max. Working %	80.34	77.95	91.12	79.42	91.12	88.24
Resource Min. Utils %	0	0	0	0	0	0
Resource Avg. Utils %	24.54	23.77	27.7	24.24	27.7	26.79
Resource Max. Utils %	84.23	81.6	95.1	83.21	95.1	91.97
Resource Min. Idle %	14.79	17.34	4.42	15.78	4.42	7.44
Resource Avg. Idle %	71.88	72.72	69.15	72.2	69.15	70.04
Resource Max. Idle %	95.38	95.52	95.81	95.44	95.81	95.94
Schedule Duration	4D 12:17	4D 15:37	3D 23:29	4D 13:33	3D 23:29	4D 2:36

Table A3-3

3 Resources, 2NSF	Scheduling Rules						
Schedule Performance	Earliest Due Date/FCFS	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
Total Lead Time	12D 21:18	14D 1:21	13D 3:38	14D 19:10	13D 3:29	14D 5:54	15D 10:06
Minimum Added Value	27.29	24.18	30.84	32.22	34.83	17.79	28.54
Average Added Value	41.52	43.2	45.91	47.3	50.16	43.51	43.81
Maximum Added Value	99.43	54.04	85.43	75.67	64.1	80.66	55.26
Resource Min. Working %	1.89	2.77	2.22	2.35	2.75	2.08	2.46
Resource Avg. Working %	47.51	69.7	56.56	59.96	70.18	53.19	61.75
Resource Max. Working %	64.58	94.74	75.69	80.24	93.91	71.17	83.93
Resource Min. Utils %	1.99	2.9	2.32	2.47	2.87	2.18	2.59
Resource Avg. Utils %	49.94	72.81	59.26	63	73.28	55.56	65.03
Resource Max. Utils %	67.87	98.96	79.3	84.3	98.06	74.35	88.38
Resource Min. Idle %	30.2	0.45	19.33	14.48	1.32	24.14	10.55
Resource Avg. Idle %	47.11	25.25	38.27	34.56	24.82	41.95	32.52
Resource Max. Idle %	92.35	91.63	92.18	91.71	91.7	92.64	91.32
Schedule Duration	4D 7:06	2D 22:17	3D 15:58	3D 10:59	2D 22:54	3D 21:33	3D 7:20

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
Total Lead Time	11D 19:23	13D 18:06	14D 4:15	13D 13:03	11D 17:09	12D 18:03
Minimum Added Value	38.99	28.59	24.18	28.12	22.69	31.36
Average Added Value	50.96	44.77	42.94	45.07	41.89	49
Maximum Added Value	89.14	83.06	61.55	83.06	77.7	64.61
Resource Min. Working %	1.74	1.7	2.4	1.7	2	2.56
Resource Avg. Working %	43.78	42.83	60.29	42.83	50.17	64.4
Resource Max. Working %	59.51	58.21	81.95	58.21	68.2	87.53
Resource Min. Utils %	1.82	1.78	2.52	1.78	2.08	2.71
Resource Avg. Utils %	45.83	44.79	63.41	44.79	52.32	67.98
Resource Max. Utils %	62.3	60.87	86.19	60.87	71.11	92.39
Resource Min. Idle %	35.68	37.08	12.66	37.08	27.31	6.7
Resource Avg. Idle %	51.26	52.11	34.11	52.11	45.17	29.62
Resource Max. Idle %	92.95	93.11	91.53	93.11	92.95	90.95
Schedule Duration	4D 15:53	4D 18:23	3D 9:15	4D 18:23	4D 1:38	3D 4:04

Table A3-4

6 Resources, 2NSF	Scheduling Rules						
Schedule Performance	Earliest Due Date/FCFS	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
Total Lead Time	13D 5:05	16D 0:52	14D 9:16	14D 19:00	13D 22:30	12D 6:33	16D 14:21
Minimum Added Value	30.81	35.77	35.58	31.67	33.1	36.42	32.6
Average Added Value	48.6	44.9	46.56	48.07	48.17	56.29	43.82
Maximum Added Value	99.42	68.14	86.33	90.42	66.59	90.42	68.14
Resource Min. Working %	0.65	0.73	0.62	0.65	0.78	0.61	0.64
Resource Avg. Working %	27.07	26.78	25.63	26.97	24.73	26.65	26.38
Resource Max. Working %	89.1	88.14	84.36	88.76	81.38	87.7	86.8
Resource Min. Utils %	0.69	0.77	0.64	0.69	0.82	0.63	0.66
Resource Avg. Utils %	28.3	27.99	26.73	28.19	26.02	27.84	27.54
Resource Max. Utils %	93.15	92.1	87.98	92.78	85.62	91.62	90.64
Resource Min. Idle %	6.21	7.22	11.2	6.57	13.35	7.69	8.63
Resource Avg. Idle %	68.28	68.62	69.97	68.4	70.04	68.78	69.1
Resource Max. Idle %	94.73	94.63	95.01	94.75	93.9	94.8	94.87
Schedule Duration	3D 20:02	3D 21:02	4D 1:12	3D 20:23	4D 4:46	3D 21:30	3D 22:28
Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	
Total Lead Time	13D 2:03	11D 17:27	15D 20:44	12D 9:26	12D 3:57	13D 3:41	
Minimum Added Value	35.6	40.36	35.77	40.06	35.6	33.92	
Average Added Value	55.7	58.31	45.05	55.7	54.43	52.95	
Maximum Added Value	90.42	90.42	62.16	90.42	77.97	87.03	
Resource Min. Working %	0.61	0.58	0.81	0.58	0.64	0.68	
Resource Avg. Working %	26.78	25.7	26.78	25.7	26.78	26.78	
Resource Max. Working %	88.14	84.57	88.14	84.57	88.14	88.14	
Resource Min. Utils %	0.64	0.61	0.84	0.61	0.67	0.71	
Resource Avg. Utils %	27.99	26.8	27.99	26.8	27.99	27.99	
Resource Max. Utils %	92.1	88.2	92.1	88.2	92.1	92.1	
Resource Min. Idle %	7.22	10.98	7.22	10.98	6.14	7.22	
Resource Avg. Idle %	68.62	69.9	68.62	69.9	68.49	68.62	
Resource Max. Idle %	94.77	94.98	94.59	94.98	94.79	94.66	
Schedule Duration	3D 21:02	4D 0:58	3D 21:02	4D 0:58	3D 21:02	3D 21:02	

Table A3-5

8 Resources, 2NSF	Scheduling Rules						
Schedule Performance	Earliest Due Date/FCFS	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
Total Lead Time	20D 11:13	23D 14:33	16D 18:38	21D 7:46	20D 9:08	18D 12:06	23D 8:36
Minimum Added Value	30.8	29.92	35.52	31.67	29.97	34.1	30.13
Average Added Value	43.3	42.44	50.51	44.67	46.48	49.19	42.39
Maximum Added Value	49.42	56.01	78.54	90.42	72.55	95.64	73.6
Resource Min. Working %	0.93	0.67	0.54	0.39	0.62	0.5	0.57
Resource Avg. Working %	26.62	27.87	26.77	26.54	25.54	26.26	26.77
Resource Max. Working %	86.57	90.61	87.04	86.29	83.06	85.4	87.04
Resource Min. Utils %	0.97	0.71	0.56	0.41	0.65	0.52	0.6
Resource Avg. Utils %	27.94	29.31	28.1	27.84	26.75	27.54	28.1
Resource Max. Utils %	90.85	95.3	91.36	90.54	86.98	89.55	91.36
Resource Min. Idle %	8.42	4.15	7.93	8.72	12.14	9.67	7.93
Resource Avg. Idle %	68.46	66.99	68.29	68.56	69.74	68.89	68.29
Resource Max. Idle %	94.17	94.19	94.58	94.81	94.67	94.68	94.47
Schedule Duration	4D 10:16	4D 5:32	4D 9:42	4D 10:37	4D 14:46	4D 11:44	4D 9:42

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
Total Lead Time	18D 16:10	18D 15:47	22D 10:02	18D 13:16	17D 12:59	19D 20:25
Minimum Added Value	36.86	30.2	31.2	29.8	32.84	30.53
Average Added Value	49.58	47.72	43.89	47.11	52.25	49.79
Maximum Added Value	90.42	95.64	57.86	95.64	84.55	79.68
Resource Min. Working %	0.52	0.39	0.67	0.43	0.67	0.51
Resource Avg. Working %	25.92	24.78	27.87	25.33	27.87	26.98
Resource Max. Working %	84.29	80.56	90.61	82.36	90.61	87.73
Resource Min. Utils %	0.54	0.41	0.71	0.45	0.71	0.53
Resource Avg. Utils %	27.27	25.91	29.31	26.52	29.31	28.33
Resource Max. Utils %	88.33	84.25	95.3	86.22	95.3	92.12
Resource Min. Idle %	10.84	14.78	4.15	12.88	4.15	7.2
Resource Avg. Idle %	69.29	70.65	66.99	70	66.99	68.04
Resource Max. Idle %	94.67	95.11	94.19	94.97	94.19	94.58
Schedule Duration	4D 13:09	4D 18:12	4D 5:32	4D 15:42	4D 5:32	4D 8:52

Table A3-6

3 Resources, 3NSF	Scheduling Rules						
Schedule Performance	Earliest Due Date	FCFS	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First
% Late Jobs	83.33	66.67	83.33	66.67	83.33	83.33	66.67
Total Late Time	14D 21:17	17D 15:30	12D 0:02	14D 3:36	13D 4:31	10D 1:10	20D 6:34
Total Lead Time	26D 10:59	29D 23:28	36D 6:35	34D 8:10	37D 7:14	32D 14:01	40D 7:04
Minimum Added Value	30.82	27.29	32.31	30.78	31.68	35.89	16.59
Average Added Value	44.95	42.02	46.14	45.6	47.05	50.91	40.66
Maximum Added Value	99.58	99.63	61.92	84	75.15	63.66	86.32
Resource Min. Working %	23.9	24.44	24.32	29.05	29.86	33.89	24.69
Resource Avg. Working %	24.09	24.64	24.51	29.28	30.11	34.17	24.89
Resource Max. Working %	24.41	24.97	24.84	29.68	30.51	34.63	25.23
Resource Min. Utils %	63.75	67.09	66.84	77.73	82.79	96.14	69.02
Resource Avg. Utils %	64.27	67.63	67.38	78.36	83.46	96.81	69.58
Resource Max. Utils %	65.14	68.55	68.29	79.42	84.59	97.89	70.52
Resource Min. Idle %	12.93	11.31	6.17	7.5	5.37	0	10.4
Resource Avg. Idle %	13.23	11.63	9.97	7.89	5.77	0.73	10.73
Resource Max. Idle %	13.47	11.87	11.95	8.18	6.06	1.2	10.96
Schedule Duration	11D 8:43	11D 2:38	11D 4:00	9D 8:20	9D 2:13	8D 0:17	10D 23:55

Schedule Performance	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
% Late Jobs	100	33.33	33.33	100	33.33	83.33	83.33
Total Late Time	14D 13:41	13D 7:15	14D 2:39	17D 14:24	13D 20:41	19D 16:50	9D 2:24
Total Lead Time	41D 12:33	30D 7:45	27D 23:17	39D 6:20	27D 17:19	36D 1:54	32D 16:43
Minimum Added Value	28.06	39.82	27.58	23.78	27.15	21.07	30.84
Average Added Value	45.47	50.88	44.15	42.7	44.4	39.52	49.69
Maximum Added Value	55.35	90.04	97.11	58.44	97.11	75.15	64.1
Resource Min. Working %	32.86	22.1	20.9	29.51	20.9	24.49	33
Resource Avg. Working %	33.12	22.28	21.07	29.75	21.07	24.69	33.27
Resource Max. Working %	33.57	22.58	21.35	30.16	21.35	25.03	33.72
Resource Min. Utils %	89.47	59.57	58.24	81.15	58.24	67.48	90.53
Resource Avg. Utils %	90.2	60.05	58.71	81.81	58.71	68.03	91.26
Resource Max. Utils %	91.42	60.86	59.5	82.92	59.5	68.95	92.5
Resource Min. Idle %	2.96	14.39	14.41	6.04	14.41	6.25	2.54
Resource Avg. Idle %	3.36	14.68	14.67	6.42	14.67	7.92	2.97
Resource Max. Idle %	3.71	14.89	14.87	6.71	14.87	11.11	3.29
Schedule Duration	8D 6:20	12D 6:54	12D 23:48	9D 4:48	12D 23:48	11D 2:04	8D 5:29

Table A3-7

6 Resources, 3NSF	Scheduling Rules						
Schedule Performance	Earliest Due Date	FCFS	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First
% Late Jobs	50	66.67	66.67	66.67	66.67	50	66.67
Total Late Time	12D 15:48	14D 3:58	9D 4:04	14D 9:18	12D 7:30	11D 5:22	8D 7:15
Total Lead Time	33D 8:40	32D 17:08	34D 5:53	36D 20:37	37D 21:58	35D 13:44	30D 21:53
Minimum Added Value	29.22	31	32.61	35.29	31.63	32.93	35.24
Average Added Value	48.1	48.83	52.96	46.13	47.78	47.86	55.91
Maximum Added Value	99.58	99.63	79.62	84	90.04	66.63	90.04
Resource Min. Working %	4.18	5.06	4.6	4.93	5.05	4.62	5
Resource Avg. Working %	11.2	13.58	12.34	13.21	13.54	12.39	13.41
Resource Max. Working %	27.96	33.9	30.82	32.97	33.8	30.93	33.49
Resource Min. Utils %	11.36	14.02	12.69	13.14	13.9	12.81	13.71
Resource Avg. Utils %	30.47	37.59	34	35.24	37.28	34.24	36.75
Resource Max. Utils %	76.06	93.84	84.89	87.98	93.08	85.14	91.74
Resource Min. Idle %	8.69	2.09	5.34	4.38	2.38	0	2.89
Resource Avg. Idle %	25.49	22.46	23.87	24.18	22.69	22.77	23
Resource Max. Idle %	32.52	30.99	31.64	32.48	31.2	31.39	31.43
Schedule Duration	12D 5:19	10D 1:53	11D 2:06	10D 8:42	10D 2:36	11D 1:09	10D 4:53
Schedule Performance	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
% Late Jobs	66.67	50	50	66.67	50	50	66.67
Total Late Time	17D 4:05	8D 0:29	11D 13:16	16D 8:29	11D 14:03	6D 18:57	9D 15:21
Total Lead Time	42D 22:52	30D 22.19	33D 22:37	41D 14:11	33D 1:46	30D 7:36	33D 19:02
Minimum Added Value	32.56	34.86	35.5	35.64	38.18	35.38	33.79
Average Added Value	43.58	57.06	50.18	44.72	52.62	54.12	52.54
Maximum Added Value	68.15	94.19	97.11	62.14	97.11	77.4	87.14
Resource Min. Working %	4.99	4.98	4.52	5.01	4.56	5.01	5.01
Resource Avg. Working %	13.37	13.36	12.11	13.43	12.22	13.43	13.43
Resource Max. Working %	33.38	33.35	30.22	33.53	30.51	33.53	33.53
Resource Min. Utils %	13.58	13.58	12.15	13.76	12.47	13.76	13.76
Resource Avg. Utils %	36.42	36.35	32.59	36.89	33.43	36.89	36.89
Resource Max. Utils %	90.93	90.74	81.35	92.1	83.45	92.1	92.1
Resource Min. Idle %	3.2	3.27	6.81	2.75	5.93	2.75	2.75
Resource Avg. Idle %	23.25	23.31	24.97	22.89	24.26	22.89	22.89
Resource Max. Idle %	31.65	31.7	32.58	31.33	31.94	31.33	31.33
Schedule Duration	10D 5:41	10D 5:52	11D 7:18	10D 4:32	11D 4:46	10D 4:32	10D 4:32

Table A3-8

8 Resources, 3NSF	Scheduling Rules						
Schedule Performance	Earliest Due Date	FCFS	Critical Ratio	*Minimum Setup Time First*	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First
% Late Jobs	44.44	55.56	55.56	55.56	55.56	44.44	55.56
Total Late Time	16D 3:30	14D 18:37	9D 14:16	14D 11:29	15D 11:40	15D 9:07	13D 3:55
Total Lead Time	48D 21:44	44D 16:13	40D 21:29	42D 4:01	51D 20:22	47D 17:25	42D 18:53
Minimum Added Value	28.55	31	32.93	36.22	32.7	31.31	34.59
Average Added Value	48.13	46.35	55.47	50.63	45.92	48.77	51.62
Maximum Added Value	99.58	99.63	72.71	78.47	90.04	81.34	94.12
Resource Min. Working %	5.86	6.54	6.54	6.45	6.53	6.39	6.5
Resource Avg. Working %	11.78	13.16	13.14	12.97	13.12	12.85	13.06
Resource Max. Working %	29.41	32.85	32.81	32.38	32.76	32.09	32.6
Resource Min. Utils %	15.71	18.18	18.12	17.66	18.05	17.23	17.81
Resource Avg. Utils %	31.59	36.55	36.43	35.5	36.28	34.64	35.8
Resource Max. Utils %	78.86	91.26	90.96	88.64	90.58	86.48	89.38
Resource Min. Idle %	7.79	3.05	3.13	4.05	3.31	4.92	3.77
Resource Avg. Idle %	25.46	22.78	22.87	23.51	22.99	24.2	23.36
Resource Max. Idle %	31.43	29.45	29.54	30.08	29.64	30.71	29.98
Schedule Duration	12D 7:49	11D 0:50	11D 1:09	11D 4:39	11D 1:33	11D 7:06	11D 2:50
Schedule Performance	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	*Highest Remaining Duration First*	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
% Late Jobs	66.67	44.44	44.44	77.78	44.44	66.67	66.67
Total Late Time	18D 20:19	14D 19:59	14D 21:58	17D 10:28	15D 0:46	7D 15:20	12D 20:23
Total Lead Time	53D 12:37	45D 16:11	46D 3:25	50D 22:43	45D 8:04	40D 2:27	45D 7:59
Minimum Added Value	29.95	36.42	30.06	31.08	29.58	34.43	31.06
Average Added Value	46.46	50.61	47.41	47.99	46.9	54.8	54.45
Maximum Added Value	72	90.04	94.12	78.37	94.12	78.37	79.75
Resource Min. Working %	6.54	6.02	5.93	7.02	6	7.02	6.56
Resource Avg. Working %	13.14	12.11	11.93	14.11	12.05	14.11	13.19
Resource Max. Working %	32.81	30.23	29.78	35.23	30.1	35.23	32.94
Resource Min. Utils %	18.12	16.78	16.26	18.95	16.58	18.95	18.32
Resource Avg. Utils %	36.43	33.74	32.68	38.09	33.33	38.09	36.83
Resource Max. Utils %	90.96	84.23	81.6	95.1	83.21	95.1	91.97
Resource Min. Idle %	3.16	5.57	6.28	1.71	5.98	1.71	2.78
Resource Avg. Idle %	22.87	23.73	24.47	22.87	24.06	22.87	21.9
Resource Max. Idle %	29.54	29.87	30.56	30.02	30.17	30.02	29.26
Schedule Duration	11D 1:09	11D 23:47	12D 4:07	10D 6:59	12D 1:03	10D 6:59	11D 0:06

Table A3-9

3-Resource Scenario, 4NSF							
Schedule Performance	Earliest Due Date	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	83.33	100	83.33	83.33	83.33	83.33	100
Total Late Time	29D 2:35	15D 14:40	23D 22:56	21D 2:00	19D 11:38	20D 2:08	24D 3:18
Total Lead Time	38D 21:39	35D 19:15	42D 12:57	46D 9:38	45D 13:09	43D 0:54	52D 3:29
Minimum Added Value	20.07	28.88	19.41	24.55	29.54	17.04	24.85
Average Added Value	43.39	51.58	45.63	47.89	49.31	47.8	44.73
Maximum Added Value	99.58	71.9	84	69.69	60.36	70	68.03
Resource Min. Working %	15.12	22.43	19.38	25.03	24.52	22.27	25.03
Resource Avg. Working %	18.63	27.63	23.86	30.82	30.2	27.43	30.82
Resource Max. Working %	21.59	32.02	27.66	35.73	35.01	31.79	35.73
Resource Min. Idle %	14.28	4.93	7.77	0	1.65	0.9	0
Resource Avg. Idle %	17.22	9.3	11.53	3.09	6.41	8.37	3.09
Resource Max. Idle %	20.7	14.46	15.98	5.31	12.05	15.05	5.31
Resource Min. Utils %	42.1	60.58	54.59	69.89	66.76	59.42	69.89
Resource Avg. Utils %	51.85	74.61	67.24	86.08	82.22	73.18	86.08
Resource Max. Utils	60.1	86.48	77.93	99.77	95.3	84.82	99.77
Schedule Duration	18D 4:58	12D 6:35	14D 5:03	11D 0:03	11D 5:29	12D 8:43	11D 0:03

Schedule Performance	First Come First Served	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
% Late Orders	66.67	33.33	33.3	100	33.3	83.33	83.3
Total Late Time	25D 22:01	13D 2:17	17D 23:52	31D 11:04	18D 8:21	33D 3:38	24D 16:48
Total Lead Time	32D 15:53	36D 17:47	39D 17:16	52D 15:51	40D 1:45	45D 17:00	44D 9:35
Minimum Added Value	25.99	49.97	38.83	19.34	38.56	16.75	30.47
Average Added Value	45.54	57.22	50.91	41.39	50.73	40.68	45.37
Maximum Added Value	99.63	84.63	97.11	73.84	97.11	77.52	73.48
Resource Min. Working %	15.33	22.31	15.3	21.06	15	16.21	17.18
Resource Avg. Working %	18.88	27.47	18.84	25.94	18.48	19.97	21.15
Resource Max. Working %	21.89	31.84	21.83	30.06	21.41	23.14	24.52
Resource Min. Idle %	13.33	5.45	13.54	5.83	14.97	12.03	10.7
Resource Avg. Idle %	16.31	9.79	16.51	9.94	17.89	15.18	14.04
Resource Max. Idle %	19.82	14.93	20.03	14.79	21.34	18.9	18
Resource Min. Utils %	43.47	59.68	43.18	58.53	41.17	46.02	48.69
Resource Avg. Utils %	53.53	73.5	53.18	72.09	50.7	56.68	59.96
Resource Max. Utils	62.05	85.19	61.64	83.55	58.77	65.7	69.5
Schedule Duration	17D 23:02	12D 8:14	18D 0:02	13D 1:48	18D 8:31	16D 23:35	16D 0:44

Table A3-10

6-Resource Scenario, 4NSF							
Schedule Performance	Earliest Due Date	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	66.67	66.67	83.33	66.67	83.33	66.67	66.67
Total Late Time	29D 21:01	27D 2:05	27D 16:09	28D 6:45	33D 21:56	31D 7:18	37D 21:20
Total Lead Time	49D 9:48	52D 11:31	49D 10:16	56D 2:48	60D 17:40	57D 0:26	65D 4:26
Minimum Added Value	20.51	21.31	35.9	23.67	25.57	07:26	21.28
Average Added Value	43.78	44.37	44.35	42.05	37.39	41.74	37.27
Maximum Added Value	99.58	78.57	84	71.39	56.02	84.63	59.95
Resource Min. Working %	1.93	2.02	2.02	2.04	2.02	2.02	2.03
Resource Avg. Working %	9.41	9.86	9.86	9.98	9.86	9.86	9.93
Resource Max. Working %	32.17	33.71	33.71	34.14	33.71	33.71	33.97
Resource Min. Idle %	3.26	1.78	1.78	1.01	1.78	1.78	1.51
Resource Avg. Idle %	26.06	25.31	25.87	25.21	25.87	25.87	25.59
Resource Max. Idle %	33.57	33.78	33.78	33.18	33.78	33.78	33.52
Resource Min. Utils %	5.43	5.64	5.64	5.8	5.64	5.64	5.72
Resource Avg. Utils %	26.5	27.53	27.53	28.34	27.53	27.53	27.94
Resource Max. Utils	90.62	94.14	94.14	96.92	94.14	94.14	95.54
Schedule Duration	18D 0:34	17D 4:50	17D 4:50	16D 23:35	17D 4:50	17D 4:50	17D 1:40
Schedule Performance	First Come First Served	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
% Late Orders	66.67	50	50	66.67	50	83.33	66.67
Total Late Time	25D 2:53	20D 18:13	23D 9:42	39D 14:40	21D 20:59	25D 14:37	29D 3:59
Total Lead Time	42D 16:21	43D 15:56	46D 7:25	64D 23:03	44D 18:42	50D 22:46	53D 3:35
Minimum Added Value	24.66	31.96	37.71	21.07	30.76	28.56	21.07
Average Added Value	47.26	49.31	48.53	36.89	45.37	44.68	43.51
Maximum Added Value	99.63	97.11	97.11	55.25	97.11	81.79	84.63
Resource Min. Working %	2.04	2.02	2.02	2.02	2.02	2.02	2.02
Resource Avg. Working %	9.99	9.86	9.86	9.86	9.86	9.86	9.86
Resource Max. Working %	34.15	33.71	33.71	33.71	33.71	33.71	33.71
Resource Min. Idle %	1	1.78	1.78	1.78	1.78	2.03	2.03
Resource Avg. Idle %	25.2	25.31	25.87	25.83	25.87	25.87	25.87
Resource Max. Idle %	33.17	33.78	33.78	33.78	33.78	33.78	33.78
Resource Min. Utils %	5.81	5.64	5.64	5.64	5.64	5.64	5.64
Resource Avg. Utils %	28.35	27.53	27.53	27.53	27.53	27.53	27.53
Resource Max. Utils	96.96	94.14	94.14	94.14	94.14	94.14	94.14
Schedule Duration	16D 23:32	17D 4:50	17D 4:50	17D 4:50	17D 4:50	17D 4:50	17D 4:50

Table A3-11

8-Resource Scenario, 4NSF							
Schedule Performance	Earliest Due Date	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	83.33	66.67	66.67	50	50	50	66.67
Total Late Time	17D 0:09	9D 20:07	14D 3:22	6D 16:42	7D 17:17	9D 15:24	8D 22:08
Total Lead Time	37D 3:03	35D 1:13	34D 8:09	31D 16:41	31D 17:18	35D 1:06	34D 3:00
Minimum Added Value	29.45	35.8	38.79	42.63	41.68	00:57	37.53
Average Added Value	53.92	62.14	59.56	68.15	66.6	62.6	62.98
Maximum Added Value	99.58	80.78	88.18	85.21	75.91	84.63	81.57
Resource Min. Working %	0	0	0	0	0	0	0
Resource Avg. Working %	10.44	12.59	10.53	14.11	14.08	12.31	13.95
Resource Max. Working %	24.79	29.9	25.02	33.52	33.45	29.23	33.13
Resource Min. Idle %	11.75	6.36	11.26	1.95	2.14	8.04	3.08
Resource Avg. Idle %	26.09	23.6	25.74	21.28	21.49	24.95	22.2
Resource Max. Idle %	36.57	36.29	36.32	35.51	35.63	37.31	36.25
Resource Min. Utils %	0	0	0	0	0	0	0
Resource Avg. Utils %	28.54	34.68	29.01	39.74	39.53	32.98	38.47
Resource Max. Utils	67.79	82.39	68.91	94.4	93.89	78.35	91.39
Schedule Duration	12D 4:27	10D 2:30	12D 1:43	9D 0:18	9D 0:43	10D 8:02	9D 2:50
Schedule Performance	First Come First Served	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
% Late Orders	66.67	50	33.33	66.67	33.33	66.67	66.67
Total Late Time	18D 5:42	11D 14:55	7D 4:03	10D 23:37	7D 4:03	9D 123:53	14D 6:57
Total Lead Time	37D 5:32	33D 18:18	29D 15:39	36D 5:21	29D 15:39	34D 10:37	38D 9:53
Minimum Added Value	29.59	31.36	56.3	42.78	56.3	47.87	42.29
Average Added Value	55.34	64.27	70.45	60.63	70.45	61.97	57.02
Maximum Added Value	99.63	97.11	97.11	76.42	97.11	90.16	84.63
Resource Min. Working %	0	0	0	0	0	0	0
Resource Avg. Working %	10.51	11.47	13.58	12.66	13.58	12.33	11.25
Resource Max. Working %	24.96	27.25	32.26	30.08	32.26	29.29	26.72
Resource Min. Idle %	11.49	9.02	5.19	5.77	5.19	7.87	10.41
Resource Avg. Idle %	25.93	23.47	23.08	23.12	23.08	24.76	25.82
Resource Max. Idle %	36.48	36.3	37.49	35.89	37.49	37.19	37.16
Resource Min. Utils %	0	0	0	0	0	0	0
Resource Avg. Utils %	28.81	31.6	36.23	35.28	36.23	33.15	30.27
Resource Max. Utils	68.43	75.06	86.05	83.82	86.05	78.75	71.9
Schedule Duration	12D 2:27	11D 2:05	9D 8:45	10D 1:00	9D 8:45	10D 7:34	11D 7:20

Table A3-12

3-Resource Scenario, 5NSF								
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	66.67	50	100	66.67	83.33	50	83.33	100
Total Late Time	7D 12:26	14D 10:50	11D 20:21	13D 19:31	19D 0:14	10D 20:00	22D 18:44	17D 22:45
Total Lead Time	31D 17:30	37D 2:54	41D 7:05	38D 4:03	45D 20:05	35D 9:27	46D 16:31	48D 3:49
Minimum Added Value	37.47	24.45	26.92	37.12	21.5	35.97	07:40	25.85
Average Added Value	57.62	52.36	51.68	54.92	46.16	55.58	43.65	46.61
Maximum Added Value	99.29	99.29	79.14	92.52	76.02	76.41	90.55	62.64
Resource Min. Working %	23.58	21.71	28.75	27.5	28.97	26.17	27.23	28.61
Resource Avg. Working %	30.85	25.51	32.63	31.46	30.12	29.27	28.69	31.1
Resource Max. Working %	36.47	32.85	36.37	34.49	31.06	34.7	31.02	35.45
Resource Min. Idle %	0.77	3.24	0.88	2.41	4.51	1.06	5.39	0
Resource Avg. Idle %	6.38	10.56	4.6	5.45	5.41	6.58	7.73	4.41
Resource Max. Idle %	13.62	14.4	8.47	9.45	6.49	9.77	9.18	6.96
Resource Min. Utils %	63.1	59.99	76.94	74.25	81.25	72.74	74.53	80.28
Resource Avg. Utils %	82.54	70.48	87.31	84.94	84.47	81.35	78.53	87.25
Resource Max. Utils	97.58	90.76	97.32	93.11	87.1	96.45	84.91	99.44
Schedule Duration	9D 8:22	11D 1:38	9D 8:20	10D 6:58	10D 23:27	10D 1:20	12D 4:17	10D 0:02

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Operation Resource Flexibility First	Highest Operation Resource Flexibility First
% Late Orders	50	50	100	50	66.67	66.67	66.67	66.67
Total Late Time	9D 22:31	8D 20:34	20D 4:00	12D 10:23	18D 22:35	12D 7:19	12D 6:08	13D 4:30
Total Lead Time	33D 3:44	28D 22:01	47D 11:18	30D 15:53	36D 11:04	38D 14:45	30D 1:09	41D 4:52
Minimum Added Value	25.8	42.4	22.17	27.05	16.45	31.01	33.54	29.09
Average Added Value	62.6	61.55	45.57	52.72	50.13	55.07	36.17	51.05
Maximum Added Value	92.65	99.58	70.72	99.58	79.64	75.36	90.24	89.92
Resource Min. Working %	28.71	25.17	34.13	26.48	26.41	29.57	26.87	18.62
Resource Avg. Working %	30.51	30.51	35.05	30.48	29.35	31.47	30.12	23.16
Resource Max. Working %	31.88	35.27	36.04	37.17	33.74	34.79	34.42	26.69
Resource Min. Idle %	0	1.28	0	0	2.17	1.41	0	9.27
Resource Avg. Idle %	4.73	6.14	0.97	6.68	6.51	4.72	5.8	12.8
Resource Max. Idle %	8.19	11.53	1.84	10.75	9.43	6.59	9.76	17.38
Resource Min. Utils %	77.48	68.45	94.39	71.02	73.4	81.4	73.06	51.64
Resource Avg. Utils %	81.87	82.95	96.92	81.74	81.57	86.63	79.19	64.22
Resource Max. Utils	84.65	95.91	99.66	99.68	93.79	95.76	85.46	74.03
Schedule Duration	10D 7:02	10D 5:57	9D 2:31	10D 7:58	11D 0:45	10D 2:39	10D 5:57	13D 7:06

Table A3-13

6-Resource Scenario, 5NSF								
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	33.33	16.67	16.67	16.67	33.33	16.67	16.67	16.67
Total Late Time	23H 2M	9H 6M	16H 48M	2D 8:33	1D 1:03	16H 46M	2D 16:41	15H 52M
Total Lead Time	24D 9:58	21D 17:32	23D 0:37	24D 13:58	24D 0:27	18D 21:47	26D 2:04	22D 7:27
Minimum Added Value	36.3	24.92	30.16	66.92	37.27	74.72	52.36	43
Average Added Value	65.17	70.9	75.01	82.01	77.98	86.4	79.47	80.71
Maximum Added Value	98.9	98.9	99.3	97.88	97.56	99.59	99.44	99.58
Resource Min. Working %	3.75	9.25	7.76	9.85	18.68	10.44	13.38	17.6
Resource Avg. Working %	19.2	22.9	25.01	21.64	25.17	25.12	21.83	27.68
Resource Max. Working %	31.11	37.21	34.56	28.85	35.61	38.35	32.63	37.77
Resource Min. Idle %	5.99	2.39	5.86	5.64	1.39	1.96	4.35	2.12
Resource Avg. Idle %	17.82	16.71	15.4	12.91	11.8	15.27	15.19	12.3
Resource Max. Idle %	32.77	30.36	32.71	24.72	18.33	30.04	23.6	22.45
Resource Min. Utils %	10.07	23.29	19.14	28.42	50.38	25.76	36.05	43.91
Resource Avg. Utils %	51.56	57.63	61.7	62.47	67.88	62	58.83	69.03
Resource Max. Utils	83.53	93.65	85.26	83.26	96.05	94.66	87.96	94.2
Schedule Duration	6D 4:56	5D 6:06	5D 7:48	6D 23:33	5D 23:12	5D 7:46	7D 7:41	5D 6:52
Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Operation Resource Flexibility First	Highest Operation Resource Flexibility First
% Late Orders	16.67	33.33	33.33	16.67	16.67	16.67	16.67	33.33
Total Late Time	2D 9:57	2D 1:46	2D 1:14	2D 8:59	16H 48M	1D 14:00	1D 9:20	3D 1:25
Total Lead Time	24D 4:13	22D 1:50	25D 17:27	22D 22:02	22D 19:31	24D 12:05	21D 17:59	23D 5:23
Minimum Added Value	45.6	65.38	33.89	39.53	33.9	45.57	39.84	68.19
Average Added Value	75.31	77.72	68.21	77.51	74.99	77.48	77.36	80.78
Maximum Added Value	99.58	99.58	99.58	99.63	94.44	91	99.58	97.51
Resource Min. Working %	6.51	3.72	11.69	1.24	9.39	15.77	11.84	13.28
Resource Avg. Working %	19.94	19.58	22.37	19.91	26.12	24.26	22.45	20.6
Resource Max. Working %	32.9	28.87	35.51	33.98	37.17	34.96	35.05	30.93
Resource Min. Idle %	2.16	5.89	1.6	0.66	3.23	2.23	2.01	3.87
Resource Avg. Idle %	15.15	15.05	14.72	14.81	14.3	12.88	14.62	14.18
Resource Max. Idle %	28.6	31.08	25.44	33.52	31.1	21.36	25.2	21.58
Resource Min. Utils %	18.5	10.68	31.42	3.56	23.17	42.34	31.83	38.1
Resource Avg. Utils %	56.68	56.22	60.15	57.19	64.43	65.14	60.38	59.07
Resource Max. Utils	93.5	82.91	95.47	97.61	91.7	73.84	94.25	88.71
Schedule Duration	7D 0:57	7D 0:00	6D 4:20	6D 23:59	5D 7:48	6D 5:00	6D 0:20	7D 0:07

Table A3-14

8-Resource Scenario, 5NSF

Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	33.33	16.67	33.33	33.33	50	16.67	50	33.33
Total Late Time	1D 1:56	9H 6M	3D 0:39	3D 22:23	3D 17:42	1D 9:02	4D 15:40	2D 17:53
Total Lead Time	23D 8:32	21D 22:10	29D 10:00	25D 21:07	28D 6:26	20D 2:20	30D 1:51	26D 19:25
Minimum Added Value	37.01	26.17	21.5	74.2	29.29	65.98	07:40	31.65
Average Added Value	66.29	71.62	65.7	80.98	68.61	85.7	69.47	71.75
Maximum Added Value	98.9	98.9	95.9	99.58	99.54	97.49	99.58	99.63
Resource Min. Working %	1.37	2.97	1.23	2.93	0	0	0	0
Resource Avg. Working %	14.17	17.12	15.23	16.72	13.59	17.04	16.12	15.69
Resource Max. Working %	28.38	31.26	29.53	34.23	29.53	32.63	36.14	34.68
Resource Min. Idle %	8.94	8.39	5.93	1.39	5.3	4.44	0	0
Resource Avg. Idle %	23.24	22.52	20.24	18.95	21.27	20.04	20.09	19.29
Resource Max. Idle %	36.08	36.68	34.29	32.78	34.92	37.16	36.27	35.08
Resource Min. Utils %	3.66	7.49	3.45	8.21	0	0	0	0
Resource Avg. Utils %	37.81	43.08	42.85	46.79	38.92	45.86	42.17	42.41
Resource Max. Utils	75.7	78.68	83.08	95.76	84.58	87.82	89.83	80.39
Schedule Duration	6D 7:50	5D 6:06	7D 1:53	7D 2:25	7D 23:18	6D 0:02	7D 5:24	7D 0:40

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Operation Resource Flexibility First	Highest Operation Resource Flexibility First
% Late Orders	33.33	33.33	16.67	33.33	50	16.67	33.33	33.33
Total Late Time	4D 2:29	3D 22:04	1D 13:20	2D 7:38	3D 18:54	2D 11:40	1D 9:36	4D 1:18
Total Lead Time	27D 21:48	24D 0:36	24D 9:54	24D 14:58	26D 7:32	25D 12:38	24D 12:39	26D 5:39
Minimum Added Value	38.58	71.68	30.03	42.64	25.62	41.78	31.63	37.39
Average Added Value	70.44	80.67	72.74	76.38	73.06	73.53	74.12	71.92
Maximum Added Value	97.49	99.58	99.58	99.66	93.08	96.68	99.58	99.58
Resource Min. Working %	0	0	0	0	0	2.2	2.47	0
Resource Avg. Working %	13.46	15.35	17.36	17.7	15.1	15.66	17.51	15.08
Resource Max. Working %	25.18	30.63	36.24	37.35	33.95	35.01	37.35	30.76
Resource Min. Idle %	3.52	5.36	0.87	0	2.54	0.77	0.01	6.29
Resource Avg. Idle %	21.39	20.72	19.75	19.35	21.42	20.11	19.9	22.09
Resource Max. Idle %	35.78	36.13	37.19	37.44	36.59	33.61	34.97	37.24
Resource Min. Utils %	0	0	0	0	0	6.13	6.59	0
Resource Avg. Utils %	37.59	42.47	46.68	45.5	41.28	43.7	46.71	40.5
Resource Max. Utils	70.31	84.78	97.43	99.76	92.79	97.68	99.65	82.61
Schedule Duration	8D 1:57	7D 5:01	6D 4:20	6D 7:16	7D 6:16	7D 2:40	6D 7:44	7D 8:04

Table A3-15

3-Resource Scenario, 5aNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First
% Late Orders	35.71	57.14	78.57	100	42.86	35.71
Total Late Time	10D 19:38	17D 20:58	17D 9:45	38D 9:58	20D 6:56	17D 0:13
Total Lead Time	49D 10:34	50D 15:04	65D 17:14	107D 10:06	59D 1:32	51D 18:25
Minimum Added Value	12.87	14.55	13.18	09:02	16.53	17.14
Average Added Value	28.08	27.79	23.65	20.61	30.51	29.82
Maximum Added Value	98.59	98.59	35.33	29.39	94.89	99.16
Resource Min. Working %	28.66	31.11	32.29	32.16	28.29	29.16
Resource Avg. Working %	31.06	31.71	33.26	33.53	29.64	30.1
Resource Max. Working %	33.8	32.77	35.14	35.94	31.33	31.19
Resource Min. Idle %	2.67	3.31	1.43	0	4.69	1.06
Resource Avg. Idle %	5.31	4.43	3.34	2.42	6.4	4.06
Resource Max. Idle %	7.74	5.14	4.33	3.71	7.74	6.23
Resource Min. Utils %	78.01	85.22	87.37	88.56	77.83	80.13
Resource Avg. Utils %	84.54	86.58	89.99	91.92	81.55	82.69
Resource Max. Utils	92	89.76	95.08	97.7	86.2	85.69
Schedule Duration	9D 6:07	9D 5:16	9D 6:52	9D 4:37	11D 2:16	10D 4:29
Schedule Performance	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	100	50	64.29	85.71	57.14	71.43
Total Late Time	40D 19:28	25D 13:42	23D 7:37	17D 4:15	17D 12:26	31D 12:19
Total Lead Time	97D 22:54	58D 19:47	56D 7:30	80D 18:06	47D 23:42	93D 5:21
Minimum Added Value	9.14	14.13	9.8	12.03	13.52	12.63
Average Added Value	20.53	25.58	25.54	25.51	27.99	22.71
Maximum Added Value	29.03	99.16	76.65	45.83	91.48	55.09
Resource Min. Working %	33.8	25.69	33.24	31.94	32.55	25.82
Resource Avg. Working %	34.51	29.06	33.58	33.64	33.84	28.96
Resource Max. Working %	35.56	35.28	34.24	35.77	35.94	33.2
Resource Min. Idle %	0	0	2.32	0	0	2.75
Resource Avg. Idle %	1.06	4.46	3.08	2.08	2.2	7.56
Resource Max. Idle %	1.81	9.63	3.56	3.79	3.51	11.01
Resource Min. Utils %	94.08	72.19	89.79	88.51	89.37	69.66
Resource Avg. Utils %	95.64	81.65	90.71	93.23	92.93	78.14
Resource Max. Utils	97.71	99.08	92.49	99.09	98.7	89.56
Schedule Duration	9D 1:44	10D 23:10	9D 7:06	9D 2:15	9D 4:58	11D 6:55

Table A3-16

6-Resource Scenario,5aNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First
% Late Orders	0	0	0	0	14.29	14.29
Total Late Time	0	0	0	0	23H 52M	2D 5:24
Total Lead Time	39D 14:01	37D 20:39	47D 3:12	49D 10:25	38D 3:54	38D 17:12
Minimum Added Value	15.38	15.07	16.27	17.04	32.76	25.71
Average Added Value	38.08	39.26	38.51	36.88	46.57	43.95
Maximum Added Value	97.83	97.83	69.88	56.53	98.19	99.16
Resource Min. Working %	9.97	16.93	30.95	23.71	15.57	11.32
Resource Avg. Working %	23.69	24.45	34.77	27.72	26.53	21.97
Resource Max. Working %	31.88	29.72	40.15	38.28	37.53	36.59
Resource Min. Idle %	6.7	6.94	0	0	0	0.37
Resource Avg. Idle %	14.95	12.29	5.39	10.72	12.89	15.11
Resource Max. Idle %	28.77	19.96	9.16	14.65	24.35	25.8
Resource Min. Utils %	25.6	45.68	76.35	61.18	38.85	30.32
Resource Avg. Utils %	60.81	65.95	85.77	71.53	63.35	58.84
Resource Max. Utils	81.85	80.16	99.04	98.79	82.03	97.98
Schedule Duration	5D 2:51	4D 23:11	4D 6:35	5D 4:05	5D 6:50	6D 6:08
Schedule Performance	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	7.14	14.29	7.14	0	0	0
Total Late Time	10H 8M	1D 4:10	8H 14M	0	0	0
Total Lead Time	36D 5:14	37D 8:01	36D 5:14	39D 10:16	33D 7:41	49D 8:00
Minimum Added Value	16.56	22.93	16.56	21.21	14.87	15.42
Average Added Value	41.95	41.48	41.95	45.79	42.05	36.22
Maximum Added Value	83.19	99.16	83.19	78.95	74.76	83.04
Resource Min. Working %	32.46	19.9	32.46	31.81	22.1	12.27
Resource Avg. Working %	34.95	26.14	34.95	34.89	28.86	27.37
Resource Max. Working %	38.82	39.84	38.82	41.14	36.72	36.21
Resource Min. Idle %	0	0.81	0	0	0	2.76
Resource Avg. Idle %	3.9	14.63	3.9	6.35	7.87	11.48
Resource Max. Idle %	6.56	20.92	6.56	9.52	14.65	26.8
Resource Min. Utils %	82.73	48.44	82.73	76.43	59.65	31.34
Resource Avg. Utils %	89.07	63.64	89.07	83.84	77.88	69.89
Resource Max. Utils	98.94	96.98	98.94	98.85	99.09	92.44
Schedule Duration	4D 4:23	5D 8:59	4D 4:23	4D 8:29	4D 23:09	5D 4:56

Table A3-17

8-Resource Scenario, 5aNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First
% Late Orders	0	0	0	0	0	0
Total Late Time	0	0	0	0	0	0
Total Lead Time	36D 22:39	34D 13:01	41D 3:55	42D 11:46	34D 18:18	36D 14:01
Minimum Added Value	18.94	24.45	16.85	17.05	39.83	36.57
Average Added Value	45.87	50.57	47.95	50.07	56.88	52.66
Maximum Added Value	98.48	98.48	74.79	73.09	99.16	99.11
Resource Min. Working %	8.44	16.47	24.97	25.74	22.64	16.46
Resource Avg. Working %	19.58	24.49	29.94	30.33	28.56	24.76
Resource Max. Working %	28.76	34.82	33.51	36.79	33.67	32.01
Resource Min. Idle %	10.87	4.93	4.29	0.24	6.87	0
Resource Avg. Idle %	20.04	15.24	7.92	6.74	11.96	11.27
Resource Max. Idle %	31.17	23.27	12.97	11.31	17.92	20.84
Resource Min. Utils %	21.19	41.15	65.44	68.87	55.49	43.87
Resource Avg. Utils %	49.14	61.19	78.46	81.14	69.99	65.6
Resource Max. Utils	72.16	87.02	87.8	98.42	82.52	85.34
Schedule Duration	5D 6:21	4D 5:42	4D 1:02	3D 23:49	4D 7:03	5D 0:01
Schedule Performance	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	0	0	0	0	0	0
Total Late Time	0	0	0	0	0	0
Total Lead Time	40D 5:08	36D 6:04	40D 9:44	33D 0:46	35D 12:16	37D 22:26
Minimum Added Value	23.01	23.29	23.89	38.2	33.43	22.09
Average Added Value	49.22	48.49	50.93	58.46	54.55	50.42
Maximum Added Value	71.76	99.16	85.26	84.95	83.66	98.74
Resource Min. Working %	25.22	16.68	21.46	25.4	24.35	10.93
Resource Avg. Working %	29.16	27.68	29.92	30.15	30.56	23.01
Resource Max. Working %	38.85	36.01	35.31	36.86	36.5	31.34
Resource Min. Idle %	0	0	2.98	0	0	6.68
Resource Avg. Idle %	9.59	9.18	8.22	6.52	6.11	14.9
Resource Max. Idle %	13.31	23.26	16.79	11.22	12.28	27.05
Resource Min. Utils %	64.59	41.61	55.83	68.67	65.91	28.65
Resource Avg. Utils %	74.67	68.22	77.84	81.53	82.63	60.31
Resource Max. Utils	99.48	89.83	91.86	99.67	98.81	82.16
Schedule Duration	4D 2:27	4D 5:49	4D 1:28	3D 23:13	3D 23:09	5D 1:15

Table A3-18

3-Resource Scenario, 6NSF								
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	33.33	50	83.33	66.67	83.33	66.67	83.33	100
Total Late Time	4D 5:57	5D 15:41	7D 16:07	10D 15:54	11D 22:43	6D 6:02	27D 0:32	22D 19:10
Total Lead Time	31D 19:51	32D 3:30	38D 26:27	39D 11:27	43D 18:28	39D 16:19	57D 18:21	57D 23:21
Minimum Added Value	35.3	18.52	33.9	33.43	21.14	32.69	10:04	14.39
Average Added Value	50.44	45.19	51.17	47.14	42.17	46.37	41.36	41.29
Maximum Added Value	99.29	99.45	76.05	76.54	76.21	83.06	25.38	74.15
Resource Min. Working %	22.38	23.63	26.48	26.92	31.28	23.51	33.01	30.98
Resource Avg. Working %	26.64	26.75	27.53	31.15	32.08	29.41	33.79	33.52
Resource Max. Working %	30.46	29.9	28.52	34.88	33.45	35.86	35.19	36.69
Resource Min. Idle %	1.46	6.31	2.03	2.11	2.86	0	1.71	0
Resource Avg. Idle %	8.48	9.46	5.79	3.97	4.27	6.51	3.15	3.19
Resource Max. Idle %	14.38	12.59	8.2	4.97	5.09	12.51	3.95	5.72
Resource Min. Utils %	60.71	65.01	76.03	72.5	85.69	65.15	89.02	84.03
Resource Avg. Utils %	72.28	73.88	79.04	83.9	87.87	81.52	91.11	86.83
Resource Max. Utils	82.64	82.25	81.86	93.94	91.64	99.37	94.89	89.22
Schedule Duration	12D 5:48	12D 1:52	14D 0:04	11D 7:11	11D 4:32	11D 1:11	12D 6:50	11D 6:04
Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	83.33	33.33	100	50	83.33	100	83.33	83.33
Total Late Time	22D 2:51	10D 10:29	24D 15:02	7D 18:51	24D 8:57	16D 8:03	6D 17:25	18D 17:55
Total Lead Time	52D 3:00	39D 5:46	56D 20:26	34D 13:35	49D 4:55	50D 5:50	40D 13:48	51D 4:37
Minimum Added Value	25.46	43.08	19.22	43.45	17.42	12.21	26.02	16.39
Average Added Value	44.59	53.54	39.75	50.71	39.06	44.24	50.21	43.5
Maximum Added Value	97.86	92.59	70.75	90.54	88.86	70.84	77.58	75.26
Resource Min. Working %	17.97	23.77	28.76	25.12	26.43	29.82	24.16	20.54
Resource Avg. Working %	22.12	25.75	33.49	28.81	28.05	32.2	27.85	24.85
Resource Max. Working %	24.57	28.42	37.36	33.56	30.36	35.93	30.11	29.91
Resource Min. Idle %	11.4	7.56	0	3.46	3.96	0	7.06	6.07
Resource Avg. Idle %	13.84	10.22	3.9	8.2	6.32	3.75	9.25	11.09
Resource Max. Idle %	17.97	12.2	8.62	11.83	9.48	6.41	12.91	15.36
Resource Min. Utils %	49.81	65.85	76.6	67.61	73.45	81.75	64.87	56.94
Resource Avg. Utils %	61.33	71.33	89.19	77.53	77.95	89.17	74.78	68.91
Resource Max. Utils	68.13	78.73	99.48	90.32	84.37	99.5	80.84	82.92
Schedule Duration	16D 7:02	14D 8:16	11D 8:59	12D 7:12	13D 2:00	11D 1:19	12D 7:36	14D 8:07

Table A3-19

6-Resource Scenario, 6NSF								
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	16.67	0	33.33	16.67	66.67	16.67	66.67	83.33
Total Late Time	11H 40M	0	22H 36M	2D 11:54	6D 20:50	2D 8:27	13D 0:31	9D 15:16
Total Lead Time	21D 16:18	26D 12:02	30D 5:50	30D 3:32	36D 16:10	24D 19:43	44D 0:32	41D 19:13
Minimum Added Value	48.49	24.23	28.18	55.31	23.14	57.13	14:24	22.78
Average Added Value	63.92	58.52	62.15	65.98	53.27	69.5	52.33	55.19
Maximum Added Value	98.9	99.42	96.36	89.4	99.54	99.59	90.19	83.52
Resource Min. Working %	1.88	2.15	9.74	6.53	8.1	9.4	8.59	7.74
Resource Avg. Working %	14.59	14.19	17.69	18.61	16.9	17.6	17.63	18.04
Resource Max. Working %	30.55	28.66	36.22	35.33	35.86	35.02	36.03	34.52
Resource Min. Idle %	5.02	7.62	0	1.62	0.5	1.13	0.98	1.03
Resource Avg. Idle %	19.84	22.14	18.6	18.4	18.44	18.6	19.44	17.56
Resource Max. Idle %	33.71	34.22	26.56	30.48	28.34	26.82	28.49	27.91
Resource Min. Utils %	5.28	5.9	26.76	17.59	22.21	25.91	23.11	21.68
Resource Avg. Utils %	40.89	38.96	48.62	50.16	46.3	48.49	47.45	50.55
Resource Max. Utils	85.61	78.67	99.56	95.2	98.29	96.5	96.96	96.73
Schedule Duration	9D 0:53	9D 5:00	9D 4:51	9D 7:24	9D 5:13	9D 2:57	10D 7:28	10D 0:13
Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	16.67	16.67	66.67	16.67	66.67	33.33	33.33	33.33
Total Late Time	1D 9:29	1D 13:40	9D 4:23	1D 16:24	8D 17:58	3D 1:22	22H 57M	2D 4:56
Total Lead Time	26D 3:05	25D 16:03	39D 10:55	27D 2:34	38D 2:28	29D 19:59	31D 15:25	27D 19:47
Minimum Added Value	51.12	62.5	19.5	40.01	24.81	32.3	29.84	51.65
Average Added Value	70.44	72.89	51.28	67.25	52.77	67.4	66.33	68.79
Maximum Added Value	90.19	92.42	90.8	93.35	90.43	90.19	98.42	78.98
Resource Min. Working %	11.63	7.49	8.48	9.41	8.12	10	11.08	9.56
Resource Avg. Working %	18.15	20.38	17.82	18.08	17.47	19.43	19.63	18.34
Resource Max. Working %	28.52	34.97	34.52	33.62	33.25	35.37	34.77	30.85
Resource Min. Idle %	8.05	2.17	1.11	1.88	1.45	0.06	1.09	4.47
Resource Avg. Idle %	18.47	16.82	17.87	17.51	17.65	16.12	16.31	17.01
Resource Max. Idle %	25.06	29.77	27.24	26.2	27.15	25.61	24.87	25.86
Resource Min. Utils %	31.68	20.09	23.69	26.38	23.01	28.05	30.74	26.98
Resource Avg. Utils %	49.43	54.63	49.8	50.67	49.5	54.51	54.47	51.75
Resource Max. Utils	77.68	93.75	96.46	94.21	94.22	99.24	96.46	87.03
Schedule Duration	9D 6:02	8D 8:10	9D 1:15	9D 0:54	8D 23:34	9D 0:45	9D 2:07	9D 0:06

Table A3-20

8-Resource Scenario, 6NSF								
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	16.67	0	16.67	16.67	66.67	16.67	66.67	33.33
Total Late Time	1D 9:51	0	1D 10:38	1D 13:46	4D 12:50	1D 15:26	7D 9:07	2D 2:21
Total Lead Time	22D 23:49	21D 17:16	30D 0:21	27D 15:52	34D 0:40	24D 19:55	38D 20:45	28D 17:12
Minimum Added Value	51.63	37.4	29.03	67.28	33.06	67.26	16:19	53.79
Average Added Value	75.23	73.33	68.02	80.09	66.55	79.26	66.66	77.13
Maximum Added Value	99.24	99.51	87.27	91.6	97.85	97.72	96.91	89.38
Resource Min. Working %	5.95	7.55	6.65	9.1	9.04	7.37	8.93	9.96
Resource Avg. Working %	14.43	13.07	16.22	16.5	16.47	14.91	17.69	15.7
Resource Max. Working %	23.22	22.85	23.89	25.92	22.29	20.99	24.48	21.41
Resource Min. Idle %	13.09	12.22	12.69	9.39	14.33	14.26	10.66	14.42
Resource Avg. Idle %	21.9	22.01	19.41	18.85	20.05	20.42	17.51	20.12
Resource Max. Idle %	30.43	27.57	29.95	26.26	27.56	27.98	26.31	25.82
Resource Min. Utils %	16.35	21.49	18.13	25.7	24.67	20.82	25.32	27.75
Resource Avg. Utils %	39.64	37.19	44.26	46.57	44.92	42.11	50.15	43.74
Resource Max. Utils	63.79	65.01	65.17	73.19	60.81	59.31	69.39	59.66
Schedule Duration	8D 5:21	8D 23:08	8D 6:08	9D 0:01	8D 6:08	8D 23:56	8D 23:31	9D 1:35
Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	16.67	16.67	33.33	16.67	33.33	16.67	16.67	33.33
Total Late Time	16H 36M	1D 11:21	1D 17:24	1D 15:26	3D 21:33	1D 13:21	1D 9:18	2D 18:21
Total Lead Time	22D 0:17	24D 22:48	29D 6:21	27D 19:05	27D 23:46	27D 19:57	29D 0:01	28D 18:08
Minimum Added Value	72.66	77.04	30.19	53.21	31.97	62.99	47.23	49.38
Average Added Value	85.35	84.03	69.75	72.89	76.37	80.07	77.44	72.51
Maximum Added Value	97.65	99.29	95.65	94.69	94.6	94.28	92.44	94.14
Resource Min. Working %	5.09	8.93	6.7	8.3	9.46	9.38	9.53	6.45
Resource Avg. Working %	16.29	17.5	16.2	15.35	17.28	17.74	17.75	14.83
Resource Max. Working %	25.01	29.08	22.06	24	23.13	22.52	26.04	20.22
Resource Min. Idle %	11.04	8.28	13.96	11.35	13.46	14.59	10.04	16.02
Resource Avg. Idle %	19.78	19.86	19.84	19.17	19.24	19.38	18.4	21.48
Resource Max. Idle %	31.02	28.45	29.35	27.04	27.14	27.75	26.64	29.89
Resource Min. Utils %	14.07	23.86	18.55	23.44	25.81	25.22	26.3	17.73
Resource Avg. Utils %	45.05	46.74	44.84	43.35	47.14	47.69	49	40.77
Resource Max. Utils	69.2	77.67	61.06	67.82	63.1	60.52	71.88	55.59
Schedule Duration	8D 4:33	8D 8:36	8D 4:28	8D 23:56	8D 6:08	8D 7:51	8D 4:48	9D 4:51

Table A3-21

3-Resources, 7NSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	50	100	100	50	50	75
Total Late Time	3D 23:36	6D 3:03	6D 3:54	4D 17:51	4D 20:27	6D 4:06
Total Lead Time	19D 9:25	23D 8:23	24D 11:32	22D 0:17	21D 10:04	23D 3:59
Minimum Added Value	37.12	28.19	37.15	46.03	46.8	30.03
Average Added Value	62.1	55.13	56.58	64.06	62.21	57.16
Maximum Added Value	99.58	95.32	82.62	82.02	78.56	90.75
Resource Min. Working %	23.33	29.17	26.04	20.82	23.74	30.21
Resource Avg. Working %	26.83	30.44	30.2	24.26	24.13	33.01
Resource Max. Working %	30.69	31.69	34.76	27.86	24.5	36.49
Resource Min. Idle %	4.93	3.06	0.52	7.71	11.41	0.78
Resource Avg. Idle %	8.83	4.39	5.15	11.31	11.79	4.26
Resource Max. Idle %	12.34	5.74	9.31	14.75	12.19	7.08
Resource Min. Utils %	65.19	83.42	73.39	58.34	65.9	80.75
Resource Avg. Utils %	74.99	87.07	85.12	68	66.99	88.23
Resource Max. Utils	85.78	90.64	97.98	78.08	68.01	97.53
Schedule Duration	9D 1:13	7D 23:26	8D 0:58	10D 0:12	10D 1:30	7D 8:33

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	25	50	75	100	100
Total Late Time	5D 11:03	8D 0:10	4D 15:58	4D 23:18	10D 7:54
Total Lead Time	19D 19:39	21D 17:05	22D 12:32	23D 6:30	28D 14:41
Minimum Added Value	48.66	21.48	39.98	29.01	19.65
Average Added Value	62.7	59.32	61.25	54.5	52.59
Maximum Added Value	91.98	89.73	86.92	87.54	78.32
Resource Min. Working %	15.76	28.76	29.07	28.23	25.85
Resource Avg. Working %	21.9	29.37	30.12	33.29	26.46
Resource Max. Working %	26.47	30.44	31.78	36.42	27.06
Resource Min. Idle %	9.73	6.21	3.76	0.32	9.07
Resource Avg. Idle %	14.29	7.26	5.41	3.25	9.62
Resource Max. Idle %	20.47	7.84	6.46	7.94	10.2
Resource Min. Utils %	43.41	78.25	81.52	76.56	71.4
Resource Avg. Utils %	60.36	79.89	84.46	90.28	73.11
Resource Max. Utils	72.93	82.82	89.13	98.76	24.74
Schedule Duration	11D 2:03	8D 6:27	8D 1:30	7D 7:03	9D 4:13

Table A3-22

6-Resources, 7NSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	20	40	60	20	20	80
Total Late Time	2D 10:01	4D 1:40	3D 16:20	2D 14:21	2D 15:14	9D 1:26
Total Lead Time	20D 15:55	26D 3:18	25D 12:29	20D 1:57	21D 3:00	31D 11:14
Minimum Added Value	71.56	31.31	50.69	68.45	63.69	39.33
Average Added Value	82.48	71	72.48	83.52	79.7	61.58
Maximum Added Value	99.58	99.61	94.05	99.63	99.63	91.49
Resource Min. Working %	7.21	5.9	7.71	7.39	5.25	4.85
Resource Avg. Working %	18.21	20.72	19.96	17.81	17.73	17.81
Resource Max. Working %	26.34	27.41	37.09	27.36	29.01	33.22
Resource Min. Idle %	9.04	7.94	0	8.95	7.52	3.05
Resource Avg. Idle %	17.19	14.51	17.2	18.5	18.86	18.43
Resource Max. Idle %	28.2	29.48	29.47	28.92	31.34	31.51
Resource Min. Utils %	20.31	16.63	20.69	20.3	14.32	13.33
Resource Avg. Utils %	51.31	58.46	53.55	48.93	48.33	48.89
Resource Max. Utils	74.19	77.33	99.52	75.16	79.06	91.21
Schedule Duration	8D 1:01	7D 1:38	7D 8:09	8D 5:21	8D 6:14	8D 5:24

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	20	80	40	40	60
Total Late Time	2D 15:38	9D 20:14	3D 5:33	1D 21:51	6D 11:14
Total Lead Time	20D 15:21	32D 8:32	23D 20:43	21D 15:16	25D 17:44
Minimum Added Value	77.53	35.54	35.86	53.62	35.3
Average Added Value	81.6	61.71	74.97	83.05	70.44
Maximum Added Value	95.65	91.49	94.12	99.61	95.65
Resource Min. Working %	7.13	5.45	5.8	12.92	4.95
Resource Avg. Working %	17.7	17.81	20.57	20.72	19.9
Resource Max. Working %	25.59	34.41	34.14	34.39	37.27
Resource Min. Idle %	11.11	1.87	1.03	0.31	0
Resource Avg. Idle %	19.02	18.43	15.13	14.51	17.42
Resource Max. Idle %	29.59	30.92	30.01	22.43	32.44
Resource Min. Utils %	19.37	14.95	16.16	36.45	13.23
Resource Avg. Utils %	48.07	48.89	57.28	58.46	53.17
Resource Max. Utils	69.51	94.46	95.06	97.01	99.57
Schedule Duration	8D 6:38	8D 5:24	7D 2:52	7D 1:38	7D 8:37

Table A3-23

8-Resources, 7NSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	25	25	50	25	25	50
Total Late Time	2D 10:38	2D 10:38	3D 3:24	2D 10:38	2D 17:55	2D 18:55
Total Lead Time	13D 19:46	17D 4:27	15D 19:48	15D 23:55	13D 21:56	15D 6:06
Minimum Added Value	77.18	55.79	54.46	68.6	81.11	59.61
Average Added Value	92.99	81.97	85.7	85.46	88.78	88.97
Maximum Added Value	99.58	99.61	98.31	90.85	99.5	98.31
Resource Min. Working %	7.37	3.44	3.32	3.68	4.71	3.44
Resource Avg. Working %	12.88	12.88	12.44	12.88	12.35	12.88
Resource Max. Working %	19.65	20.53	22.06	22.5	25.91	22.84
Resource Min. Idle %	15.71	14.85	14.95	12.88	11.56	12.53
Resource Avg. Idle %	22.44	22.44	23.59	22.44	25.13	22.44
Resource Max. Idle %	28.03	31.98	33.74	31.74	32.8	31.98
Resource Min. Utils %	20.79	9.7	8.96	10.39	12.55	9.7
Resource Avg. Utils %	36.34	36.34	33.55	36.34	32.9	36.34
Resource Max. Utils	55.43	57.93	59.49	63.47	69.01	64.44
Schedule Duration	7D 1:38	7D 1:38	7D 7:38	7D 1:38	7D 8:55	7D 1:38

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	25	50	50	50	50
Total Late Time	2D 17:55	2D 18:55	3D 2:12	2D 21:24	3D 3:03
Total Lead Time	13D 21:56	15D 6:06	15D 11:48	15D 13:48	17D 9:43
Minimum Added Value	81.11	59.61	54.46	54.46	56.9
Average Added Value	88.78	89.33	84.39	89.14	78.11
Maximum Added Value	99.5	99.5	94.63	99.61	90.39
Resource Min. Working %	4.71	3.44	1.67	7.37	0
Resource Avg. Working %	12.35	12.88	12.53	12.88	12.38
Resource Max. Working %	25.91	22.84	21.98	21.62	25.02
Resource Min. Idle %	11.56	12.53	14.59	13.8	12.28
Resource Avg. Idle %	25.13	22.44	24.07	22.44	24.96
Resource Max. Idle %	32.8	31.98	34.98	28.03	37.4
Resource Min. Utils %	12.55	9.7	4.56	20.79	0
Resource Avg. Utils %	32.9	36.34	34.18	36.34	33.1
Resource Max. Utils	69.01	64.44	59.96	60.98	66.9
Schedule Duration	7D 8:55	7D 1:38	7D 6:26	7D 1:38	7D 8:31

Table A3-24

3-Resources, 7aNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	45.45	54.55	100	27.27	27.27	72.73
Total Late Time	2D 19:00	9D 1:09	14D 17:14	8D 21:18	8D 17:18	15D 0:34
Total Lead Time	36D 1:29	35D 2:25	69D 16:21	44D 15:57	39D 10:46	58D 13:08
Minimum Added Value	5.54	5.78	8.38	12.8	11.6	7.7
Average Added Value	21.74	22.39	22.45	31.19	29.43	21.21
Maximum Added Value	99.16	94.38	42.07	59.49	97.92	43.13
Resource Min. Working %	32.14	32.8	30.45	27.61	24.74	29.48
Resource Avg. Working %	33.44	33.34	33.75	29.03	29.23	33.15
Resource Max. Working %	36.01	34.13	35.57	31.05	32.35	36.74
Resource Min. Idle %	0.17	2.38	0	5.99	4.3	0
Resource Avg. Idle %	2.66	2.99	1.83	8.06	7.44	3.56
Resource Max. Idle %	3.9	3.4	5.12	9.56	12	7.1
Resource Min. Utils %	87.84	89.17	84.56	73.66	66.76	79.38
Resource Avg. Utils %	91.42	90.63	93.72	77.46	78.86	89.25
Resource Max. Utils	98.43	92.79	98.77	82.85	87.28	98.9
Schedule Duration	7D 6:15	7D 6:48	7D 4:41	8D 8:44	8D 7:24	7D 7:48

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	27.27	45.45	81.82	81.82	54.55
Total Late Time	8D 16:32	12D 3:45	8D 18:56	7D 19:00	11D 2:27
Total Lead Time	33D 10:07	32D 1:25	60D 21:02	57D 3:10	59D 16:01
Minimum Added Value	10.06	6.11	7.61	5.92	7.91
Average Added Value	28.59	21.95	22.40	20.42	24.56
Maximum Added Value	85.14	89.94	46.08	58.93	51.44
Resource Min. Working %	25.52	26.95	32.22	32.49	28.21
Resource Avg. Working %	29.4	30.11	33.58	33.66	30.49
Resource Max. Working %	32.12	33.89	35.96	35.86	33.31
Resource Min. Idle %	3.78	0.94	0	0	1.05
Resource Avg. Idle %	4.53	4.97	1.07	1	3.95
Resource Max. Idle %	5.64	8.38	3.22	3	6.41
Resource Min. Utils %	69.56	75.57	79.2	79.11	80.9
Resource Avg. Utils %	80.14	84.42	89.21	89.46	87.44
Resource Max. Utils	87.55	95	98.84	99.1	95.52
Schedule Duration	8D 6:13	8D 1:32	7D 5:34	7D 5:09	7D 23:09

Table A3-25

6-Resources, 7aNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	0	46.15	38.46	15.38	15.38	38.46
Total Late Time	0	8D 18:08	5D 7:01	1D 23:37	2D 0:24	5D 11:42
Total Lead Time	36D 9:01	56D 19:47	55D 7:10	42D 17:54	39D 22:11	52D 16:55
Minimum Added Value	12.37	6.45	9.69	18.58	16.18	9.83
Average Added Value	40.77	27.24	30.87	39.49	41.36	30.96
Maximum Added Value	99.16	98.71	57.27	81.46	89.18	57.9
Resource Min. Working %	21.11	7.28	22.69	4.57	5.15	22.16
Resource Avg. Working %	27.06	20.45	26.68	19.83	20.25	26.73
Resource Max. Working %	34.29	32.26	40.61	30.95	29.99	40.55
Resource Min. Idle %	5.59	2.17	0	4.81	5.18	0
Resource Avg. Idle %	12.82	14.18	14.03	16.19	15.02	13.86
Resource Max. Idle %	18.73	27.47	18.05	31.64	30.23	18.4
Resource Min. Utils %	52.51	20.88	55.31	12.59	14.51	54.15
Resource Avg. Utils %	67.3	58.62	65.03	54.69	57.03	65.34
Resource Max. Utils	85.29	92.47	98.96	85.34	84.44	99.11
Schedule Duration	5D 7:06	7D 0:10	5D 8:53	7D 5:23	7D 1:48	5D 8:38

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	7.69	15.38	23.08	23.08	46.15
Total Late Time	2D 10:41	3D 6:44	1D 14:20	1D 15:58	5D 1:35
Total Lead Time	40D 3:28	40D 13:13	45D 10:26	43D 6:28	53D 0:47
Minimum Added Value	13.24	12.44	12.92	9.25	11.19
Average Added Value	37.59	36.98	36.86	32.86	33.38
Maximum Added Value	96.53	87.23	61.64	80.38	63.16
Resource Min. Working %	5.12	12.45	23.89	23.08	6.15
Resource Avg. Working %	17.76	27.63	27.46	28.43	20.48
Resource Max. Working %	28.57	35.89	38.92	37.61	32.46
Resource Min. Idle %	6.9	2.71	0	0	2.01
Resource Avg. Idle %	17.75	10.97	11.54	9.23	14.06
Resource Max. Idle %	30.5	26.22	15.14	14.52	28.58
Resource Min. Utils %	14.33	31.99	60.74	60.73	17.69
Resource Avg. Utils %	49.71	70.98	69.83	74.81	58.89
Resource Max. Utils	79.98	92.19	98.98	98.98	93.32
Schedule Duration	8D 1:41	5D 4:27	5D 5:15	5D 0:58	6D 23:54

Table A3-26

8-Resources, 7aNSF						
Schedule Performance	Earliest Due Date	First Come First Served	*Lowest Position Of Operation First*	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	0	0	0	9.09	0	0
Total Late Time	0	0	0	9H 33M	0	0
Total Lead Time	24D 22:41	24D 19:26	30D 11:08	23D 17:21	19D 19:48	27D 8:24
Minimum Added Value	15.61	15.4	15.34	34.38	26.58	15.06
Average Added Value	48.17	51.08	46.73	52.6	57.85	46.42
Maximum Added Value	99.16	98.71	84.72	84.04	92.7	86.07
Resource Min. Working %	10.94	15.42	19.55	6.36	14.9	19.71
Resource Avg. Working %	21.56	22.98	27.41	18.13	22.85	28.39
Resource Max. Working %	31.57	30.31	41.71	30.28	33.64	39.52
Resource Min. Idle %	7.91	6.27	0	7.13	3.31	0.24
Resource Avg. Idle %	17.97	13.65	14.51	19.42	14.12	11.48
Resource Max. Idle %	28.6	21.15	22.39	31.26	22.06	20.2
Resource Min. Utils %	27.47	41.77	46.22	16.83	39.99	48.98
Resource Avg. Utils %	54.16	62.23	61.22	47.98	61.33	70.57
Resource Max. Utils	79.31	82.11	87.49	80.13	90.27	98.22
Schedule Duration	4D 5:21	3D 23:07	3D 7:43	5D 0:33	3D 23:38	3D 4:58

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	*Maximum Cost Of Operation First*	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	0	0	0	0	0
Total Late Time	0	0	0	0	0
Total Lead Time	19D 19:34	27D 14:38	23D 23:40	29D 10:58	28D 22:41
Minimum Added Value	18.98	12.63	17.6	13.46	14.71
Average Added Value	56.93	46.66	51.96	43.91	44.85
Maximum Added Value	98.74	91.45	87.29	74.47	75.53
Resource Min. Working %	17.58	14.13	20.16	20.66	13.08
Resource Avg. Working %	22.6	22.33	27.54	27.36	27.22
Resource Max. Working %	28.43	32.86	36.13	41.94	37.57
Resource Min. Idle %	0	5.53	5.57	0	4.52
Resource Avg. Idle %	13.38	16.09	14.14	14.69	15.15
Resource Max. Idle %	20.09	24.33	21.45	21.35	29.43
Resource Min. Utils %	46.3	36.52	47.98	48.72	30.61
Resource Avg. Utils %	59.34	57.69	65.53	64.53	63.71
Resource Max. Utils	74.9	84.91	85.96	98.92	87.95
Schedule Duration	4D 0:43	4D 1:53	3D 7:21	3D 7:52	3D 8:18

Table A3-27

3-Resources, 7bNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	26.32	42.11	78.95	26.32	26.32	78.95
Total Late Time	2D 14:19	13D 10:49	25D 23:46	15D 10:56	15D 17:30	25D 19:28
Total Lead Time	38D 11:10	37D 21:18	117D 14:58	68D 11:22	59D 22:38	98D 14:47
Minimum Added Value	5.22	5.21	7.07	11.86	10.97	7.12
Average Added Value	13.98	12.92	13.25	19.94	18.14	12.44
Maximum Added Value	98.33	93.72	25.72	40.17	88.01	26.17
Resource Min. Working %	31.99	32.22	31.17	24.48	22.82	29.77
Resource Avg. Working %	33.24	33.24	33.59	27.05	26.87	33.25
Resource Max. Working %	34.13	34.55	35.54	30.13	30.2	36.28
Resource Min. Idle %	1.84	0	0	4.49	4.78	0
Resource Avg. Idle %	2.78	1.97	1.99	7.6	8.04	0.89
Resource Max. Idle %	4.06	3.92	4.35	10.11	11.9	2.66
Resource Min. Utils %	86.5	78.54	85.82	69.45	63.97	76.94
Resource Avg. Utils %	89.89	86.36	91.97	76.73	75.31	88.3
Resource Max. Utils	92.29	93.42	96.33	85.47	84.64	96.7
Schedule Duration	7D 7:20	7D 7:21	7D 5:31	8D 23:27	9D 0:53	7D 7:15
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First	
% Late Orders	21.05	31.58	78.95	52.63	47.37	
Total Late Time	6D 2:25	18D 12:43	15D 19:05	9D 12:05	16D 12:29	
Total Lead Time	29D 2:44	41D 23:42	103D 12:32	89D 3:43	93D 16:25	
Minimum Added Value	11.02	6.17	7.7	5.46	6.71	
Average Added Value	20.1	13.68	13.53	12.2	15.15	
Maximum Added Value	92.52	89.6	33.22	48.76	41.12	
Resource Min. Working %	33.14	32.55	32.35	32.34	31.12	
Resource Avg. Working %	33.39	33.87	33.72	33.61	32.97	
Resource Max. Working %	33.61	35.02	35.48	35.75	35.46	
Resource Min. Idle %	0	0.26	0	0	0	
Resource Avg. Idle %	1.84	1.14	0.4	1.72	3.18	
Resource Max. Idle %	3.2	2.35	1.21	2.69	5.27	
Resource Min. Utils %	79.01	90.96	78.42	89.14	80.12	
Resource Avg. Utils %	86.81	94.66	89.72	92.63	83.16	
Resource Max. Utils	91.1	97.86	98.37	98.54	86.31	
Schedule Duration	7D 6:32	7D 4:04	7D 4:51	7D 5:25	7D 8:44	

Table A3-28

6-Resources, 7bNSF						
Schedule Performance	Earliest Due Date	First Come First Served	*Lowest Position Of Operation First*	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	0	36	36	12	8	36
Total Late Time	0	10D 14:52	7D 15:17	3D 9:43	1D 21:12	8D 21:56
Total Lead Time	67D 12:24	86D 0:38	99D 17:30	68D 4:12	61D 12:26	95D 19:36
Minimum Added Value	9.49	6.84	9.94	13.63	14.42	9.99
Average Added Value	21.71	16.8	17.6	24.51	24.36	17.83
Maximum Added Value	98.33	98.07	40.51	58.46	86.4	41.44
Resource Min. Working %	12.51	10.32	23.99	5.52	4.99	23.8
Resource Avg. Working %	27.61	23.14	26.9	19.81	20.38	26.69
Resource Max. Working %	36.67	35.39	39.9	31.92	30.61	40.36
Resource Min. Idle %	1.74	0	0	0	3.91	0
Resource Avg. Idle %	10.76	13.39	12.93	15.51	14.2	13.75
Resource Max. Idle %	25.99	26.37	16	30.58	29.92	16.75
Resource Min. Utils %	32.11	27.73	59.16	15.18	14.2	58.03
Resource Avg. Utils %	70.86	59.29	66.35	52.88	58.02	61.63
Resource Max. Utils	94.09	77.71	98.39	78.14	87.18	77.79
Schedule Duration	5D 4:32	6D 4:36	5D 7:50	7D 5:37	7D 0:46	5D 8:51
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	*Lowest Op/Resource Flexibility First*	Highest Op/Resource Flexibility First	
% Late Orders	8	32	12	20	60	
Total Late Time	1D 21:30	9D 20:08	1D 9:54	3D 4:45	22D 16:34	
Total Lead Time	63D 22:53	74D 23:03	74D 12:59	65D 22:54	118D 23:48	
Minimum Added Value	12.63	8.55	12.86	8.89	8.53	
Average Added Value	22.96	20.36	21.54	18.12	16.19	
Maximum Added Value	86.08	86.42	36.13	54	58.7	
Resource Min. Working %	9.67	15.14	24.14	24.46	4.17	
Resource Avg. Working %	20.57	28.02	27.15	27.65	19.54	
Resource Max. Working %	31.9	38.29	39.34	38.33	36.64	
Resource Min. Idle %	2.04	0	0	0	0	
Resource Avg. Idle %	12.08	10.13	12.27	10.63	16.89	
Resource Max. Idle %	24.6	23.51	15.38	13.76	32.93	
Resource Min. Utils %	28.03	38.93	60.34	62.91	11.19	
Resource Avg. Utils %	59.63	72.04	67.85	71.12	49.42	
Resource Max. Utils	92.49	98.46	98.32	98.59	80.09	
Schedule Duration	6D 23:10	5D 2:44	5D 6:41	5D 4:21	7D 8:02	

Table A3-29

8-Resources, 7bNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	0	0	0	0	0	0
Total Late Time	0	0	0	0	0	0
Total Lead Time	27D 11:17	31D 0:38	51D 3:19	29D 7:55	27D 18:14	46D 14:40
Minimum Added Value	14.22	13.21	14.95	19.6	17.26	16.1
Average Added Value	35.76	32.3	28.18	38.08	35.68	28.84
Maximum Added Value	98.33	98.07	56.65	82.64	92.52	62.19
Resource Min. Working %	13.37	25.05	22.38	13.4	16.06	23.25
Resource Avg. Working %	22.33	29.86	27.04	22.68	27.34	28.36
Resource Max. Working %	33.81	35.63	40.73	32.95	36.8	39.47
Resource Min. Idle %	4.33	0	1.51	4.27	5.15	0
Resource Avg. Idle %	15.87	5.59	15.46	14.57	14.37	11.34
Resource Max. Idle %	24.9	10.77	20.15	23.85	25.92	16.72
Resource Min. Utils %	34.57	55.58	51.94	35.52	37.82	57.67
Resource Avg. Utils %	57.74	73.91	62.77	60.09	64.4	66.54
Resource Max. Utils	87.41	92.49	94.54	87.31	86.69	95.23
Schedule Duration	4D 1:51	3D 1:12	3D 8:49	4D 0:22	3D 7:56	3D 5:04

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	0	0	0	0	0
Total Late Time	0	0	0	0	0
Total Lead Time	30D 1:46	36D 23:43	38D 22:52	46D 22:45	46D 11:42
Minimum Added Value	16.38	13.9	18.22	13.51	15.49
Average Added Value	36.06	28.91	33.30	26.25	28.41
Maximum Added Value	94.38	82.96	60.96	49.89	62.57
Resource Min. Working %	20.8	14.53	22.78	22.89	16.11
Resource Avg. Working %	29.16	27.61	29.43	27.66	27.98
Resource Max. Working %	35.14	35.9	38.94	90.93	35.95
Resource Min. Idle %	3.67	5.58	0	0	0
Resource Avg. Idle %	10.15	13.68	9.35	13.35	10.27
Resource Max. Idle %	18.66	26.87	16.02	18.19	24.62
Resource Min. Utils %	52.06	34.69	57.8	54.8	39.18
Resource Avg. Utils %	73.01	65.93	74.67	66.22	64.63
Resource Max. Utils	87.97	85.72	98.8	97.98	87.44
Schedule Duration	3D 2:56	3D 7:09	3D 2:16	3D 7:00	3D 6:07

Table A3-30

3-Resource Scenario, 8NSF				
Schedule Performance	FF1/FF2	FF3	BF1/BF2	BF3/BF4
% Late Orders	33.33	33.33	33.33	66.67
Total Late Time	8D 6:04	9D 7:03	7D 3:45	11D 1:14
Total Lead Time	25D 6:34	31D 8:08	26D 19:28	37D 14:26
Minimum Added Value	24.38	32.75	24.32	21.53
Average Added Value	48.88	45.5	36.4	42.39
Maximum Added Value	90.04	90.04	77.96	77.96
Resource Min. Working %	28.17	20.5	20.34	21.23
Resource Avg. Working %	29.85	26.4	24.36	24.76
Resource Max. Working %	31.5	33.79	29.6	27.95
Resource Min. Idle %	4.35	3.42	7	8.02
Resource Avg. Idle %	6.09	10.91	8.64	9.31
Resource Max. Idle %	7.82	16.96	11.06	10.87
Resource Min. Utils %	77.88	54.64	55.3	58.79
Resource Avg. Utils %	82.52	70.39	66.23	68.56
Resource Max. Utils	87.09	90.09	80.48	77.4
Schedule Duration	9D 4:07	10D 8:50	11D 5:41	11D 1:19
6-Resource Scenario, 8NSF				
Schedule Performance	FF1/FF2	FF3	BF1/BF2	BF3/BF4
% Late Orders	16.67	16.67	33.33	50
Total Late Time	1D 14:16	1D 14:16	4D 20:14	5D 13:17
Total Lead Time	23D 18:22	22D 11:35	28D 18:30	30D 18:14
Minimum Added Value	43.89	35.08	37.24	36.04
Average Added Value	69.03	63.03	46.47	51.87
Maximum Added Value	94.19	90.04	68.74	72.82
Resource Min. Working %	6.21	8.74	5.67	4.42
Resource Avg. Working %	16.65	16.65	15.19	14.87
Resource Max. Working %	32.19	32.19	30.53	31.47
Resource Min. Idle %	4.08	4.08	4.8	4.73
Resource Avg. Idle %	19.82	19.62	20.17	21.39
Resource Max. Idle %	30.09	27.53	29.73	31.88
Resource Min. Utils %	17.07	24.04	15.97	12.14
Resource Avg. Utils %	45.77	45.77	42.83	40.89
Resource Max. *Utils*	88.48	88.48	86.07	86.52
Schedule Duration	8D 5:16	8D 5:16	9D 0:11	9D 4:50
8-Resource Scenario, 8NSF				
Schedule Performance	FF1/FF2	FF3	BF1/BF2	BF3/BF4
% Late Orders	44.44	22.22	22.22	33.33
Total Late Time	9D 23:09	7D 20:51	5D 1:53	10D 6:12
Total Lead Time	37D 10:24	34D 15:46	36D 18:56	40D 13:30
Minimum Added Value	39.88	44.69	16.04	16.04
Average Added Value	53.02	55.6	45.64	44.89
Maximum Added Value	90.04	90.04	72.82	72.82
Resource Min. Working %	8.91	7.14	7.74	6.02
Resource Avg. Working %	17.91	14.36	15.55	12.09
Resource Max. Working %	29.6	29.67	29.9	24.99
Resource Min. Idle %	6.24	6.6	7.33	6.06
Resource Avg. Idle %	18.02	21.92	20.11	22.61
Resource Max. Idle %	27.1	29.2	29.55	29.95
Resource Min. Utils %	24.74	19.65	20.75	16.73
Resource Avg. Utils %	49.73	39.51	41.7	33.62
Resource Max. Utils	82.18	81.63	80.19	69.48
Schedule Duration	8D 2:34	10D 2:42	9D 8:03	12D 0:08

Table A3-31

6-Resource Scenario, 8NSF							
Schedule Performance	A1 + Earliest Due Date	A1 + Critical Ratio	A1 + Minimum Setup Time First	A1 + Maximum Setup Time First	A1 + Minimum Operation Time First	A1 + Maximum Operation Time First	A1 + Lowest Position Of Operation First
% Late Orders	33.33	50	50	33.33	33.33	50	33.33
Total Late Time	3D 22:53	2D 18:08	4D 20:02	1D 8:08	2D 17:34	4D 9:34	2D 3:01
Total Lead Time	24D 0:25	26D 13:44	25D 20:46	23D 8:05	25D 17:06	25D 17:56	26D 9:28
Minimum Added Value	44.22	49.35	44.47	55.46	53.56	38.54	47.33
Average Added Value	60.09	62.69	59.26	66.68	66.09	65.23	64.44
Maximum Added Value	99.58	79.62	84	90.04	84.02	90.04	77.24
Resource Min. Working %	14.27	16.11	16.78	21.8	16.68	14.63	22.11
Resource Avg. Working %	16.7	18.84	19.63	25.5	19.52	17.11	25.86
Resource Max. Working %	19.27	21.75	22.65	29.43	22.53	19.75	29.85
Resource Min. Idle %	16.81	14.72	11.77	11.37	7.16	15.28	6.87
Resource Avg. Idle %	19.41	17.65	14.82	15.34	13.92	17.94	12.32
Resource Max. Idle %	21.82	20.38	17.67	19.03	18.13	20.42	15.74
Resource Min. Utils %	39.42	43.99	48.53	53.17	47.75	41.6	55.03
Resource Avg. Utils %	46.11	51.46	56.76	62.19	55.85	48.86	64.36
Resource Max. Utils	53.23	59.4	65.52	71.79	64.47	56.17	74.3
Schedule Duration	8D 4:44	7D 6:20	6D 23:22	5D 8:49	7D 0:19	8D 0:00	5D 7:02
Schedule Performance	A1 + First Come First Served	A1 + Highest Position Of Operation First	A1 + Lowest Remaining Duration First	A1 + Highest Remaining Duration First	A1 + Lowest Number Of Operations First	A1 + Highest Number Of Operations First	A1 + Maximum Cost Of Operation First
% Late Orders	50	33.33	33.3	33.33	16.67	66.67	50
Total Late Time	4D 11:46	2D 0:54	2D 20:57	1D 23:07	1D 14:46	2D 23:57	1D 21:22
Total Lead Time	22D 15:08	22D 4:34	24D 21:22	24D 8:49	22D 18:40	23D 9:24	24D 18:13
Minimum Added Value	42.69	63.4	51.47	50.84	58.97	50.12	49.84
Average Added Value	58.32	72.6	66.32	66.39	71.74	64.58	65.69
Maximum Added Value	99.63	97.11	97.11	83.51	90.18	81.01	87.14
Resource Min. Working %	16.68	18.77	16.45	18.85	18.75	16.2	16.17
Resource Avg. Working %	19.51	21.96	19.24	22.05	21.93	18.95	18.91
Resource Max. Working %	22.52	25.35	22.21	25.45	25.32	21.87	21.83
Resource Min. Idle %	12.31	11.79	13.49	11.62	11.83	14.24	14.41
Resource Avg. Idle %	15.34	15.2	16.49	15.06	15.24	17.19	17.35
Resource Max. Idle %	18.17	18.38	19.27	18.25	18.42	19.93	20.09
Resource Min. Utils %	47.68	50.33	45.89	50.82	50.25	44.68	44.44
Resource Avg. Utils %	55.77	58.87	53.67	59.2	58.78	52.26	51.97
Resource Max. Utils	64.37	67.95	61.96	68.34	67.85	60.33	59.99
Schedule Duration	7D 0:24	6D 5:36	7D 2:42	6D 4:58	6D 5:46	7D 5:21	7D 5:42

Table A3-32

8-Resource Scenario, 8NSF							
Schedule Performance	A1 + Earliest Due Date	A1 + Critical Ratio	A1 + Minimum Setup Time First	A1 + Maximum Setup Time First	A1 + Minimum Operation Time First	A1 + Maximum Operation Time First	A1 + Lowest Position Of Operation First
% Late Orders	44.44	55.56	55.56	55.56	44.44	55.56	55.56
Total Late Time	9D 21:23	6D 6:00	6D 18:49	4D 14:27	7D 9:28	6D 23:40	5D 10:08
Total Lead Time	42D 15:37	37D 13:13	34D 11:21	39D 21:13	38D 16:43	36D 14:38	38D 16:07
Minimum Added Value	34.79	42.46	43.24	27.79	48.8	38.54	41.01
Average Added Value	53.52	59.59	59.47	55.06	59.2	60.11	57.81
Maximum Added Value	99.58	74.57	78.47	90.04	81.34	94.12	72
Resource Min. Working %	10.78	12.94	13.36	14.87	13.08	11.81	15.14
Resource Avg. Working %	14.54	17.45	18.01	20.05	17.64	15.93	20.41
Resource Max. Working %	19.13	22.95	23.7	26.38	23.2	20.95	26.85
Resource Min. Idle %	16.41	14.2	11.93	10.02	13.27	15.28	8.99
Resource Avg. Idle %	20.92	19.62	17.54	16.26	18.75	20.23	15.34
Resource Max. Idle %	24.75	24.21	22.27	21.53	23.39	24.42	20.71
Resource Min. Utils %	30.34	34.82	37.48	40.84	35.85	32.6	42.22
Resource Avg. Utils %	40.92	46.97	50.56	55.09	48.36	43.97	56.95
Resource Max. Utils	53.83	61.78	66.51	72.46	63.61	57.83	74.91
Schedule Duration	9D 23:39	8D 7:41	8D 1:25	7D 5:45	8D 5:33	9D 2:45	7D 2:41
Schedule Performance	A1 + First Come First Served	A1 + Highest Position Of Operation First	A1 + Lowest Remaining Duration First	A1 + Highest Remaining Duration First	A1 + Lowest Number Of Operations First	A1 + Highest Number Of Operations First	A1 + Maximum Cost Of Operation First
% Late Orders	44.44	33.33	44.44	66.67	44.44	66.67	55.56
Total Late Time	7D 1:27	7D 2:29	6D 19:42	2D 20:05	7D 0:34	6D 14:06	6D 6:31
Total Lead Time	38D 10:08	37D 14:21	37D 6:04	37D 5:56	37D 10:54	40D 4:57	37D 7:55
Minimum Added Value	18.18	46.99	38.94	18.93	34.67	18.93	43.76
Average Added Value	52.62	60.55	57.57	58.61	55.69	55.93	62.52
Maximum Added Value	99.63	90.04	94.12	84.51	94.12	83.02	79.75
Resource Min. Working %	14.96	13.46	13.46	15.16	12.95	13.4	13.33
Resource Avg. Working %	20.18	18.15	18.15	20.45	17.47	18.07	17.98
Resource Max. Working %	26.54	23.89	23.88	26.91	22.97	23.77	23.66
Resource Min. Idle %	9.47	11.25	11.26	8.82	14.12	11.68	12.09
Resource Avg. Idle %	15.74	16.9	16.84	15.17	19.55	17.29	17.69
Resource Max. Idle %	21.05	21.67	21.68	20.56	24.14	22.05	22.41
Resource Min. Utils %	41.54	38.31	38.3	42.45	34.91	37.8	37.3
Resource Avg. Utils %	56.03	51.67	51.66	57.26	47.09	50.98	50.32
Resource Max. Utils	73.71	67.97	67.95	75.32	61.94	67.06	66.19
Schedule Duration	7D 4:41	7D 23:56	7D 23:57	7D 2:21	8D 7:30	8D 0:51	8D 1:45

Table A3-33

3-Resource Scenario, 9NSF				
Schedule Performance	FF1/2	FF3	BF1/2	BF3/4
% Late Orders	50	16.67	50	50
Total Late Time	7D 16:01	6D 10:29	7D 16:33	8D 18:13
Total Lead Time	27D 17:28	24D 14:47	31D 17:59	33D 23:39
Minimum Added Value	42.4	29.58	26.67	26.67
Average Added Value	58.99	42.43	47.81	46.45
Maximum Added Value	99.58	99.58	64.41	54.78
Resource Min. Working %	34.19	27.99	27.15	31.48
Resource Avg. Working %	34.51	28.38	30.37	32
Resource Max. Working %	35.11	28.65	34.07	32.45
Resource Min. Idle %	0.57	2.22	0	0
Resource Avg. Idle %	1.17	5.86	3.67	3.31
Resource Max. Idle %	1.52	8.05	9.96	5.43
Resource Min. Utils %	95.42	77.41	72.83	71.57
Resource Avg. Utils %	96.31	78.51	78.99	81.38
Resource Max. Utils	97.99	79.24	84.02	87.59
Schedule Duration	9D 1:24	11D 1:29	9D 8:01	9D 7:10
6-Resource Scenario, 9NSF				
Schedule Performance	FF1/2	FF3	BF1/2	BF3/4
% Late Orders	0	0	0	16.67
Total Late Time	0	0	0	14H 10M
Total Lead Time	20D 23:34	20D 23:34	14D 12:38	16D 2:56
Minimum Added Value	43	43	13.39	17:14
Average Added Value	74.74	74.74	42.36	49.61
Maximum Added Value	99.58	99.58	72.17	87.49
Resource Min. Working %	33.05	33.05	8.91	12.79
Resource Avg. Working %	35.12	35.12	18.37	23.91
Resource Max. Working %	37.45	37.45	27.93	31.78
Resource Min. Idle %	1.67	1.67	8.94	9.01
Resource Avg. Idle %	3.94	3.94	18.49	17.05
Resource Max. Idle %	6.09	6.09	27.96	28.26
Resource Min. Utils %	84.26	84.26	24.09	31.13
Resource Avg. Utils %	39.55	39.55	49.68	58.2
Resource Max. Utils	98.48	98.48	75.53	77.36
Schedule Duration	4D 4:22	4D 4:22	6D 7:33	5D 0:00
8-Resource Scenario, 9NSF				
Schedule Performance	FF1/2	FF3	BF1/2	BF3/4
% Late Orders	0	0	0	0
Total Late Time	0	0	0	0
Total Lead Time	22D 0:08	22D 0:08	16D 0:50	16D 0:50
Minimum Added Value	30.03	30.03	17.14	17.14
Average Added Value	61.74	61.74	42.23	42.23
Maximum Added Value	99.58	99.58	68.67	68.67
Resource Min. Working %	5.45	5.45	0	0
Resource Avg. Working %	21.04	21.04	12.75	12.75
Resource Max. Working %	37.39	37.39	24.67	24.67
Resource Min. Idle %	0	0	10.65	10.65
Resource Avg. Idle %	16.56	16.56	22.54	22.54
Resource Max. Idle %	33.22	33.22	35.36	35.36
Resource Min. Utils %	14.08	14.08	0	0
Resource Avg. Utils %	53.55	53.55	36.04	36.04
Resource Max. Utils	96.59	96.59	69.7	69.7
Schedule Duration	5D 2:22	5D 2:22	6D 2:16	6D 2:16

Table A3-34

3-Resources, 10aNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	83.33	50	100	66.67	33.33	100
Total Late Time	18D 1:18	14D 14:02	22D 5:49	13D 0:36	10D 5:27	23D 1:42
Total Lead Time	39D 15:10	31D 5:34	52D 11:18	36D 3:50	28D 21:43	48D 17:31
Minimum Added Value	30.3	32.62	25.03	34.93	52.47	21.8
Average Added Value	51.9	58.22	46.23	59.24	64.76	46.45
Maximum Added Value	99.58	99.58	70.99	96.05	99.58	70.97
Resource Min. Working %	23.92	29.22	30.39	29.34	30.91	30.98
Resource Avg. Working %	26.1	30.75	33.76	33.22	33.1	32.96
Resource Max. Working %	27.79	31.74	35.78	36.44	34.33	36.85
Resource Min. Idle %	8.03	4.06	0	0	2.31	0
Resource Avg. Idle %	9.69	5.08	2.01	3.24	3.54	2.07
Resource Max. Idle %	11.84	6.63	5.43	7.09	5.74	5.95
Resource Min. Utils %	66.63	81.26	84.63	80.23	84.07	83.64
Resource Avg. Utils %	72.71	85.52	94	90.8	90.03	88.99
Resource Max. Utils	77.43	88.27	99.56	99.67	93.38	99.49
Schedule Duration	12D 23:52	11D 0:40	10D 1:03	10D 5:08	10D 5:54	10D 6:58
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First	
% Late Orders	50	83.33	100	66.67	66.67	
Total Late Time	10D 14:15	19D 9:54	15D 7:16	15D 10:00	17D 22:41	
Total Lead Time	27D 8:58	34D 8:46	42D 0:59	32D 21:33	47D 7:06	
Minimum Added Value	31.31	19.49	37.63	30.95	35.08	
Average Added Value	59.78	52.6	52.51	53.8	48.66	
Maximum Added Value	99.58	85.04	76	97.21	67.73	
Resource Min. Working %	28.37	26.33	28.46	27.01	14	
Resource Avg. Working %	30.15	30.29	32.89	30.26	22.53	
Resource Max. Working %	33.62	35.36	37.05	36.52	28.83	
Resource Min. Idle %	3.07	1.04	0	0	6.3	
Resource Avg. Idle %	6.56	6.13	4.12	6.24	12.52	
Resource Max. Idle %	8.4	10.1	8.55	9.47	21.15	
Resource Min. Utils %	77.03	72.07	76.6	73.77	39.75	
Resource Avg. Utils %	81.87	82.91	88.52	82.77	63.95	
Resource Max. Utils	91.28	96.77	99.67	98.66	81.85	
Schedule Duration	11D 5:55	11D 4:40	10D 7:26	11D 5:00	15D 1:16	

Table A3-35

6-Resources, 10aNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	50	50	16.67	33.33	33.33	16.67
Total Late Time	7D 8:24	6D 16:53	2D 14:41	4D 8:39	5D 4:49	2D 14:57
Total Lead Time	33D 23:42	29D 1:27	28D 5:33	25D 18:23	26D 19:23	27D 21:47
Minimum Added Value	45.06	47.36	51.14	63.82	75.04	47.14
Average Added Value	67.46	75.27	78.13	82.04	82.79	75.37
Maximum Added Value	99.58	99.63	99.63	99.58	99.58	99.63
Resource Min. Working %	4.06	6.98	13.82	8.09	3.17	15.52
Resource Avg. Working %	18.72	20.53	23.43	20.35	20.62	23.39
Resource Max. Working %	29.98	31.19	35.31	29.26	30.91	36.03
Resource Min. Idle %	5.35	5.43	0.91	7.95	5.43	0.34
Resource Avg. Idle %	16.95	16.09	12.86	16.8	15.71	12.9
Resource Max. Idle %	31.71	29.64	22.46	29.08	33.22	20.93
Resource Min. Utils %	11.34	19.01	37.98	21.71	8.7	42.55
Resource Avg. Utils %	52.26	55.94	64.41	54.66	56.64	64.14
Resource Max. Utils	83.69	84.99	97.07	78.58	84.9	98.77
Schedule Duration	9D 1:22	8D 6:15	7D 5:41	8D 7:57	8D 5:21	7D 5:57

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	33.33	66.67	50	50	66.67
Total Late Time	5D 6:47	10D 4:56	5D 8:05	6D 15:20	8D 22:24
Total Lead Time	28D 4:52	37D 13:47	30D 6:11	32D 15:18	33D 23:56
Minimum Added Value	50.72	31.04	34.44	39.2	40.52
Average Added Value	75.24	63.09	75.89	68.96	65.59
Maximum Added Value	99.63	89.69	99.58	56.94	95.65
Resource Min. Working %	2.92	3.14	9.48	8.67	2.08
Resource Avg. Working %	20.39	18.27	23.87	20.95	16.96
Resource Max. Working %	36.99	33.07	35.68	23.17	28.75
Resource Min. Idle %	0	3.34	0	2.09	6.77
Resource Avg. Idle %	16.67	18.52	11.73	14.77	18.6
Resource Max. Idle %	34.18	33.76	26.19	27.14	33.54
Resource Min. Utils %	7.87	8.51	26.5	24.15	5.85
Resource Avg. Utils %	54.91	49.47	66.69	58.39	47.61
Resource Max. Utils	99.62	89.55	99.7	92.42	80.72
Schedule Duration	8D 7:37	9D 6:46	7D 2:31	8D 2:12	9D 23:59

Table A3-36

8-Resources, 10aNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	50	33.33	33.33	33.33	33.33	16.67
Total Late Time	6D 7:54	6D 2:16	3D 5:29	4D 5:14	4D 4:37	2D 10:38
Total Lead Time	29D 21:31	26D 10:01	26D 17:09	26D 11:35	26D 20:12	24D 20:33
Minimum Added Value	45.22	67.97	58.9	46.65	67.08	49.45
Average Added Value	78.1	83.93	83.93	81.83	82.42	87.36
Maximum Added Value	99.58	99.63	99.58	99.58	90.43	99.63
Resource Min. Working %	6.44	7.23	9.12	8.06	7.11	9.33
Resource Avg. Working %	15.72	15.4	17.57	15.53	17.59	17.99
Resource Max. Working %	30.04	23.79	26.29	25.44	33.63	27.76
Resource Min. Idle %	5.76	12.88	10.01	10.6	2.61	7.61
Resource Avg. Idle %	20.04	21.24	18.74	20.55	18.64	17.31
Resource Max. Idle %	29.4	29.4	27.26	28.09	29.15	26.12
Resource Min. Utils %	17.94	19.7	25.06	22.29	19.59	26.33
Resource Avg. Utils %	43.81	41.95	48.31	42.97	48.47	50.76
Resource Max. Utils	83.73	64.83	72.28	70.39	92.64	78.3
Schedule Duration	8D 2:10	8D 6:15	7D 5:41	8D 4:32	7D 5:28	7D 1:38
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First	
% Late Orders	33.33	33.33	33.33	33.33	33.33	
Total Late Time	4D 23:04	3D 4:06	3D 2:26	3D 4:10	6D 0:55	
Total Lead Time	26D 21:18	25D 14:19	26D 2:15	24D 8:52	28D 6:10	
Minimum Added Value	62.9	59.61	46.58	79.16	48.58	
Average Added Value	81.45	87.89	83.71	89.19	79.67	
Maximum Added Value	99.63	99.58	94.79	96.05	99.58	
Resource Min. Working %	7.38	9.33	8.89	8.99	7.33	
Resource Avg. Working %	15.9	17.99	17.99	17.99	14.13	
Resource Max. Working %	29.44	31.1	30.11	29.38	32.09	
Resource Min. Idle %	5.63	4.27	5.22	5.96	3.32	
Resource Avg. Idle %	19.16	17.31	17.31	17.31	21.26	
Resource Max. Idle %	27.69	26.12	26.48	26.42	28.11	
Resource Min. Utils %	21.02	26.33	25.08	25.36	20.68	
Resource Avg. Utils %	45.28	50.76	50.76	50.76	39.86	
Resource Max. Utils	83.83	87.72	87.72	82.87	90.55	
Schedule Duration	7D 23:54	7D 1:38	7D 1:38	7D 1:38	9D 0:04	

Table A3-37

3-Resources, 10bNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	66.67	50	100	50	50	100
Total Late Time	7D 12:26	14D 10:50	17D 22:45	9D 22:31	8D 20:34	20D 4:00
Total Lead Time	31D 17:30	37D 2:54	48D 3:49	33D 3:44	28D 22:01	47D 11:18
Minimum Added Value	37.47	24.45	25.85	25.8	42.4	22.17
Average Added Value	57.62	52.36	46.61	62.6	61.55	45.57
Maximum Added Value	99.29	99.29	62.64	92.65	99.58	70.72
Resource Min. Working %	23.58	21.71	28.61	28.71	25.17	34.13
Resource Avg. Working %	30.85	25.51	31.1	30.51	30.51	35.05
Resource Max. Working %	36.47	32.85	35.45	31.88	35.27	36.04
Resource Min. Idle %	0.77	3.24	0	0	1.38	0
Resource Avg. Idle %	6.38	10.56	4.41	4.73	6.14	0.97
Resource Max. Idle %	13.62	14.4	6.96	8.19	11.53	1.84
Resource Min. Utils %	63.1	59.99	80.28	77.48	68.45	94.39
Resource Avg. Utils %	82.54	70.48	87.25	81.87	82.95	96.92
Resource Max. Utils	97.58	90.76	99.44	84.65	95.91	99.66
Schedule Duration	9D 8:22	11D 1:38	10D 0:02	10D 7:02	10D 5:57	9D 2:31

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	50	66.67	66.67	66.67	66.67
Total Late Time	12D 10:23	18D 22:35	12D 7:19	12D 6:08	13D 4:30
Total Lead Time	30D 15:53	36D 11:04	38D 14:45	30D 1:09	41D 4:52
Minimum Added Value	27.05	16.45	31.01	33.54	29.09
Average Added Value	52.72	50.13	55.07	56.17	51.05
Maximum Added Value	99.58	79.64	75.38	90.24	89.92
Resource Min. Working %	26.48	26.41	29.57	26.87	18.62
Resource Avg. Working %	30.48	29.35	31.47	30.12	23.16
Resource Max. Working %	37.17	33.74	34.79	34.42	26.69
Resource Min. Idle %	0	2.17	1.41	0	9.27
Resource Avg. Idle %	6.68	6.51	4.72	5.8	12.8
Resource Max. Idle %	10.75	9.43	6.59	9.76	17.38
Resource Min. Utils %	71.02	73.4	81.4	73.06	51.64
Resource Avg. Utils %	81.74	81.57	86.63	79.19	64.22
Resource Max. Utils	99.68	93.79	95.76	85.46	74.03
Schedule Duration	10D 7:58	11D 0:45	10D 2:39	10D 5:57	13D 7:06

Table A3-38

6-Resources,10bNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	33.33	16.67	16.67	16.67	33.33	33.33
Total Late Time	23H 02M	9H 06M	15H 52M	2D 9:57	2D 1:46	2D 1:14
Total Lead Time	24D 9:58	21D 17:32	22D 7:27	24D 4:13	22D 1:50	25D 17:27
Minimum Added Value	36.3	24.92	43	45.6	65.38	33.89
Average Added Value	65.17	70.9	80.71	75.31	77.72	68.21
Maximum Added Value	98.9	98.9	99.58	99.58	99.58	99.58
Resource Min. Working %	3.75	9.25	17.6	6.51	3.72	11.69
Resource Avg. Working %	19.2	22.9	27.68	19.94	19.58	22.37
Resource Max. Working %	31.11	37.21	37.77	32.9	28.87	35.51
Resource Min. Idle %	5.99	2.39	2.12	2.16	5.89	1.6
Resource Avg. Idle %	17.82	16.71	12.3	15.15	15.05	14.72
Resource Max. Idle %	32.77	30.36	22.45	28.6	31.08	25.44
Resource Min. Utils %	10.07	23.29	43.91	18.5	10.68	31.42
Resource Avg. Utils %	51.56	57.63	69.03	56.68	56.22	60.15
Resource Max. Utils	83.53	93.65	94.2	93.5	82.91	95.47
Schedule Duration	6D 4:56	5D 6:06	5D 6:52	7D 0:57	7D 0:00	6D 4:20
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First	
% Late Orders	16.67	16.67	16.67	16.67	33.33	
Total Late Time	2D 8:59	16H 48M	1D 14:00	1D 9:20	3D 1:25	
Total Lead Time	22D 22:02	22D 19:31	24D 12:05	21D 17:59	23D 5:23	
Minimum Added Value	39.53	33.9	45.57	39.84	68.19	
Average Added Value	77.51	74.99	77.48	77.36	80.78	
Maximum Added Value	99.63	94.44	91	99.58	97.51	
Resource Min. Working %	1.24	9.39	15.77	11.84	13.28	
Resource Avg. Working %	19.91	26.12	24.26	22.45	20.6	
Resource Max. Working %	33.98	37.17	34.96	35.05	30.93	
Resource Min. Idle %	0.66	3.23	2.23	2.01	3.87	
Resource Avg. Idle %	14.81	14.3	12.88	14.62	14.18	
Resource Max. Idle %	33.52	31.1	21.36	25.2	21.58	
Resource Min. Utils %	3.56	23.17	42.34	31.83	38.1	
Resource Avg. Utils %	57.19	64.43	65.14	60.38	59.07	
Resource Max. Utils	97.61	91.7	93.84	94.25	88.71	
Schedule Duration	6D 23:59	5D 7:48	6D 5:00	6D 0:20	7D 0:07	

Table A3-39

8-Resources, 10bNSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	33.33	33.33	33.33	33.33	33.33	16.67
Total Late Time	2D 3:03	2D 0:08	2D 22:39	3D 9:14	4D 2:24	2D 8:58
Total Lead Time	26D 16:47	22D 16:21	24D 7:32	23D 16:46	25D 17:31	23D 1:48
Minimum Added Value	35.19	60.62	51.49	38.48	74.35	61.28
Average Added Value	71.12	81.41	85.02	81.64	84.56	85.37
Maximum Added Value	99.36	99.24	99.58	99.58	99.58	99.62
Resource Min. Working %	5.95	11.06	9.13	7.55	5.75	8.43
Resource Avg. Working %	14.55	16.54	16.81	15.4	17.17	16.56
Resource Max. Working %	31.79	27.8	27.26	30.21	32.46	26.64
Resource Min. Idle %	4.06	9.36	8.97	7.08	3.95	8.02
Resource Avg. Idle %	21.31	20.57	18.37	21.94	19.27	18.17
Resource Max. Idle %	29.94	26.11	27.12	29.79	30.72	26.31
Resource Min. Utils %	16.55	29.75	25.19	20.19	15.74	24.23
Resource Avg. Utils %	40.5	44.47	46.36	41.17	47.03	47.59
Resource Max. Utils	88.47	74.75	75.18	80.77	88.91	76.54
Schedule Duration	7D 2:55	6D 4:22	7D 5:21	7D 8:32	7D 6:03	6D 23:58

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	33.33	33.33	33.33	33.33	33.33
Total Late Time	5D 4:17	3D 3:46	3D 3:27	3D 2:37	5D 4:41
Total Lead Time	26D 4:41	23D 21:15	25D 8:32	23D 6:49	27D 2:36
Minimum Added Value	51.92	48.53	66.33	69.77	59.32
Average Added Value	79.71	86.04	84.99	87.25	79.68
Maximum Added Value	99.66	99.58	93.44	99.16	99.58
Resource Min. Working %	5.46	3.09	6.72	6.46	4.12
Resource Avg. Working %	14.73	16.35	17.17	16.66	14.75
Resource Max. Working %	28.03	28.25	33.46	32.64	32.03
Resource Min. Idle %	8.14	7.1	2	2.52	3.79
Resource Avg. Idle %	21.43	18.96	18.3	18.49	21.05
Resource Max. Idle %	30.74	32.32	28.72	28.72	31.72
Resource Min. Utils %	15.08	8.73	18.92	18.34	11.49
Resource Avg. Utils %	40.67	46.11	48.31	47.31	41.13
Resource Max. Utils	77.39	79.68	94.17	92.69	89.3
Schedule Duration	8D 4:47	7D 1:38	7D 1:51	7D 1:01	8D 2:07

Table A3-40

3-Resource Scenario, 1SF

Schedule Performance	Earliest Due Date	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	83.33	66.67	50	83.33	66.67	66.67	66.67
Total Late Time	27D 22:22	14D 17:56	16D 21:37	19D 5:50	16D 12:36	20D 23:04	17D 12:22
Total Lead Time	42D 5:03	19D 12:44	23D 22:08	33D 11:40	29D 14:14	38D 16:48	27D 5:04
Minimum Added Value	30.46	25.6	25.03	19.59	29.67	27.88	19.76
Average Added Value	43.54	39.56	40.38	35.58	39.53	38.29	40.28
Maximum Added Value	99.58	74.25	57.62	76.77	61.3	73.48	73.97
Resource Min. Working %	16.15	10.88	8.96	11.4	10.86	13.64	11.4
Resource Avg. Working %	19.89	14.62	14.15	15.32	14.59	15.08	15.32
Resource Max. Working %	23.05	19.39	19.69	20.32	19.36	17.29	20.32
Resource Min. Idle %	12.4	16.17	15.75	16.07	16.24	18.2	16.07
Resource Avg. Idle %	15.54	20.93	21.28	21.06	20.98	20.41	21.05
Resource Max. Idle %	19.25	24.68	26.48	24.98	24.73	21.83	24.97
Resource Min. Utils %	45.49	30.55	25.24	31.28	30.47	38.36	31.28
Resource Avg. Utils %	56.02	41.05	39.87	42.04	40.94	42.41	42.04
Resource Max. Utils	64.93	54.45	55.48	55.77	54.31	48.62	55.77
Schedule Duration	17D 1:17	23D16:41	24D 12:02	22D 18:09	23D 17:35	22D 23:30	22D 18:41

Schedule Performance	First Come First Served	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
% Late Orders	50	66.67	66.67	100	66.67	83.33	66.67
Total Late Time	23D 19:07	12D 10:33	11D 11:22	22D 23:34	11D 11:22	24D 3:50	14D 17:56
Total Lead Time	28D 13:17	27D 2:50	27D 3:05	35D 17:45	27D 3:05	37D 15:56	19D 12:44
Minimum Added Value	20.26	34.94	37.24	25.45	37.24	25.45	25.6
Average Added Value	47.75	42.56	45.22	33.8	45.22	34.04	39.56
Maximum Added Value	99.63	73.48	84.63	48.24	84.63	48.24	74.25
Resource Min. Working %	18.39	11.41	11.41	9.66	11.41	12.27	10.88
Resource Avg. Working %	22.65	15.34	15.34	14.8	15.34	14.87	14.62
Resource Max. Working %	26.26	20.35	20.34	20.43	20.34	18.07	19.39
Resource Min. Idle %	8.54	15.98	5.99	15.63	5.99	18.19	16.17
Resource Avg. Idle %	12.12	20.97	20.98	21.24	20.98	21.4	20.93
Resource Max. Idle %	16.36	24.9	24.91	26.38	24.91	24.03	24.68
Resource Min. Utils %	52.75	31.38	31.37	26.74	31.37	33.76	30.55
Resource Avg. Utils %	64.97	42.17	42.16	40.98	42.16	40.92	41.05
Resource Max. Utils	75.31	55.94	55.92	56.58	55.92	49.49.74	54.45
Schedule Duration	14D 23:16	22D 18:10	22D 18:13	23D 14:08	22D 18:13	23D 11:12	23D 17:00

Table A3-41

6-Resource Scenario, 1SF							
Schedule Performance	Earliest Due Date	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	66.67	100	66.67	100	100	66.67	100
Total Late Time	14D 10:54	30D 5:13	14D 10:54	42D 9:36	46D 0:34	13D 19:01	52D 10:28
Total Lead Time	29D 9:01	51D 10:14	29D 9:01	67D 5:21	70D 21:47	30D 13:55	76D 23:54
Minimum Added Value	35.73	28.62	35.73	20	20.35	01:55	19.2
Average Added Value	44.1	39.43	44.1	34.05	32.19	42.48	30.41
Maximum Added Value	69.27	55.58	69.27	46.44	40.31	84.63	44.54
Resource Min. Working %	1.71	1.8	1.71	1.8	1.73	1.8	1.8
Resource Avg. Working %	7.59	8.8	7.59	8.79	8.44	8.38	8.8
Resource Max. Working %	23.97	30.08	23.97	30.06	28.85	27.48	30.09
Resource Min. Idle %	11.59	6.09	11.59	6.16	6.68	8.44	6.07
Resource Avg. Idle %	27.99	27.41	27.99	27.46	27.12	27.58	27.39
Resource Max. Idle %	33.9	34.43	33.9	34.48	33.86	34.18	34.41
Resource Min. Utils %	4.81	4.97	4.81	4.96	4.85	5.02	4.97
Resource Avg. Utils %	21.32	24.27	21.32	24.23	23.7	23.28	24.29
Resource Max. Utils	67.31	83.01	67.31	82.85	81.06	76.36	83.06
Schedule Duration	22D 14:04	19D 6:39	22D 14:04	19D 6:59	20D 2:22	20D 14:14	19D 6:33
Schedule Performance	First Come First Served	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
% Late Orders	66.67	66.67	66.67	83.33	66.67	83.33	50
Total Late Time	33D 2:40	11D 16:28	11D 16:28	34D 20:01	17D 15:02	32D 10:59	28D 16:38
Total Lead Time	44D 9:04	28D 2:24	28D 2:24	55D 0:14	34D 0:58	52D 15:12	46D 10:25
Minimum Added Value	20.92	38.52	38.52	31.47	23.21	29.23	27.09
Average Added Value	40.83	44.67	44.67	38.41	38.91	39.99	41.69
Maximum Added Value	99.63	84.63	84.63	70.06	84.63	70.06	87.14
Resource Min. Working %	1.91	1.8	1.8	1.83	1.8	1.83	1.7
Resource Avg. Working %	9.33	8	8	8.93	8.05	8.93	8.32
Resource Max. Working %	31.91	25.26	25.26	30.54	25.59	30.54	28.47
Resource Min. Idle %	3.82	10.82	10.82	4.86	7.51	4.86	7.15
Resource Avg. Idle %	26.43	28.11	28.11	26.51	27.61	26.51	27.32
Resource Max. Idle %	33.88	34.33	34.33	33.64	34.39	33.64	33.97
Resource Min. Utils %	5.34	4.99	4.99	5.16	4.98	5.16	4.78
Resource Avg. Utils %	26.07	22.13	22.13	25.17	22.24	25.17	23.33
Resource Max. Utils	89.14	69.89	69.89	86.09	70.7	86.09	79.77
Schedule Duration	18D 4:07	21D 13:22	21D 13:22	18D 23:39	21D 13:48	18D 23:39	20D 8:54

Table A3-42

8-Resource Scenario, 1SF							
Schedule Performance	Earliest Due Date	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	83.33	83.33	66.67	83.33	83.33	66.67	100
Total Late Time	32D 20:14	28D 7:26	25D 9:25	39D 16:30	34D 22:35	36D 1:53	34D 15:12
Total Lead Time	42D 13:11	48D 11:02	45D 19:59	65D 1:35	60D 7:40	58D 4:40	59D 3:38
Minimum Added Value	22.04	30.23	29.5	17.24	25.84	14:52	27.35
Average Added Value	41.05	42.52	42.92	33.14	34.99	36.64	38.01
Maximum Added Value	99.58	59.36	70.11	47.21	45.74	59.72	51.16
Resource Min. Working %	0	0	0	0	0	0	0
Resource Avg. Working %	7.77	6.7	6.66	7.39	7.39	7.45	7.77
Resource Max. Working %	18.45	15.9	15.81	17.56	17.56	17.7	18.46
Resource Min. Idle %	17.9	19.57	20.02	18.24	18.25	17.84	17.85
Resource Avg. Idle %	28.58	28.79	29.18	28.4	28.41	27.66	28.53
Resource Max. Idle %	36.37	35.51	35.87	35.82	35.82	35.57	36.34
Resource Min. Utils %	0	0	0	0	0	0	0
Resource Avg. Utils %	21.36	18.86	18.56	20.63	20.63	20.95	21.39
Resource Max. Utils	50.73	44.79	44.09	49.01	49.01	49.75	50.81
Schedule Duration	16D 8:55	18D 23:52	19D 2:26	17D 4:56	17D 4:56	17D 1:43	16D 8:41
Schedule Performance	First Come First Served	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
% Late Orders	66.67	66.67	66.67	83.33	66.67	83.33	66.67
Total Late Time	27D 10:16	22D 2:37	22D 2:37	33D 20:20	22D 20:39	31D 23:20	25D 3:08
Total Lead Time	36D 19:37	44D 0:54	44D 0:54	56D 12:23	44D 18:56	54D 15:23	47D 9:25
Minimum Added Value	20.52	36.37	36.37	26.49	32.1	28.65	28.16
Average Added Value	46.74	44.16	44.16	39.13	43.92	39.86	41.94
Maximum Added Value	99.63	65.67	65.67	53.44	65.67	53.44	66.38
Resource Min. Working %	0	0	0	0	0	0	0
Resource Avg. Working %	8.86	7.03	7.03	7.44	7.08	7.44	7.03
Resource Max. Working %	21.06	16.7	16.7	17.66	16.82	17.66	16.7
Resource Min. Idle %	15.03	19.01	19.01	17.99	18.44	17.99	15.78
Resource Avg. Idle %	27.21	28.26	28.26	27.79	27.77	27.79	28.27
Resource Max. Idle %	36.11	35.73	35.73	35.68	35.28	35.68	35.73
Resource Min. Utils %	0	0	0	0	0	0	0
Resource Avg. Utils %	24.55	19.68	19.68	20.84	20.07	20.84	19.67
Resource Max. Utils	58.31	46.75	46.75	49.51	47.67	49.51	46.73
Schedule Duration	14D 8:20	18D 2:05	18D 2:05	17D 2:26	17D 23:05	17D 2:26	18D 2:08

Table A3-43

3-Resources, 2SF							
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Maximum Cost Of Operation First
No. of Incomplete Orders	0	0	1(3)	1(2)	1(2)	1(3)	1(2)
% Late Orders	83.33	50	83.33	33.33	50	83.33	50
Total Late Time	25D 16:39	29D 8:17	33D 15:09	16D 0:56	16D 7:46	53D 19:51	17D 18:06
Total Lead Time	42D 1:28	36D 8:50	37D 0:15	27D 8:24	31D 11:16	46D 12:34	33D 16:50
Minimum Added Value	26.79	22.72	18.96	24.61	28.64	14.14	24.31
Average Added Value	43.75	41.57	25.72	37.07	38.3	19.87	34.03
Maximum Added Value	99.58	99.63	36.74	69.87	54.58	26.81	55.36
Resource Min. Working %	20.31	17.63	13.18	14.74	14.22	13.21	14.24
Resource Avg. Working %	23.17	20.11	14.73	15.2	14.66	14.75	14.8
Resource Max. Working %	27.16	23.56	16.13	15.99	15.43	16.16	15.45
Resource Min. Idle %	7.78	12.01	19.71	20.41	20.02	19.59	19.99
Resource Avg. Idle %	11.76	15.46	21	21.24	20.82	21.03	20.67
Resource Max. Idle %	14.63	17.95	22.25	21.72	21.28	22.58	21.25
Resource Min. Utils %	57.94	49.4	36.65	40.35	39.98	36.82	40.04
Resource Avg. Utils %	66.1	56.36	40.94	41.61	41.22	41.13	41.61
Resource Max. Utils	77.47	66.05	44.84	43.79	43.38	45.05	43.45
Schedule Duration	14D 1:13	16D 4:39	19D 4:46	19D 8:45	20D 1:42	19D 4:00	20D 1:10

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Critical Ratio
No. of Incomplete Orders	1(2)	1(3)	1(3)	1(2)	1(3)	1(4)	1(2)
% Late Orders	50	83.33	33.33	50	83.33	33.33	50
Total Late Time	14D 11:19	28D 6:10	5D 5:52	17D 8:59	29D 20:12	14D 6:15	21D 14:31
Total Lead Time	30D 19:15	28D 1:57	19D 8:13	32D 21:33	33D 9:37	29D 21:09	34D 11:18
Minimum Added Value	29.77	18.44	31.77	15.06	23.48	35.61	27.32
Average Added Value	40.38	28.82	44.83	30.78	26.86	39.5	35.89
Maximum Added Value	84.58	41.86	76.99	57.75	36.67	53.67	64.44
Resource Min. Working %	14.79	13.09	14.06	14.12	13.1	12.17	10.75
Resource Avg. Working %	15.37	14.62	14.55	14.9	14.63	14.66	14.91
Resource Max. Working %	16.05	16.01	15.37	16.3	16.03	18.18	18.75
Resource Min. Idle %	20.12	20.33	20.18	19.19	20.24	17.28	16.83
Resource Avg. Idle %	20.83	21.75	21	20.59	21.66	20.8	20.67
Resource Max. Idle %	21.43	23.29	21.52	21.39	23.2	23.31	24.85
Resource Min. Utils %	40.76	35.89	39.44	39.69	36	34.23	30.14
Resource Avg. Utils %	42.36	40.09	40.83	41.89	40.22	41.25	41.8
Resource Max. Utils	44.23	43.91	43.13	45.82	44.05	51.15	52.58
Schedule Duration	19D 7:04	19D 8:16	20D 7:22	20D 5:12	19D 7:44	20D 0:48	20D 8:20

Table A3-44

6-Resources, 2SF							
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Maximum Cost Of Operation First
% Late Orders	66.67	50	66.67	50	50	66.67	50
Total Late Time	12D 0:40	13D 18:07	33D 17:33	17D 18:08	19D 10:26	30D 3:24	17D 9:30
Total Lead Time	29D 20:16	22D 13:38	52D 1:33	33D 15:15	36D 10:00	49D 4:02	35D 6:11
Minimum Added Value	17.81	20.64	24.2	34.03	32.85	24.36	34.93
Average Added Value	43.77	44.73	29.64	42.19	40.32	30.29	43.07
Maximum Added Value	98.9	98.9	40.75	99.58	80.16	35.82	73.71
Resource Min. Working %	3.65	2.62	1.04	0.96	0.92	1.04	0.97
Resource Avg. Working %	11.53	11.59	8.82	8.1	7.95	8.7	8.23
Resource Max. Working %	23.01	24.1	27.91	24.81	24.63	19.39	18.44
Resource Min. Idle %	13.28	12.38	6.78	11.05	10.59	15.83	17.09
Resource Avg. Idle %	24.77	24.89	25.96	27.84	27.35	26.64	27.36
Resource Max. Idle %	32.68	33.84	33.78	35.02	34.42	34.34	34.66
Resource Min. Utils %	10.02	7.16	3	2.67	2.6	2.92	2.72
Resource Avg. Utils %	31.69	31.68	25.33	22.51	22.49	24.58	23.08
Resource Max. Utils	63.23	65.9	80.1	68.92	69.66	54.79	51.73
Schedule Duration	10D 4:28	10D 5:09	14D 23:09	16D 6:37	17D 0:23	15D 2:13	16D 2:54
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Critical Ratio
% Late Orders	50	100	50	50	50	66.67	66.67
Total Late Time	17D 13:01	36D 3:13	20D 16:16	19D 1:51	18D 20:35	23D 3:19	21D 11:38
Total Lead Time	36D 12:47	46D 3:00	35D 4:33	40D 1:54	38D 2:47	40D 9:43	40D 22:15
Minimum Added Value	32.28	9.97	27.38	32.14	30.77	33.06	29.75
Average Added Value	38.03	26.81	40.90	40.55	37.46	36.87	34.28
Maximum Added Value	65.16	49.51	90.21	54.58	62.78	66.57	44.69
Resource Min. Working %	1.1	1.19	1.09	0.98	1.1	0.86	1.89
Resource Avg. Working %	8.88	9.63	9.01	8.52	8.85	8.14	8.79
Resource Max. Working %	21.58	24.07	21.94	18.17	20.91	22.07	20.81
Resource Min. Idle %	13.9	11.72	14.02	16.52	12.09	13.57	14.37
Resource Avg. Idle %	26.61	26.22	27.01	26.45	25.89	27.55	26.4
Resource Max. Idle %	34.43	34.71	34.96	34.08	34.34	34.86	33.37
Resource Min. Utils %	3.09	3.3	3.02	2.79	3.1	2.42	5.35
Resource Avg. Utils %	24.98	26.82	24.96	24.29	24.94	22.77	24.9
Resource Max. Utils	60.71	67.02	60.8	51.8	58.92	61.75	58.94
Schedule Duration	14D 5:20	13D 4:02	14D 8:11	15D 23:30	14D 5:04	18D 2:12	14D 4:02

Table A3-45

8-Resources, 2SF							
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Maximum Cost Of Operation First
% Late Orders	66.67	66.67	83.33	66.67	66.67	83.33	66.67
Total Late Time	19D 18:39	27D 12:11	27D 19:51	19D 7:01	19D 7:01	22D 13:36	18D 17:22
Total Lead Time	39D 6:37	37D 23:44	46D 3:58	37D 23:30	37D 23:30	39D 4:09	39D 6:08
Minimum Added Value	18.53	20.27	28.2	34.28	34.28	28.01	25.96
Average Added Value	42.54	42.01	40.58	46.17	46.17	42.49	43.44
Maximum Added Value	99.58	99.63	54.44	65.67	65.67	61.56	69.15
Resource Min. Working %	3.65	3.9	3.63	3.41	3.41	3.25	3.41
Resource Avg. Working %	8.54	9.13	8.51	7.99	7.99	7.62	7.99
Resource Max. Working %	15.11	16.15	15.06	14.13	14.13	13.48	14.14
Resource Min. Idle %	20.69	19.93	20.98	21.77	21.77	21.73	21.74
Resource Avg. Idle %	27.26	26.95	27.52	27.43	27.43	27.59	27.88
Resource Max. Idle %	32.17	32.21	32.4	32.5	32.5	31.98	32.48
Resource Min. Utils %	10.17	10.78	10.07	9.48	9.48	9.22	9.49
Resource Avg. Utils %	23.84	25.27	23.6	22.22	22.22	21.61	22.25
Resource Max. Utils	42.16	44.7	41.74	39.31	39.31	38.23	39.36
Schedule Duration	14D 6:56	13D 8:54	14D 8:11	15D 6:52	15D 6:52	16D 0:34	15D 6:42
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Critical Ratio
% Late Orders	66.67	83.33	83.33	83.33	83.33	66.67	83.33
Total Late Time	19D 7:01	25D 6:31	21D 18:49	18D 23:26	20D 22:00	19D 7:01	27D 12:38
Total Lead Time	37D 23:30	41D 22:50	39D 4:37	39D 7:34	39D 1:00	38D 5:30	44D 0:03
Minimum Added Value	34.28	28.61	28.73	30.55	33.41	34.28	27.46
Average Added Value	46.17	40.61	43.46	44.53	42.85	46.17	38.58
Maximum Added Value	65.67	61.56	73.78	65.96	56.97	65.67	61.56
Resource Min. Working %	3.41	3.35	3.39	3.45	3.4	3.41	3.06
Resource Avg. Working %	7.99	7.63	7.95	8.09	7.97	7.99	7.18
Resource Max. Working %	14.13	13.49	14.07	14.3	14.09	14.13	12.7
Resource Min. Idle %	21.77	21.64	22.11	21.08	21.97	21.77	22.59
Resource Avg. Idle %	27.43	27.51	28.23	27.26	28.09	27.43	28.1
Resource Max. Idle %	32.5	31.9	32.8	31.94	32.66	32.5	32.24
Resource Min. Utils %	9.48	9.25	9.37	9.74	9.41	9.48	8.67
Resource Avg. Utils %	22.22	21.68	21.95	22.83	22.06	22.22	20.32
Resource Max. Utils	39.31	38.35	38.84	40.38	39.03	39.31	35.95
Schedule Duration	15D 6:52	16D 0:09	15D 8:28	15D 2:21	15D 7:48	15D 6:52	17D 0:11

Table A3-46

3-Resources, 3SF							
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Maximum Cost Of Operation First
% Late Orders	75	100	100	75	75	100	100
Total Late Time	12D 12:28	18D 2:57	27D 23:31	17D 12:15	16D 8:40	27D 23:31	20D 3:26
Total Lead Time	28D 3:12	32D 8:40	46D 16:30	32D 23:39	30D 17:01	44D 9:51	38D 20:25
Minimum Added Value	24.86	18.18	19.71	30.72	33.73	19.71	27.49
Average Added Value	46.13	39.2	32.83	36.3	37.95	31.36	34.11
Maximum Added Value	99.58	73.37	43.58	59.06	63.9	41.94	38
Resource Min. Working %	4.91	4.49	3.09	3.09	3.09	3.09	3.09
Resource Avg. Working %	21.47	19.64	13.52	13.52	13.52	13.52	13.52
Resource Max. Working %	29.78	27.24	18.75	18.75	18.75	18.75	18.75
Resource Min. Idle %	7.31	10.15	13.24	16.24	16.24	13.22	10.48
Resource Avg. Idle %	15.63	17.76	20.63	21.63	21.63	20.54	21.72
Resource Max. Idle %	32.24	32.96	32.17	32.17	32.17	32.17	32.18
Resource Min. Utils %	13.21	11.99	8.76	8.76	8.76	8.76	8.76
Resource Avg. Utils %	57.72	52.39	38.31	38.31	38.31	38.31	38.29
Resource Max. Utils	80.06	72.67	53.13	53.13	53.13	53.13	53.12
Schedule Duration	11D 7:28	12D 8:44	17D 23:08	17D 23:08	17D 23:08	17D 23:08	17D 23:11
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Critical Ratio
% Late Orders	75	75	100	100	100	100	100
Total Late Time	16D 2:40	29D 11:51	19D 21:01	17D 13:49	21D 21:49	30D 5:20	17D 16:42
Total Lead Time	30D 16:03	44D 17:56	35D 20:24	34D 0:09	37D 9:14	47D 11:44	34D 0:24
Minimum Added Value	33.93	10.18	32.52	29.56	26.39	10.18	30.83
Average Added Value	38.16	29.56	35.42	36.38	33.27	30.92	35.46
Maximum Added Value	59.26	46.99	44.49	57.78	39.15	44.37	57.85
Resource Min. Working %	3.09	3.08	3.09	3.09	3.09	3.08	3.09
Resource Avg. Working %	13.52	13.46	13.52	13.52	13.52	13.46	13.52
Resource Max. Working %	18.75	18.68	18.75	18.75	18.75	18.68	18.75
Resource Min. Idle %	16.24	16.8	16.24	16.24	16.24	16.8	16.24
Resource Avg. Idle %	21.63	22.01	21.63	21.63	21.63	22.02	21.63
Resource Max. Idle %	32.17	32.44	32.17	32.17	32.17	32.44	32.17
Resource Min. Utils %	8.76	8.67	8.76	8.76	8.76	8.67	8.76
Resource Avg. Utils %	38.31	37.88	38.31	38.31	38.31	37.88	38.31
Resource Max. Utils	53.13	52.55	53.13	53.13	53.13	52.55	53.13
Schedule Duration	17D 23:08	18D 0:50	17D 23:08	17D 23:08	17D 23:08	18D 0:50	17D 23:08

Table A3-47

6-Resources, 3SF							
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Maximum Cost Of Operation First
% Late Orders	80	100	100	80	80	100	100
Total Late Time	14D 18:37	20D 12:24	25D 15:07	11D 10:39	11D 10:39	22D 21:19	13D 20:40
Total Lead Time	27D 4:46	33D 2:11	49D 21:09	32D 8:34	32D 8:34	45D 4:38	34D 9:38
Minimum Added Value	24.5	17.64	27.42	39.97	39.97	28.33	34.91
Average Added Value	45.58	38.52	35.06	48.27	48.27	36.45	44.21
Maximum Added Value	99.58	87.12	48.02	90.21	90.21	45.47	53.28
Resource Min. Working %	2.71	3.18	2.67	2.51	2.51	2.69	2.68
Resource Avg. Working %	10.18	11.91	10.01	9.4	9.4	10.08	10.06
Resource Max. Working %	17.32	20.26	17.03	15.99	15.99	17.15	17.12
Resource Min. Idle %	17.73	15.69	18.81	19.68	19.68	14.14	18.43
Resource Avg. Idle %	24.87	24.12	25.22	26.32	26.32	24.69	25.48
Resource Max. Idle %	32.42	32.9	33.27	33.24	33.24	32.8	32.65
Resource Min. Utils %	7.72	8.8	7.42	7.01	7.01	7.57	7.53
Resource Avg. Utils %	28.97	33.01	27.84	26.29	26.29	28.4	28.23
Resource Max. Utils	49.28	56.15	47.36	44.72	44.72	48.31	48.03
Schedule Duration	14D 1:42	12D 0:41	14D 7:31	15D 5:48	15D 5:48	14D 5:05	14D 5:48
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Critical Ratio
% Late Orders	80	100	80	100	100	100	100
Total Late Time	13D 2:22	21D 11:48	11D 5:35	19D 6:19	16D 12:57	21D 1:47	14D 10:25
Total Lead Time	35D 8:04	42D 21:52	29D 11:50	43D 15:24	39D 22:42	41D 22:31	34D 2:41
Minimum Added Value	32.72	31.06	39.69	26.97	34.62	34.44	32.17
Average Added Value	44.83	38.99	48.13	37.81	42.8	41.57	43.34
Maximum Added Value	62.88	47.15	64.14	48.21	49.16	47.65	54.14
Resource Min. Working %	2.52	2.71	2.72	2.68	2.66	2.38	2.88
Resource Avg. Working %	9.44	10.16	10.19	10.07	9.99	8.93	10.79
Resource Max. Working %	16.06	17.29	17.33	17.13	16.99	15.19	18.35
Resource Min. Idle %	19.35	13.74	17.69	18.35	18.7	20.06	17.58
Resource Avg. Idle %	26.01	24.37	24.88	25.46	25.33	26.36	25.2
Resource Max. Idle %	32.96	32.55	32.39	32.87	33.42	32.94	33.15
Resource Min. Utils %	7.09	7.68	7.73	7.55	7.38	6.74	7.98
Resource Avg. Utils %	26.6	28.81	29.01	28.31	27.67	25.28	29.93
Resource Max. Utils	45.24	49.02	49.35	48.16	47.08	43	50.91
Schedule Duration	15D 4:18	14D 2:21	14D 1:32	14D 5:28	14D 8:16	16D 1:03	13D 6:48

Table A3-48

8-Resources, 3SF							
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Maximum Cost Of Operation First
% Late Orders	75	75	75	25	25	75	75
Total Late Time	11D 16:09	7D 2:36	8D 13:25	6D 9:45	6D 9:45	11D 11:23	9D 15:58
Total Lead Time	28D 20:43	16D 21:59	26D 20:55	21D 17:02	21D 17:02	29D 18:50	28D 2:20
Minimum Added Value	31.02	22.73	33.84	40.76	40.76	24.27	30.9
Average Added Value	51.09	52.14	47.72	55.27	55.27	44.04	46.10
Maximum Added Value	99.58	85.72	62.87	61.04	61.04	66.34	55.7
Resource Min. Working %	0	0	0	0	0	0	0
Resource Avg. Working %	8.95	9.8	8.07	8.25	8.25	8.28	7.57
Resource Max. Working %	17.41	19.06	15.68	16.05	16.05	16.1	14.72
Resource Min. Idle %	18.78	17.83	21.31	19.84	19.84	19.63	21.31
Resource Avg. Idle %	27.29	27.15	28.98	27.68	27.68	27.49	28.5
Resource Max. Idle %	36.28	36.99	37.08	35.98	35.98	35.81	36.1
Resource Min. Utils %	0	0	0	0	0	0	0
Resource Avg. Utils %	24.68	26.5	21.75	22.94	22.94	23.11	20.97
Resource Max. Utils	48	51.53	42.3	44.62	44.62	44.95	40.77
Schedule Duration	10D 4:03	9D 6:59	11D 6:58	11D 0:45	11D 0:45	11D 0:03	12D 0:44
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Critical Ratio
% Late Orders	25	75	50	75	75	75	75
Total Late Time	6D 9:45	11D 11:23	6D 19:22	10D 17:01	7D 11:14	11D 11:23	7D 16:39
Total Lead Time	21D 17:02	28D 22:22	22D 17:35	28D 20:28	23D 0:19	30D 1:45	24D 4:01
Minimum Added Value	40.76	26.21	40.76	26.35	38.17	24.27	44.16
Average Added Value	55.27	46.71	55.81	45.49	54.5	44.04	52.22
Maximum Added Value	61.04	65.18	64.44	60.52	70.76	66.34	59.66
Resource Min. Working %	0	0	0	0	0	0	0
Resource Avg. Working %	8.25	8.2	8.23	8.23	8.04	8.28	8.2
Resource Max. Working %	16.05	15.94	16	16.01	15.65	16.1	15.95
Resource Min. Idle %	19.84	20.38	20.11	20.04	21.51	19.63	20.37
Resource Avg. Idle %	27.68	28.17	27.88	27.81	29.16	27.49	28.16
Resource Max. Idle %	35.98	36.41	36.19	36.13	37.24	35.81	36.4
Resource Min. Utils %	0	0	0	0	0	0	0
Resource Avg. Utils %	22.94	22.52	22.73	22.79	21.61	23.11	22.53
Resource Max. Utils	44.62	43.79	44.2	44.32	42.02	44.95	43.81
Schedule Duration	11D 0:45	11D 2:33	11D 1:39	11D 1:24	11D 7:39	11D 0:03	11D 2:31

Table A3-49

3-Resources, 4SF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	20	40	80	60	40	80
Total Late Time	1D 14:17	5D 0:05	11D 2:14	8D 22:33	9D 2:40	12D 20:01
Total Lead Time	19D 0:10	15D 23:55	32D 11:16	24D 12:06	24D 7:07	31D 23:08
Minimum Added Value	43.88	37.53	30.48	32.09	34.41	31.27
Average Added Value	57.53	60.69	40.1	46.77	45.56	40.13
Maximum Added Value	99.58	99.58	57.05	99.58	93.19	65.55
Resource Min. Working %	18.8	22.34	6.84	6.54	7.85	10.19
Resource Avg. Working %	23.84	27.17	18.91	18.91	17.8	17.74
Resource Max. Working %	32.95	34.56	28.52	28.35	26.84	25.81
Resource Min. Idle %	3.29	1.48	8.75	8.93	8.84	10.1
Resource Avg. Idle %	12.4	8.83	18.43	18.43	17.94	16.43
Resource Max. Idle %	17.45	13.64	30.59	30.59	27.94	25.79
Resource Min. Utils %	51.66	61.75	18.25	18.25	21.9	28.25
Resource Avg. Utils %	65.51	75.1	50.49	50.49	49.64	49.21
Resource Max. Utils	90.55	95.55	76.13	76.13	74.86	71.59
Schedule Duration	8D 5:17	7D 5:07	10D 8:39	10D 8:39	11D 0:14	11D 1:04

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	60	80	60	60	60
Total Late Time	10D 15:47	9D 8:54	11D 19:32	14D 13:11	9D 12:25
Total Lead Time	28D 7:12	26D 13:02	29D 11:05	31D 6:42	32D 5:46
Minimum Added Value	32.09	32.09	33.44	27.6	35.56
Average Added Value	44.07	43.71	41.20	40.98	42.33
Maximum Added Value	91.8	56.19	59.87	71.21	50.7
Resource Min. Working %	7.64	6.84	6.33	6.23	6.84
Resource Avg. Working %	18.92	18.91	17.5	17.23	18.91
Resource Max. Working %	27.55	28.52	27.63	29.38	28.52
Resource Min. Idle %	9.71	8.75	8.72	7.98	8.75
Resource Avg. Idle %	18.41	18.43	18.92	20.18	18.43
Resource Max. Idle %	29.75	30.59	30.18	31.25	30.59
Resource Min. Utils %	20.41	18.25	17.31	16.6	18.25
Resource Avg. Utils %	50.51	50.49	47.9	45.93	50.49
Resource Max. Utils	73.58	76.13	75.62	78.3	76.13
Schedule Duration	10D 8:36	10D 8:39	11D 4:41	11D 8:53	10D 8:39

Table A3-50

6-Resources, 4SF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	66.67	50	100	50	50	66.67
Total Late Time	23D 3:31	24D 17:34	42D 14:33	11D 10:22	23D 19:16	36D 9:31
Total Lead Time	45D 14:11	32D 12:28	59D 7:25	26D 23:55	36D 5:33	51D 3:54
Minimum Added Value	24.95	19.67	15.36	29.73	32.99	16.78
Average Added Value	42.93	45.45	28.86	41.47	39.9	31.95
Maximum Added Value	99.58	99.63	41.15	99.58	88.1	67.31
Resource Min. Working %	1.17	1.11	0.85	0.82	0.77	0.81
Resource Avg. Working %	12.19	11.54	8.86	8.11	8.04	8.42
Resource Max. Working %	26.09	24.25	26.87	27.92	24.88	27.13
Resource Min. Idle %	9.93	10.97	9.48	7.53	10.62	9.19
Resource Avg. Idle %	23.85	23.7	27.56	27.42	27.5	27.97
Resource Max. Idle %	34.92	34.18	35.61	34.74	34.8	35.61
Resource Min. Utils %	3.24	3.14	2.33	2.31	2.17	2.22
Resource Avg. Utils %	33.77	32.69	24.3	22.78	22.6	23.1
Resource Max. Utils	72.24	68.69	73.67	78.49	69.91	74.46
Schedule Duration	13D 8:24	14D 2:30	18D 8:45	19D 0:20	20D 5:42	19D 8:06

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	50	100	66.67	50	66.67
Total Late Time	22D 15:19	64D 22:30	29D 19:04	33D 21:05	36D 6:08
Total Lead Time	36D 15:22	65D 18:39	48D 1:10	52D 13:37	52D 8:48
Minimum Added Value	32.61	12.74	19.46	19.72	17.27
Average Added Value	39.34	24.72	35.33	34.28	32.23
Maximum Added Value	90.1	40.15	59.87	70.96	65.02
Resource Min. Working %	0.81	0.81	0.82	0.77	0.78
Resource Avg. Working %	8.41	8.46	8.56	8.06	8.13
Resource Max. Working %	24.9	27.74	25.77	25.88	25.81
Resource Min. Idle %	8.48	8.22	9.72	9.57	9.6
Resource Avg. Idle %	27.53	27.61	27.01	27.44	27.36
Resource Max. Idle %	35.66	35.29	34.78	34.77	34.74
Resource Min. Utils %	2.21	2.25	2.31	2.18	2.2
Resource Avg. Utils %	23.05	23.43	24.02	22.68	22.83
Resource Max. Utils	68.25	76.8	72.35	72.8	72.62
Schedule Duration	19D 8:28	19D 5:46	19D 0:38	20D 4:32	20D 0:30

Table A3-51

8-Resources, 4SF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	66.67	50	100	66.67	66.67	83.33
Total Late Time	18D 21:33	23D 22:03	46D 3:51	24D 8:13	25D 4:39	32D 19:46
Total Lead Time	36D 11:33	28D 19:35	57D 20:34	43D 10:40	42D 21:53	48D 23:34
Minimum Added Value	23.29	19.22	17.31	28.11	30.37	23.98
Average Added Value	46	46.74	30.52	39.61	41.27	35.5
Maximum Added Value	99.58	99.63	48.55	64.59	88.1	52.16
Resource Min. Working %	1.24	2.31	2.21	0.95	0.91	1.99
Resource Avg. Working %	8.72	8.56	7.47	6.66	6.4	7.13
Resource Max. Working %	19.64	16.51	26.07	25.24	23.75	23.68
Resource Min. Idle %	15.16	19.19	10.05	11.02	11.94	11.98
Resource Avg. Idle %	26.08	27.12	28.73	29.68	29.37	28.6
Resource Max. Idle %	33.6	33.4	34.04	35.43	34.89	33.77
Resource Min. Utils %	3.56	6.47	6.09	2.6	2.54	5.56
Resource Avg. Utils %	25.02	23.96	20.59	18.3	17.87	19.94
Resource Max. Utils	56.36	46.2	71.86	69.39	66.32	66.22
Schedule Duration	14D 0:06	14D 6:18	16D 8:17	18D 8:05	19D 1:58	17D 2:59

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	66.67	100	83.33	83.33	83.33
Total Late Time	25D 11:51	32D 20:35	28D 8:11	26D 12:19	29D 18:52
Total Lead Time	45D 8:29	45D 13:42	47D 22:14	44D 16:26	45D 13:19
Minimum Added Value	29.55	18.2	27.63	29.46	23.7
Average Added Value	39.48	37.62	35.37	38.83	39.05
Maximum Added Value	65.43	50.87	68.61	53.21	54.58
Resource Min. Working %	1.07	0.96	0.96	0.95	0.96
Resource Avg. Working %	7.51	6.74	6.78	6.71	6.72
Resource Max. Working %	21.34	21.98	23.22	22.64	23.09
Resource Min. Idle %	14.43	13.7	12.11	13.13	12.61
Resource Avg. Idle %	28.35	29.01	28.62	29.11	29.03
Resource Max. Idle %	34.84	34.83	34.47	34.91	34.83
Resource Min. Utils %	2.97	2.68	2.72	2.66	2.67
Resource Avg. Utils %	20.92	18.84	19.13	18.72	18.78
Resource Max. Utils	59.44	61.41	65.51	63.13	64.5
Schedule Duration	16D 6:04	18D 2:31	18D 0:09	18D 4:34	18D 4:04

Table A3-52

3-Resources, 5SF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	25	100	100	100	75	100
Total Late Time	7D 15:02	13D 13:40	34D 23:23	19D 7:06	16D 20:40	30D 21:47
Total Lead Time	21D 16:17	23D 2:20	51D 22:09	34D 12:22	32D 11:37	38D 8:33
Minimum Added Value	39.04	21.85	15.48	26.94	31.48	18.9
Average Added Value	55.36	45.4	29.38	36.94	39.83	27.66
Maximum Added Value	99.58	73.34	40.72	47.81	68.41	39.17
Resource Min. Working %	14.94	15.04	7.5	7.45	7.43	7.49
Resource Avg. Working %	18.32	22.14	14.99	14.88	14.85	14.97
Resource Max. Working %	22.35	27.7	24.6	24.96	24.9	24.04
Resource Min. Idle %	13.56	7.78	10.99	11.1	11.3	11.58
Resource Avg. Idle %	17.6	13.35	20.66	21.22	21.41	20.73
Resource Max. Idle %	21.01	20.48	28.19	28.71	28.87	28.26
Resource Min. Utils %	41.48	42.24	21	20.59	20.46	20.95
Resource Avg. Utils %	50.89	62.2	41.97	41.13	40.88	41.86
Resource Max. Utils	62.07	77.82	68.89	68.99	68.56	67.21
Schedule Duration	13D 6:02	10D 23:12	16D 4:52	16D 7:41	16D 8:34	16D 5:14

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	75	100	100	100	100
Total Late Time	12D 13:23	36D 21:27	18D 2:47	32D 16:37	39D 2:21
Total Lead Time	25D 13:02	45D 18:01	34D 20:52	44D 14:55	56D 19:20
Minimum Added Value	36.07	14.58	29.05	19.48	13.68
Average Added Value	42.61	28.29	37.60	30.13	27.53
Maximum Added Value	62.71	46.4	46.77	46.24	39
Resource Min. Working %	7.52	7.49	7.51	7.15	8.24
Resource Avg. Working %	15.02	14.97	15	14.28	14.05
Resource Max. Working %	25.73	25.32	25.59	22.36	19.75
Resource Min. Idle %	9.71	10.34	9.92	12.62	16.25
Resource Avg. Idle %	20.48	20.74	20.57	20.89	21.99
Resource Max. Idle %	28.02	28.27	28.11	28.16	27.85
Resource Min. Utils %	21.13	20.94	21.07	20.23	22.81
Resource Avg. Utils %	42.22	41.84	42.1	40.42	38.91
Resource Max. Utils	72.33	70.78	71.82	63.29	54.7
Schedule Duration	16D 4:02	16D 5:17	16D 4:26	17D 0:11	17D 6:46

Table A3-53

6-Resources, 5SF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	60	100	100	60	60	80
Total Late Time	9D 15:34	18D 7:26	28D 20:01	21D 16:42	21D 13:36	26D 14:35
Total Lead Time	29D 16:05	33D 16:24	49D 23:41	43D 8:03	35D 3:47	44D 4:16
Minimum Added Value	31.54	26.79	16.59	23.83	24.31	17.79
Average Added Value	57.36	48.06	31.67	38.4	40.7	33.94
Maximum Added Value	99.58	79.66	45.5	78.53	82.17	67.31
Resource Min. Working %	1.39	2.6	0.96	0.86	0.87	0.9
Resource Avg. Working %	13	10.48	8.96	8.1	8.14	8.43
Resource Max. Working %	23.05	22.28	26.55	25.87	25.69	25.83
Resource Min. Idle %	13.81	12.54	9.59	9.71	9.62	10.46
Resource Avg. Idle %	23.87	24.44	27.26	27.56	27.25	27.94
Resource Max. Idle %	35.53	32.33	35.29	34.81	34.55	35.51
Resource Min. Utils %	3.75	7.44	2.63	2.42	2.45	2.47
Resource Avg. Utils %	35.19	29.88	24.7	22.69	22.96	23.15
Resource Max. Utils	62.41	63.75	73.19	72.44	72.51	70.91
Schedule Duration	11D 6:23	14D 0:39	16D 8:19	18D 1:57	18D 0:05	17D 8:50
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First	
% Late Orders	60	100	80	80	80	
Total Late Time	21D 16:50	49D 5:58	17D 12:17	24D 0:09	26D 0:57	
Total Lead Time	43D 12:34	61D 10:34	36D 23:41	40D 23:28	45D 8:25	
Minimum Added Value	23.86	12.4	33.83	23.7	18.19	
Average Added Value	37.71	26.74	39.75	39.07	33.94	
Maximum Added Value	72.64	44.69	60.98	68.65	65.02	
Resource Min. Working %	0.86	0.91	0.82	0.91	0.87	
Resource Avg. Working %	8.1	8.51	7.67	8.58	8.13	
Resource Max. Working %	25.65	26.28	25.44	26.41	24.68	
Resource Min. Idle %	9.97	9.43	10.31	9.07	10.68	
Resource Avg. Idle %	27.59	27.31	28.14	26.97	27.32	
Resource Max. Idle %	34.84	34.95	35.02	34.67	34.61	
Resource Min. Utils %	2.42	2.53	2.28	2.57	2.44	
Resource Avg. Utils %	22.66	23.72	21.4	24.09	22.9	
Resource Max. Utils	71.77	73.26	70.96	74.18	69.55	
Schedule Duration	18D 2:07	17D 5:13	19D 2:18	17D 1:56	18D 0:29	

Table A3-54

8-Resources, 5SF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	75	75	75	100	50	100
Total Late Time	10D 13:25	8D 19:15	11D 16:53	14D 18:08	11D 21:26	16D 2:29
Total Lead Time	21D 2:39	19D 17:16	29D 3:28	32D 0:05	27D 4:29	32D 21:29
Minimum Added Value	21.04	24.25	34.79	28.65	37.06	31.23
Average Added Value	45.83	51.84	44.43	40.09	45.53	41.7
Maximum Added Value	99.58	79.66	51.16	50.02	68.41	53.41
Resource Min. Working %	0	0	0	0	0	0
Resource Avg. Working %	8.9	9.75	6.37	6	6	5.97
Resource Max. Working %	18.78	17.4	19.92	22.03	22.03	20.14
Resource Min. Idle %	17.81	19.75	15.87	13.37	13.35	15.62
Resource Avg. Idle %	26.98	27.51	29.47	29.46	29.46	29.83
Resource Max. Idle %	36.64	37.3	35.87	35.49	35.49	35.83
Resource Min. Utils %	0	0	0	0	0	0
Resource Avg. Utils %	24.3	26.14	17.76	16.9	16.9	16.66
Resource Max. Utils	51.24	46.65	55.54	62.07	62.07	56.2
Schedule Duration	10D 5:26	9D 8:06	14D 7:02	15D 4:17	15D 4:17	15D 6:13

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	25	50	75	75	75
Total Late Time	10D 14:08	10D 22:21	11D 16:10	11D 13:20	13D 13:23
Total Lead Time	24D 13:21	27D 0:35	27D 4:51	29D 1:41	31D 2:55
Minimum Added Value	42.2	42.8	39.26	32.81	29.99
Average Added Value	47.29	45.2	46.33	44.55	39.32
Maximum Added Value	71.16	50.16	55.56	51.17	43.71
Resource Min. Working %	0	0	0	0	0
Resource Avg. Working %	5.99	6.09	5.94	6.37	5.98
Resource Max. Working %	21.75	20.72	23.32	19.92	23.13
Resource Min. Idle %	13.8	14.05	12.73	15.87	12.49
Resource Avg. Idle %	29.63	28.24	30.19	29.46	29.72
Resource Max. Idle %	35.64	34.84	36.16	35.86	35.73
Resource Min. Utils %	0	0	0	0	0
Resource Avg. Utils %	16.79	17.47	16.42	17.77	16.73
Resource Max. Utils	61.03	59.48	64.49	55.55	64.76
Schedule Duration	15D 5:08	14D 23:07	15D 8:06	14D 7:01	15D 5:37

Table A3-55

3-Resources, 5aSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	45.45	54.55	63.64	27.27	27.27	90.91
Total Late Time	2D 19:00	9D 1:09	12D 13:44	10D 4:22	8D 17:18	16D 6:54
Total Lead Time	31D 1:46	35D 2:25	52D 2:31	46D 2:59	38D 13:15	52D 17:43
Minimum Added Value	5.52	5.78	6.51	11.7	11.6	6.71
Average Added Value	21.72	22.39	22.29	30.91	29.43	21.06
Maximum Added Value	99.16	94.38	47.51	59.49	97.92	47.91
Resource Min. Working %	32.38	32.8	31.11	25.68	24.74	31.04
Resource Avg. Working %	33.44	33.34	33.73	27.01	29.23	33.14
Resource Max. Working %	34.86	34.13	35.69	29.58	32.35	36.44
Resource Min. Idle %	1.42	2.38	0	5.37	4.3	0.29
Resource Avg. Idle %	2.67	2.99	1.58	7.99	7.44	3.61
Resource Max. Idle %	3.72	3.4	4.46	9.37	12	5.68
Resource Min. Utils %	88.5	89.17	86.28	72.63	66.76	83.5
Resource Avg. Utils %	91.42	90.63	93.54	76.38	78.86	89.16
Resource Max. Utils	95.29	92.79	98.98	83.66	87.28	98.04
Schedule Duration	7D 6:15	7D 6:48	7D 4:48	8D 23:48	8D 7:24	7D 7:52
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First	
% Late Orders	27.27	45.45	27.27	81.82	36.36	
Total Late Time	8D 16:32	12D 3:45	9D 13:57	7D 19:00	13D 16:42	
Total Lead Time	33D 9:06	32D 1:25	46D 14:39	57D 3:10	51D 8:37	
Minimum Added Value	10.06	6.11	11.18	5.92	9.52	
Average Added Value	28.59	21.95	26.54	20.42	25.74	
Maximum Added Value	85.14	89.94	34.54	58.93	55.83	
Resource Min. Working %	25.52	26.95	27.71	32.49	28.75	
Resource Avg. Working %	29.4	30.11	29.5	33.66	30.37	
Resource Max. Working %	32.12	33.89	32.56	35.86	33.05	
Resource Min. Idle %	3.78	0.94	3.51	0	1.75	
Resource Avg. Idle %	4.53	4.97	6.59	2.06	4.35	
Resource Max. Idle %	5.64	8.38	8.44	3.19	5.91	
Resource Min. Utils %	69.56	75.57	75.97	89.78	81.87	
Resource Avg. Utils %	80.14	84.42	80.87	93.02	86.49	
Resource Max. Utils	87.55	95	89.27	99.1	94.11	
Schedule Duration	8D 6:13	8D 1:32	8D 5:34	7D 5:09	7D 23:53	

Table A3-56

6-Resources, 5aSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	0	53.85	69.23	23.08	15.38	61.54
Total Late Time	0	9D 5:03	23D 7:02	4D 21:17	5D 2:56	18D 11:19
Total Lead Time	34D 9:28	54D 17:42	64D 9:46	47D 5:39	44D 12:16	57D 18:19
Minimum Added Value	10.99	8.72	6.64	11.67	11.44	7.49
Average Added Value	38.61	29.69	21.96	33.53	31.41	23.27
Maximum Added Value	99.16	98.71	51.28	75.2	83.33	55.05
Resource Min. Working %	13.97	7.12	1.21	1.46	1.82	2.33
Resource Avg. Working %	27.06	19.99	17.8	17.21	15.35	19.66
Resource Max. Working %	34.55	33.86	32	32.45	27.3	32.28
Resource Min. Idle %	5.32	1.4	1.18	4.22	9.3	4.25
Resource Avg. Idle %	12.82	15.52	16.36	19.67	21.68	15.55
Resource Max. Idle %	25.85	28.47	34.34	35.68	35.4	34.5
Resource Min. Utils %	34.74	19.91	3.39	3.93	4.89	6.33
Resource Avg. Utils %	67.3	55.9	50.02	46.29	41.17	53.3
Resource Max. Utils	85.94	94.69	89.94	87.28	73.22	87.57
Schedule Duration	5D 7:06	7D 4:01	8D 1:15	8D 7:47	9D 8:02	7D 7:01

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	30.77	69.23	30.77	61.54	46.15
Total Late Time	6D 0:23	23D 15:31	4D 20:06	10D 2:38	15D 0:12
Total Lead Time	40D 22:43	59D 10:38	40D 21:51	55D 11:18	57D 6:42
Minimum Added Value	10.17	7.51	13	6.43	7.28
Average Added Value	28.65	23.22	32.56	23.03	28.28
Maximum Added Value	98.13	72.23	57.62	52.35	58.17
Resource Min. Working %	2.73	0.35	5.43	0.69	1.14
Resource Avg. Working %	15.88	17.82	19.47	17.9	17.47
Resource Max. Working %	29.2	29.66	29.3	29.46	26.12
Resource Min. Idle %	6.1	5.41	7.89	5.54	9.79
Resource Avg. Idle %	19.53	17.47	17.72	17.07	18.56
Resource Max. Idle %	32.81	35.14	31.88	34.47	35.05
Resource Min. Utils %	7.67	0.97	14.5	1.97	3.15
Resource Avg. Utils %	44.6	50.19	52.03	50.87	48.2
Resource Max. Utils	82.04	83.56	78.29	83.7	72.06
Schedule Duration	9D 0:36	8D 1:01	7D 8:36	8D 0:06	8D 4:51

Table A3-57

8-Resources, 5aSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	0	9.09	18.18	18.18	18.18	18.18
Total Late Time	0	15H 11M	4D 4:50	1D 0:50	1D 4:12	4D 2:53
Total Lead Time	21D 23:40	20D 23:53	36D 11:22	29D 15:57	29D 10:00	33D 5:11
Minimum Added Value	10.7	10.86	9.74	11.94	13.19	9.56
Average Added Value	41.23	42.24	29.32	36.12	37.48	30.64
Maximum Added Value	99.16	98.71	70.29	70.15	84.84	59.78
Resource Min. Working %	9.04	11.62	5.58	3.69	7.68	6.46
Resource Avg. Working %	21.56	22.91	17.83	17.29	17.06	18.01
Resource Max. Working %	28.28	30.4	32.3	32.37	34.28	31.39
Resource Min. Idle %	11.31	6.34	5.97	7.17	6.02	5.52
Resource Avg. Idle %	17.97	13.89	20.75	22.37	23.39	19.83
Resource Max. Idle %	30.57	25.11	33.12	36.12	32.85	31.61
Resource Min. Utils %	22.72	31.32	14.37	9.26	18.87	16.91
Resource Avg. Utils %	54.16	61.76	45.94	43.35	41.95	47.18
Resource Max. Utils	71.05	81.96	83.22	81.16	84.29	82.22
Schedule Duration	4D 5:21	3D 23:23	5D 2:34	5D 6:25	5D 8:06	5D 1:19

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	18.18	18.18	18.18	18.18	27.27
Total Late Time	1D 1:10	4D 6:43	1D 0:50	18H 39M	3D 20:55
Total Lead Time	27D 23:55	37D 1:47	27D 23:26	44D 5:38	30D 11:11
Minimum Added Value	13.8	9.32	13.84	7.54	12.9
Average Added Value	36.9	29.51	38.06	27.6	35.19
Maximum Added Value	91.44	71.19	63.61	56.14	70.1
Resource Min. Working %	5.99	0.53	4.79	2.78	5.83
Resource Avg. Working %	17.26	17.25	17.43	14.29	17.37
Resource Max. Working %	27.98	30.45	26.86	20.05	30.53
Resource Min. Idle %	11.76	9.23	12.05	11.17	8.75
Resource Avg. Idle %	22.48	22.56	21.71	21.96	22.02
Resource Max. Idle %	33.84	39.47	34.52	34.72	33.66
Resource Min. Utils %	14.99	1.31	12.16	7.4	14.71
Resource Avg. Utils %	43.2	43.09	44.28	38.03	43.84
Resource Max. Utils	70.02	76.08	68.22	69.32	77.06
Schedule Duration	5D 6:35	5D 6:43	5D 5:21	6D 8:56	5D 5:51

Table A3-58

3-Resources, 5bSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	26.32	42.11	78.95	26.32	26.32	76.68
Total Late Time	2D 14:19	13D 10:49	31D 0:39	16D 9:46	15D 17:30	26D 15:42
Total Lead Time	38D 6:48	36D 6:36	84D 0:37	69D 23:46	56D 11:13	74D 15:52
Minimum Added Value	5.22	5.21	5.73	12.19	10.97	5.97
Average Added Value	13.99	12.87	11.72	19.8	18.14	12.45
Maximum Added Value	98.33	93.72	34.53	40.17	88.01	39
Resource Min. Working %	32.32	32.51	26.57	24.89	22.44	27.17
Resource Avg. Working %	33.24	33.24	29.69	26.82	26.87	30.26
Resource Max. Working %	34.17	34.64	34.77	30.34	30.2	34.61
Resource Min. Idle %	2.24	0	0.61	4.77	4.78	0.16
Resource Avg. Idle %	2.78	1.82	5.56	8.36	8.04	4.27
Resource Max. Idle %	3.73	3.58	8.82	10.23	12.31	7.1
Resource Min. Utils %	87.4	78.37	73.66	69.55	62.89	76.83
Resource Avg. Utils %	89.89	86.69	82.29	74.94	75.31	85.56
Resource Max. Utils	92.42	93.68	96.38	84.76	84.64	97.87
Schedule Duration	7D 7:20	7D 7:21	8D 4:19	9D 1:16	9D 0:53	8D 0:37
Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First	
% Late Orders	21.05	26.32	47.37	36.84	52.63	
Total Late Time	6D 2:25	18D 4:23	19D 21:44	4D 18:49	19D 2:10	
Total Lead Time	29D 2:44	40D 11:48	65D 0:31	81D 7:08	73D 11:17	
Minimum Added Value	11.02	6.17	7.83	5.61	5.43	
Average Added Value	20.1	13.77	17.81	13.86	15.4	
Maximum Added Value	92.52	89.1	26.37	52.66	56.28	
Resource Min. Working %	33.14	32.55	29.27	33.4	28.43	
Resource Avg. Working %	33.39	33.87	30.41	34.14	30.4	
Resource Max. Working %	33.61	35.02	32.66	34.76	33.21	
Resource Min. Idle %	0	0.26	0	0.49	0.57	
Resource Avg. Idle %	1.84	1.16	2.09	0.92	3.8	
Resource Max. Idle %	3.2	2.4	5.1	1.62	6.13	
Resource Min. Utils %	79.01	90.96	78.54	93.16	81.08	
Resource Avg. Utils %	86.81	94.66	85.1	95.25	86.7	
Resource Max. Utils	91.1	97.86	93.22	96.98	94.72	
Schedule Duration	7D 6:32	7D 4:04	7D 23:38	7D 2:41	7D 23:43	

Table A3-59

6-Resources, 5bSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	0	40	36	8	8	36
Total Late Time	0	11D 1:06	16D 21:49	2D 7:06	2D 6:42	14D 19:59
Total Lead Time	40D 11:47	70D 22:47	69D 15:15	65D 11:00	60D 13:41	67D 3:51
Minimum Added Value	8.27	8.26	7.18	14.18	14.29	7.22
Average Added Value	21.33	17.08	15.89	24.6	24	15.44
Maximum Added Value	98.33	98.07	46.3	68.71	86.4	48.48
Resource Min. Working %	13.82	5.96	12.89	3.48	4.74	11.57
Resource Avg. Working %	27.41	20.32	23.54	19.95	19.96	23.63
Resource Max. Working %	37.13	32.55	34.45	30.69	31.64	35.11
Resource Min. Idle %	1.59	0	2.28	4.6	0	1.39
Resource Avg. Idle %	11.41	14.16	13.28	15.52	14.86	11.53
Resource Max. Idle %	25.12	29.06	24.26	32.3	30.94	25.43
Resource Min. Utils %	35.05	16.88	34.52	9.69	13.22	31.03
Resource Avg. Utils %	69.54	55.29	63.04	55.56	54.01	63.39
Resource Max. Utils	94.2	78.5	92.27	85.49	82.3	94.16
Schedule Duration	5D 5:27	7D 1:14	6D 2:06	7D 4:24	7D 4:16	6D 1:30

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	8	20	4	16	24
Total Late Time	1D 23:30	12D 15:12	1D 16:08	1D 15:40	17D 0:34
Total Lead Time	64D 20:47	52D 14:27	41D 13:16	55D 8:16	73D 8:30
Minimum Added Value	9.66	7.26	9.3	11.02	6.61
Average Added Value	21.78	17.38	26.38	19.92	19.88
Maximum Added Value	86.08	82.47	56.03	77.56	41.7
Resource Min. Working %	5.32	7.94	14.54	18.91	1.83
Resource Avg. Working %	20.32	23.74	26.78	28.27	20.38
Resource Max. Working %	31.18	32.51	39.33	34.67	32.65
Resource Min. Idle %	3.55	3.69	0.87	2.37	1.62
Resource Avg. Idle %	14.51	12.74	13.46	9.18	14.25
Resource Max. Idle %	29.78	29	25.83	18.91	33.15
Resource Min. Utils %	15.08	21.33	35.61	49.32	5.21
Resource Avg. Utils %	57.6	63.78	65.61	73.74	58.07
Resource Max. Utils	88.36	87.33	96.34	90.42	93.02
Schedule Duration	7D 1:12	6D 0:50	5D 8:25	5D 1:38	7D 0:43

Table A3-60

8-Resources, 5bSF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	0	15.79	21.05	0	0	21.05
Total Late Time	0	1D 5:12	4D 5:00	0	0	5D 13:48
Total Lead Time	24D 10:50	21D 10:37	40D 14:22	28D 5:04	30D 8:52	44D 14:56
Minimum Added Value	10.17	10.31	10.65	23.72	16.97	10.33
Average Added Value	25.98	23.34	25.79	38.55	34.95	23.2
Maximum Added Value	98.33	98.07	71.47	68.71	91.09	68.54
Resource Min. Working %	12.52	13.94	11.97	12.48	11.36	8.17
Resource Avg. Working %	22.32	27.08	22.58	21.81	22.57	22.32
Resource Max. Working %	33.81	34.59	31.17	32.77	31.24	31.15
Resource Min. Idle %	4.33	0	5.98	6.01	6.39	0
Resource Avg. Idle %	15.87	14.33	14.92	16.83	14.97	14.72
Resource Max. Idle %	25.82	28.65	25.75	26.15	26.29	30.22
Resource Min. Utils %	32.36	32.42	31.5	31.9	29.88	21.11
Resource Avg. Utils %	57.74	61.22	59.44	55.77	59.36	56.65
Resource Max. Utils	87.41	80.45	82.05	83.79	82.16	80.47
Schedule Duration	4D 1:51	3D 8:42	4D 0:46	4D 4:11	4D 0:49	4D 1:54

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	0	21.05	0	0	21.05
Total Late Time	0	4D 4:46	0	0	4D 3:34
Total Lead Time	28D 1:30	36D 5:30	27D 3:50	44D 3:07	31D 0:12
Minimum Added Value	16.95	10.72	19.58	13.51	10.55
Average Added Value	35.56	23.54	37.78	30.84	29.76
Maximum Added Value	86.4	83.64	78.22	80.75	65.51
Resource Min. Working %	10.15	7.42	16.29	12.13	7.1
Resource Avg. Working %	22.19	22.64	22.97	22.1	22.42
Resource Max. Working %	32.32	33.93	29.25	28.23	33.09
Resource Min. Idle %	6.41	3.16	7.37	0	4.41
Resource Avg. Idle %	16.41	14.59	13.48	15.44	15.54
Resource Max. Idle %	28.55	30.11	20.27	26.85	31.07
Resource Min. Utils %	25.99	19.62	44.1	30.85	18.46
Resource Avg. Utils %	56.79	59.82	62.17	55.43	58.33
Resource Max. Utils	82.72	89.64	79.18	70.05	86.08
Schedule Duration	4D 2:29	4D 0:32	3D 23:09	4D 2:54	4D 1:28

Table A3-61

3-Resources, 6SF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	80	40	100	40	40	100
Total Late Time	15D 7:09	12D 7:23	46D 17:35	13D 22:06	13D 18:52	25D 10:42
Total Lead Time	29D 4:08	25D 6:31	58D 1:13	25D 8:14	25D 20:56	35D 10:41
Minimum Added Value	27.82	32.47	14.1	35.46	35.9	23.15
Average Added Value	46.27	53.37	28.06	44.56	44.42	36.74
Maximum Added Value	99.58	99.58	42.18	99.58	93.19	49.91
Resource Min. Working %	14.34	14.45	7.1	7.19	8.08	7.18
Resource Avg. Working %	22.68	20.54	14.95	15.14	15.19	15.12
Resource Max. Working %	31.61	30.59	28.99	27.85	28.05	28.44
Resource Min. Idle %	4.58	5.39	7.11	7.71	7.26	7.21
Resource Avg. Idle %	13.49	15.43	21.2	20.46	20.17	20.57
Resource Max. Idle %	21.84	21.54	29.09	28.45	27.3	28.54
Resource Min. Utils %	39.54	40.06	19.6	20.15	22.82	20.08
Resource Avg. Utils %	62.53	56.95	41.29	42.44	42.89	42.28
Resource Max. Utils	87.17	84.82	80.04	78.08	79.18	79.56
Schedule Duration	12D 1:28	13D 7:30	18D 6:59	18D 1:39	18D 0:02	18D 2:14

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	40	100	60	100	20
Total Late Time	13D 22:00	48D 10:40	20D 23:23	20D 18:43	12D 16:28
Total Lead Time	27D 9:57	50D 16:13	36D 22:49	43D 4:47	27D 20:15
Minimum Added Value	33.65	15.55	24.13	36.43	34.68
Average Added Value	42.84	26.94	39.55	39.59	43.03
Maximum Added Value	91.8	40.98	69.08	42.1	91.62
Resource Min. Working %	7.65	6.76	7.1	7.57	7.5
Resource Avg. Working %	15.14	14.24	14.95	14.98	15.8
Resource Max. Working %	27.39	29.17	29.5	26.95	29.16
Resource Min. Idle %	8.16	6.72	6.6	9.05	6.92
Resource Avg. Idle %	20.45	21.69	21.2	20.97	20.35
Resource Max. Idle %	27.97	29.2	29.09	28.47	28.69
Resource Min. Utils %	21.45	18.79	19.6	20.98	20.71
Resource Avg. Utils %	42.46	39.57	41.29	41.51	43.62
Resource Max. Utils	76.81	81.03	81.46	74.68	80.53
Schedule Duration	18D 1:36	19D 4:53	18D 4:53	18D 6:07	17D 7:28

Table A3-62

6-Resources, 6SF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	80	60	60	60	60	60
Total Late Time	20D 1:14	13D 12:00	24D 22:45	18D 11:30	18D 11:30	24D 22:45
Total Lead Time	38D 0:54	25D 13:16	43D 11:40	35D 2:30	35D 2:30	43D 3:56
Minimum Added Value	27.01	24.87	19.91	36.59	36.59	19.7
Average Added Value	45.68	53.73	36.43	46.19	46.19	36.3
Maximum Added Value	99.58	99.63	78.53	99.58	99.58	78.53
Resource Min. Working %	1.12	1.38	0.9	0.86	0.86	0.9
Resource Avg. Working %	10.01	12.37	8.06	7.67	7.67	8.06
Resource Max. Working %	25.2	23.33	25.53	24.16	24.16	25.53
Resource Min. Idle %	9.47	13.82	10.73	11.84	11.84	10.73
Resource Avg. Idle %	24.69	24.76	28.27	28.37	28.37	28.27
Resource Max. Idle %	33.61	35.79	85.46	35.19	35.19	85.46
Resource Min. Utils %	3.22	3.71	2.48	2.37	2.37	2.48
Resource Avg. Utils %	28.79	33.25	22.17	21.25	21.25	22.17
Resource Max. Utils	72.52	62.71	70.19	66.96	66.96	70.19
Schedule Duration	13D 23:38	11D 7:30	17D 8:30	18D 6:03	18D 6:03	17D 8:30

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	60	60	60	60	60
Total Late Time	18D 11:30	24D 22:45	21D 16:12	27D 11:49	18D 14:12
Total Lead Time	35D 2:30	43D 3:56	40D 3:32	44D 22:35	37D 15:05
Minimum Added Value	36.59	20.14	35.67	21.43	37.21
Average Added Value	45.15	36.57	40.65	38.81	43.28
Maximum Added Value	99.58	78.53	77.05	84.63	99.58
Resource Min. Working %	0.86	0.9	0.81	0.85	0.82
Resource Avg. Working %	7.67	8.06	7.24	7.66	7.33
Resource Max. Working %	24.16	25.53	24.84	25.88	27.03
Resource Min. Idle %	11.84	10.73	11.44	10.2	8.66
Resource Avg. Idle %	28.37	28.27	29.09	28.46	28.44
Resource Max. Idle %	35.19	85.46	35.55	35.29	34.98
Resource Min. Utils %	2.37	2.48	2.22	2.36	2.29
Resource Avg. Utils %	21.25	22.17	19.92	21.17	20.47
Resource Max. Utils	66.96	70.19	68.3	71.56	75.49
Schedule Duration	18D 6:03	17D 8:30	19D 7:37	18D 6:36	19D 2:03

Table A3-63

8-Resources, 6SF						
Schedule Performance	Earliest Due Date	First Come First Served	Lowest Position Of Operation First	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First
% Late Orders	60	40	100	60	40	60
Total Late Time	14D 15:47	12D 3:53	18D 3:03	14D 13:55	12D 20:08	20D 11:00
Total Lead Time	31D 7:42	24D 15:36	38D 5:27	33D 12:12	27D 19:24	39D 20:22
Minimum Added Value	23.41	26.74	33.33	34.88	37.5	25.26
Average Added Value	46.05	56.91	42.65	43.71	45.27	39.16
Maximum Added Value	99.58	99.63	51.04	76.67	88.1	58.95
Resource Min. Working %	0	1.38	0	0	0	0
Resource Avg. Working %	8.33	9.07	6.28	6.37	6.02	6.43
Resource Max. Working %	19.66	17.13	22.64	22.07	22.46	22.45
Resource Min. Idle %	17.5	20.01	13.47	13.4	12.92	12.46
Resource Avg. Idle %	28.83	28.09	29.91	29.15	29.4	28.55
Resource Max. Idle %	37.2	35.8	36.21	35.55	35.44	35
Resource Min. Utils %	0	3.71	0	0	0	0
Resource Avg. Utils %	22.4	24.37	17.34	17.92	16.98	18.36
Resource Max. Utils	52.86	46.04	62.53	62.08	63.36	64.13
Schedule Duration	12D 7:23	11D 7:30	16D 7:56	16D 2:20	17D 0:56	15D 23:06

Schedule Performance	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	80	60	60	80	40
Total Late Time	18D 22:06	20D 12:47	13D 14:47	15D 19:13	14D 17:26
Total Lead Time	39D 7:14	39D 9:22	32D 22:44	35D 8:30	33D 16:27
Minimum Added Value	25.17	26.41	40.65	34.58	39.99
Average Added Value	38.86	39.47	48.28	44.3	43.79
Maximum Added Value	60.68	59.72	71.1	53.21	63.77
Resource Min. Working %	0	0	0	0	0
Resource Avg. Working %	6.02	6.37	6.38	5.94	6.05
Resource Max. Working %	19.36	25.54	23.05	21.27	22.06
Resource Min. Idle %	15.98	9.96	12.36	14.7	13.03
Resource Avg. Idle %	29.39	29.19	29.1	30.09	29.09
Resource Max. Idle %	35.43	35.59	35.5	36.05	35.16
Resource Min. Utils %	0	0	0	0	0
Resource Avg. Utils %	16.99	17.89	17.96	16.47	17.19
Resource Max. Utils	54.64	71.77	64.94	59.01	62.75
Schedule Duration	17D 0:53	16D 2:35	16D 2:03	17D 6:25	16D 23:10

Table A3-64

3-Resource Scenario, 7SF

Planned Maintenance	Breakdowns
M1 - 5/1, 19/1 - 8AM - 3PM, 12/1 - 8AM - 12PM	M1 - 8/1 6AM - 9/1 4:40AM
M2 - 2/1, 16/1 - 8AM - 3PM, 9/1 - 8AM - 12PM	M2 - 1/1 1:30AM - 2/1 8:00AM
M3 - 3/1, 17/1 - 8AM - 3PM, 10/1 - 8AM - 12PM	M3 - 14/1 0:00AM - 15/1 4:30AM

Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	66.67	66.67	100	66.67	100	50	100	100
Total Late Time	18D 7:48	17D 23:54	21D 19:39	21D 3:05	24D 3:02	15D 18:33	29D 17:23	25D 13:39
Total Lead Time	44D 9:54	38D 11:43	49D 21:33	39D 8:39	53D 2:31	42D 17:03	51D 10:09	55D 10:03
Minimum Added Value	29.22	31.29	24.74	36.12	17.83	35.67	01:12	20.3
Average Added Value	50.26	53.94	48.04	54.57	43.78	57.41	42.55	44.62
Maximum Added Value	99.29	99.63	82.69	82	75.97	76.34	90.55	75.46
Resource Min. Working %	19.4	24.44	20.75	17.01	25.37	21.19	18.93	24.98
Resource Avg. Working %	23.97	25.86	21.93	21.59	27.71	25.87	22.57	29.38
Resource Max. Working %	26.39	27.1	22.85	25.89	28.96	28.96	24.8	33.35
Resource Min. Idle %	3.9	2.27	4.62	2.53	0	2.58	4.75	0
Resource Avg. Idle %	6.8	4.58	6.42	8.48	2.42	5.29	6.38	2.26
Resource Max. Idle %	10.18	7.99	9.67	12.65	4.26	9.29	7.69	5.27
Resource Min. Utils %	65.25	75	69.41	57.24	85.35	69.4	64.02	82.47
Resource Avg. Utils %	77.5	84.98	73.77	71.95	91.69	82.31	74.43	92.18
Resource Max. Utils	86.89	91.93	81.77	90.81	99.83	91.02	80.16	99.48
Schedule Duration	12D 1:35	11D 2:17	14D 0:34	15D 0:11	11D 0:08	11D 7:21	15D 1:55	10D 8:53

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	66.67	50	100	50	83.33	83.33	66.67	66.67
Total Late Time	17D 19:33	14D 9:40	29D 9:42	14D 11:07	26D 1:11	19D 15:46	20D 22:15	22D 0:15
Total Lead Time	40D 11:25	36D 11:41	56D 7:08	32D 6:24	51D 3:32	46D 7:37	38D 17:01	49D 4:37
Minimum Added Value	51.72	46.92	20.71	37.67	16.36	12.62	32.01	21.71
Average Added Value	62.26	62.45	44.04	60.29	47.07	50.6	55.26	46.83
Maximum Added Value	90.04	99.58	71.23	99.58	80.74	75.36	94.03	79.11
Resource Min. Working %	21.02	20.98	20.71	22.59	15.32	26.45	17.03	11.63
Resource Avg. Working %	24.95	25.71	26.19	26.13	20.68	29.37	21.31	20.33
Resource Max. Working %	31.94	32.6	29.68	32.27	25.39	31.6	25.14	25.67
Resource Min. Idle %	0	0	0	0	4.32	0	3.18	3.54
Resource Avg. Idle %	4.89	2.96	4.61	4.19	10.2	0.16	8.71	10.1
Resource Max. Idle %	8.57	8.89	9.34	6.9	14.25	0.49	12.67	17.59
Resource Min. Utils %	70.8	70.05	68.75	76.28	51.65	81.89	57.24	39.72
Resource Avg. Utils %	82.81	81.92	84.72	85.02	66.87	93.17	71.12	66.39
Resource Max. Utils	99.65	99.63	99.69	98.44	85.21	99.59	85.48	87.64
Schedule Duration	14D 1:03	12D 1:06	12D 1:46	11D 23:43	15D 8:14	10D 4:13	14D 23:41	15D 5:34

Table A3-65

6-Resource Scenario, 7SF

Planned Maintenance	Breakdowns
M1 - 5/1, 19/1 - 8AM - 3PM	M1 - 8/1 6AM - 9/1 4:40AM
M2 - 2/1, 16/1 - 8AM - 3PM	M2 - 1/1 1:30AM - 2/1 8:00AM
M3 - 3/1, 17/1 - 8AM - 3PM	M3 - 14/1 0:00AM - 15/1 4:30AM
M4 - 1/1, 15/1 - 8AM - 3PM	M5 - 13/1 0:00AM - 9/1 0:00AM
M5 - 4/1, 18/1 - 8AM - 3PM	
M6 - 6/1, 20/1 - 8AM - 3PM	

Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	83.33	50	83.33	50	66.67	50	50	66.67
Total Late Time	17D 0:47	12D 13:34	35D 17:12	16D 23:13	21D 3:25	19D 17:34	20D 10:41	24D 0:15
Total Lead Time	33D 22:22	26D 20:28	51D 19:22	41D 1:47	47D 18:43	42D 19:25	40D 9:35	45D 20:07
Minimum Added Value	26.85	26.91	22.6	39.87	22.92	31.36	00:57	22.31
Average Added Value	45.92	56.76	36.16	50.47	41.18	44	49.34	39.99
Maximum Added Value	98.9	99.54	64.21	87.83	81.43	96.18	99.58	80.74
Resource Min. Working %	4.42	4.42	0	3.4	0	0.77	0	1.36
Resource Avg. Working %	11.72	11.49	8.3	8.73	8.94	7.85	7.97	8.47
Resource Max. Working %	20.43	17.18	19.68	18.4	19.85	21.42	19.69	20.09
Resource Min. Idle %	10.95	12.91	13.05	13.48	11.79	10.69	11.58	13.1
Resource Avg. Idle %	21.3	21.53	24.01	23.19	22.76	24.36	23.62	23.35
Resource Max. Idle %	30.63	30.64	34.95	30.26	34.16	31.9	34.55	31.29
Resource Min. Utils %	12.6	12.6	0	11.14	0	2.48	0	3.93
Resource Avg. Utils %	34.9	34.23	25.35	27.04	28.03	24.17	24.86	26.03
Resource Max. Utils	64.92	54.57	60.01	57.86	62.62	66.58	62.83	60.47
Schedule Duration	10D 8:48	10D 8:50	17D 8:38	15D 7:13	15D 6:03	16D 6:40	18D 5:05	15D 8:22

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	50	50	66.67	50	83.33	50	50	66.67
Total Late Time	24D 21:39	24D 21:39	21D 14:04	24D 21:39	36D 2:01	18D 10:54	24D 3:31	22D 6:53
Total Lead Time	49D 0:05	49D 12:02	43D 9:07	49D 12:02	58D 16:47	38D 10:35	43D 20:25	44D 13:07
Minimum Added Value	32.4	32.4	22.31	32.4	21.68	30.09	34.99	30.3
Average Added Value	41.54	41.24	41.77	40.54	34.87	43.61	41.24	44.2
Maximum Added Value	70.08	70.08	80.74	70.08	54.92	84.63	88.68	75.24
Resource Min. Working %	0	0	2.73	0	0	0	0.49	0.65
Resource Avg. Working %	7.65	7.56	8.6	7.48	7.77	7.84	7.69	8.12
Resource Max. Working %	24.71	24.51	18.03	24.51	24.71	21.74	21.32	18.46
Resource Min. Idle %	7.84	8.04	12.82	8.04	7.89	9.91	6.94	13.16
Resource Avg. Idle %	24.47	24.56	22.46	24.64	24.71	23.27	22.57	22.71
Resource Max. Idle %	34.77	33.79	31.41	34.74	34.84	33.9	31.44	31.54
Resource Min. Utils %	0	0	8	0	0	0	1.62	1.92
Resource Avg. Utils %	23.52	23.22	26.88	23.02	23.78	24.76	24.23	25.52
Resource Max. Utils	75.81	75.19	56.89	75.19	75.61	68.57	67.22	58.21
Schedule Duration	17D 7:26	17D 7:26	15D 6:01	17D 7:26	17D 7:54	17D 0:33	17D 0:33	17D 0:33

Table A3-66

8-Resource Scenario, 7SF	
Planned Maintenance	Breakdowns
M1 - 5/1, 19/1 - 8AM - 3PM	M1 - 8/1 6AM - 9/1 4:40AM
M2 - 2/1, 16/1 - 8AM - 3PM	M2 - 1/1 1:30AM - 2/1 8:00AM
M3 - 3/1, 17/1 - 8AM - 3PM	M3 - 14/1 0:00AM - 15/1 4:30AM
M4 - 1/1, 15/1 - 8AM - 3PM	M5 - 13/1 0:00AM - 9/1 0:00AM
M5 - 4/1, 18/1 - 8AM - 3PM	M8 - 10/1 0:00AM - 12/1 0:00AM
M6 - 6/1, 20/1 - 8AM - 3PM	
M7 -7/1, 21/1 - 8AM - 3PM	
M8 - 8/1, 22/1 - 8AM - 3PM	

Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First	Lowest Position Of Operation First
% Late Orders	83.33	50	83.33	50	66.67	50	50	100
Total Late Time	17D 18:55	12D 20:01	22D 7:29	24D 9:49	19D 21:30	16D 20:58	18D 19:14	23D 6:16
Total Lead Time	38D 9:00	30D 12:20	44D 4:50	45D 3:02	45D 13:26	39D 23:43	38D 10:48	49D 4:42
Minimum Added Value	22.64	25.78	29.84	30.81	29.4	37.21	12:14	24.84
Average Added Value	45.3	52.24	39.67	38.91	40.51	43.92	43.46	42.6
Maximum Added Value	99.01	99.55	57.67	81.74	58.89	59.19	69.94	73.92
Resource Min. Working %	0	0	0	0	0	0	0	0
Resource Avg. Working %	8.18	8.16	6.22	6.26	5.96	6.1	6.25	6.2
Resource Max. Working %	17.94	19	19.27	26.85	20.74	19.11	24.72	19.07
Resource Min. Idle %	12	15.51	12.82	8.26	14.76	16.8	11.38	12.56
Resource Avg. Idle %	23.11	23.87	24.97	28.91	29.59	29.88	29.91	24.94
Resource Max. Idle %	32.29	35.29	34.2	35.2	35.58	36.01	36.19	32.28
Resource Min. Utils %	0	0	0	0	0	0	0	0
Resource Avg. Utils %	25.59	24.62	19.7	17.79	16.76	16.94	7.26	19.55
Resource Max. Utils	59.7	54.97	59.97	76.27	58.29	53.08	68.31	60.14
Schedule Duration	10D 23:47	11D 2:40	15D 23:07	16D 0:16	17D 1:50	16D 6:40	17D 7:18	17D 0:33

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	Lowest Op/Resource Flexibility First	Highest Op/Resource Flexibility First
% Late Orders	50	66.67	83.33	50	50	50	50	50
Total Late Time	24D 10:09	20D 9:00	28D 16:43	24D 16:55	25D 21:36	25D 18:05	18D 5:48	17D 14:09
Total Lead Time	45D 5:42	40D 22:23	51D 9:37	45D 12:46	46D 10:55	46D 0:19	37D 4:48	40D 11:50
Minimum Added Value	31.24	31.45	15.38	30.55	21.14	21.58	32.72	32.88
Average Added Value	40.98	43.75	37.72	40.23	40.07	39.35	43.69	42.93
Maximum Added Value	96.18	91.09	76.86	97.38	73.92	88.62	83.53	78.64
Resource Min. Working %	0	0	0	0	0	0	0	0
Resource Avg. Working %	5.64	5.49	6.74	5.65	5.87	5.99	5.72	5.81
Resource Max. Working %	24.19	20.03	20.76	25.77	19.79	25.25	22.96	23.24
Resource Min. Idle %	4.42	11.45	11.5	6.68	11.86	2.87	12.46	12.07
Resource Avg. Idle %	25.84	26.28	24.45	26.79	25.27	25.07	29.75	29.17
Resource Max. Idle %	35	35.06	34.5	35.39	34.63	34.54	35.5	35.42
Resource Min. Utils %	0	0	0	0	0	0	0	0
Resource Avg. Utils %	17.59	17.16	21.22	17.4	18.54	18.97	16.12	16.41
Resource Max. Utils	75.35	63.5	64.25	79.22	62.4	79.88	64.69	65.63
Schedule Duration	17D 2:56	18D 2:25	15D 2:00	17D 6:58	17D 0:33	16D 23:57	18D 0:33	18D 0:00

Table A3-67

3-Resource Scenario, 8SF							
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First
% Late Orders	66.67	50	83.33	66.67	83.33	66.67	66.67
Total Late Time	17D 13:12	16D 19:02	16D 12:10	14D 11:27	20D 7:00	14D 6:54	14D 5:15
Total Lead Time	41D 0:03	29D 0:01	33D 0:13	32D 15:21	42D 6:24	30D 16:21	38D 20:20
Minimum Added Value	22.84	29.73	31.02	30.99	27.78	28.33	02:24
Average Added Value	43.67	47.76	48.87	52.07	46.22	53.31	49.68
Maximum Added Value	99.47	99.47	70.52	78.82	77.56	77.5	77.67
Resource Min. Working %	10.08	11.64	10.9	14.04	11.94	15.92	10.75
Resource Avg. Working %	18.33	21.16	19.81	25.53	21.72	28.94	19.54
Resource Max. Working %	21.36	24.67	23.09	29.75	25.31	33.73	22.78
Resource Min. Idle %	14.4	7.22	12.79	7.3	10.11	2.47	13.64
Resource Avg. Idle %	17.38	14.17	16	11.44	13.55	7.19	16.81
Resource Max. Idle %	25.49	24.84	24.77	22.74	22.89	20.04	25.48
Resource Min. Utils %	28.09	31.59	30.26	37.72	33.58	43.69	29.41
Resource Avg. Utils %	51.07	57.44	55.02	68.58	61.05	79.45	53.47
Resource Max. Utils	59.53	66.95	64.13	79.93	71.16	92.61	62.32
Schedule Duration	12D 23:42	11D 5:57	12D 0:20	9D 7:48	10D 23:04	8D 5:24	12D 4:20
Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First	
% Late Orders	33.33	33.33	83.33	33.33	83.33	66.67	
Total Late Time	15D 6:18	15D 1:06	23D 14:04	15D 1:42	22D 15:35	13D 6:40	
Total Lead Time	33D 10:25	37D 15:56	38D 3:55	37D 16:32	37D 3:15	37D 6:47	
Minimum Added Value	43.06	32.62	23.49	32.48	24.05	35.73	
Average Added Value	54.33	48.58	42.01	48.46	43.62	53.81	
Maximum Added Value	95.79	89.98	59.67	89.98	78.83	65.96	
Resource Min. Working %	9.9	10.02	10.8	10.01	10.89	10.75	
Resource Avg. Working %	18.01	18.22	19.64	18.2	19.8	19.54	
Resource Max. Working %	20.99	21.24	22.89	21.21	23.08	22.78	
Resource Min. Idle %	14.87	14.6	13.55	14.65	12.8	13.64	
Resource Avg. Idle %	17.8	17.56	16.75	17.6	16.04	16.81	
Resource Max. Idle %	25.78	25.62	25.45	25.65	24.83	25.48	
Resource Min. Utils %	27.53	27.87	29.52	27.82	30.22	29.41	
Resource Avg. Utils %	50.05	50.67	53.67	50.58	54.95	53.47	
Resource Max. Utils	58.34	59.06	62.56	58.96	64.04	62.32	
Schedule Duration	13D 5:16	13D 1:28	12D 2:56	13D 1:52	12D 0:28	12D 4:20	

Table A3-68

6-Resource Scenario, 8SF							
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First
% Late Orders	66.67	66.67	83.33	66.67	83.33	83.33	66.67
Total Late Time	13D 21:49	18D 4:86	13D 9:09	17D 2:22	17D 13:27	17D 19:58	17D 10:30
Total Lead Time	35D 6:19	33D 21:49	33D 10:24	36D 13:47	41D 14:24	36D 16:00	39D 20:59
Minimum Added Value	31.46	31.69	34.92	39.12	32.08	28.81	22:33
Average Added Value	51.65	49.82	53.1	51.35	48.85	46.21	50.01
Maximum Added Value	99.47	99.47	79.66	87.16	88.65	77.68	95.79
Resource Min. Working %	3.81	3.86	4.55	4.62	3.91	3.26	4.5
Resource Avg. Working %	9.68	11.61	10.61	10.77	11.55	10.74	10.5
Resource Max. Working %	27.78	33.33	30.45	30.92	33.15	30.82	30.13
Resource Min. Idle %	9.27	3.34	6.11	5.05	3.85	5.35	7.09
Resource Avg. Idle %	27.34	25.07	25.98	25.22	24.07	24.13	26.75
Resource Max. Idle %	33.21	32.8	32.07	31.41	33.09	31.62	32.79
Resource Min. Utils %	10.26	10.49	12.4	12.8	10.52	8.98	12.05
Resource Avg. Utils %	26.04	31.55	28.91	29.84	31.09	29.58	28.1
Resource Max. Utils	74.77	90.57	83.01	85.67	89.24	84.93	80.67
Schedule Duration	12D 7:10	10D 6:02	11D 5:17	11D 1:13	10D 7:22	11D 2:03	11D 8:09

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
% Late Orders	66.67	66.67	83.33	66.67	83.33	50
Total Late Time	14D 20:57	12D 11:02	25D 18:22	16D 22:42	17D 14:20	11D 10:12
Total Lead Time	38D 8:03	35D 19:08	41D 17:25	40D 6:48	35D 12:55	34D 6:01
Minimum Added Value	33.38	37.36	24.56	35.59	29.67	46.64
Average Added Value	53.78	52.71	41.86	46.77	49.6	56.04
Maximum Added Value	95.79	95.79	71.7	95.79	75.04	81.21
Resource Min. Working %	4	3.5	4.5	3.36	4.65	2.91
Resource Avg. Working %	9.93	9.84	10.49	9.84	10.83	10.72
Resource Max. Working %	28.52	28.24	30.12	28.24	31.1	30.78
Resource Min. Idle %	7.21	8.12	7.15	8.12	4.5	5.49
Resource Avg. Idle %	25.81	26.53	25.41	26.53	23.36	25.56
Resource Max. Idle %	31.72	32.84	32.82	32.97	31.01	33.37
Resource Min. Utils %	11.16	9.6	12.04	9.21	13.01	7.99
Resource Avg. Utils %	27.72	26.98	28.06	26.98	30.33	29.46
Resource Max. Utils	79.57	77.44	80.56	77.44	87.06	84.58
Schedule Duration	11D 23:33	12D 2:23	11D 8:17	12D 2:23	10D 23:41	11D 2:27

Table A3-69

8-Resource Scenario, 8SF							
Schedule Performance	Earliest Due Date	First Come First Served	Critical Ratio	Minimum Setup Time First	Maximum Setup Time First	Minimum Operation Time First	Maximum Operation Time First
Incompleted Operations	2	7	1	1	1	1	2
% Late Orders	66.67	66.67	77.79	33.33	66.67	66.67	44.44
Total Late Time	20D 5:51	24D 6:31	23D 21:05	9D 22:49	16D 21:26	19D 19:18	10D 21:35
Total Lead Time	45D 3:42	48D 9:52	46D 1:02	39D 5:05	43D 11:30	49D 14:56	33D 9:58
Minimum Added Value	23.92	23.64	27.69	38.3	25.36	29.81	03:50
Average Added Value	49.02	48.11	52.11	58.99	49.43	53.33	61.7
Maximum Added Value	99.47	99.47	90.75	69.13	86.46	86.17	95.6
Resource Min. Working %	3.18	4.9	5.97	5.99	7.06	5.84	7.07
Resource Avg. Working %	10.24	10.65	12.2	11.4	13.42	12.32	13.29
Resource Max. Working %	27.67	29.75	31.97	27.49	32.36	32.28	29.64
Resource Min. Idle %	8.26	6.74	5.27	8.61	4.24	4.37	6.64
Resource Avg. Idle %	25.71	24.99	25.07	24.72	22.69	24.36	23.01
Resource Max. Idle %	32.8	31.68	31.26	30.2	29.65	30.88	29.25
Resource Min. Utils %	8.83	13.4	15.99	16.56	19.22	15.9	19.42
Resource Avg. Utils %	28.43	29.12	32.67	31.5	36.56	33.52	36.53
Resource Max. Utils	76.83	81.32	85.63	75.96	88.15	87.83	81.46
Schedule Duration	13D 2:28	12D 4:29	11D 8:06	12D 1:10	10D 5:41	11D 5:33	10D 2:53

Schedule Performance	Highest Position Of Operation First	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Number Of Operations First	Highest Number Of Operations First	Maximum Cost Of Operation First
Incompleted Operations	1	1	1	1	1	1
% Late Orders	55.56	55.56	77.79	55.56	77.79	44.44
Total Late Time	17D 15:30	13D 16:22	29D 20:15	15D 23:54	24D 22:07	16D 0:21
Total Lead Time	48D 18:54	39D 13:12	50D 18:16	41D 20:44	46D 15:28	42D 16:34
Minimum Added Value	31.02	32.81	26.23	32.81	24.02	35.35
Average Added Value	56.21	55.96	48.64	53.61	52.48	56.76
Maximum Added Value	95.6	95.6	73.15	95.6	87.55	78.33
Resource Min. Working %	5.73	5.58	6.51	6.14	6.54	5.99
Resource Avg. Working %	11.36	12.26	12.47	12.26	12.52	11.38
Resource Max. Working %	29.77	29.57	32.68	29.57	32.81	27.45
Resource Min. Idle %	6.66	6.91	3.55	6.91	3.18	8.75
Resource Avg. Idle %	25.09	24.24	23.79	24.24	23.49	24.84
Resource Max. Idle %	30.7	30.9	29.82	30.38	29.55	30.31
Resource Min. Utils %	15.7	15.25	17.92	16.78	18.11	16.49
Resource Avg. Utils %	31.11	33.52	34.32	33.52	34.69	31.37
Resource Max. Utils	81.52	80.83	89.95	80.83	90.91	75.64
Schedule Duration	12D 4:13	11D 4:51	11D 2:13	11D 4:51	11D 1:12	12D 1:36

Table A3-70

3-Resource Scenario						
Order Set	A			B		
Tool Utilisation	Tool Cost Rule	Tool Flexibility Rule	Tool Life Rule	Tool Cost Rule	Tool Flexibility Rule	Tool Life Rule
T101	95.16	95.16		37.1	37.1	
T102	100	100	100			13.33
T103	88.18	65.45	99.09	11.36		38.64
T104		22.32			43.3	32.14
T105	33.9	16.95		64.41		
T106		20	20		35	35
T107	25.71	25.71		10.71		
T108			77.14			88.1
T109						
T110	22.12	22.12	63.72	64.16	64.16	
T111	9.52	9.52	9.52	9.52	9.52	9.52
T112						
T113	45.52	45.52	33.1	28.97	66.21	20.69
T114	81.25	64.58	82.92	81.25	64.58	87.1
T115	91.41	39.06	52.34	85.55	19.53	42.58
T116	31.43	14.29	31.43	31.43	14.29	31.43
T117	13.99	26.57			26.57	
T118	17.24	54.48			18.97	
T119			32.26	9.68		22.58
T120	12.66	46.84	18.99	22.15	37.34	9.49
T121	70	70	70	40	40	40
T122	8.33	8.33	8.33		8.33	8.33
T123		39.06			19.53	19.53
T124	71.23	50.68	71.23	17.12	13.7	
T125	61.9	42.86	61.9	71.43	52.38	71.43
T126	94.91	76.39	94.91	67.13	83.33	67.13
T127	15.63		15.63	44.92		44.92
T128						
T129	48.83	48.83	48.83	29.3	29.3	29.3
T130		28.57			28.57	

Table A3-71

6-Resource Scenario						
Order Set	A			B		
Tool Utilisation	Tool Cost Rule	Tool Flexibility Rule	Tool Life Rule	Tool Cost Rule	Tool Flexibility Rule	Tool Life Rule
T101	24.19	24.19		24.19	24.19	
T103			27.27			27.27
T104					32.14	32.14
T105				30.51		
T106					15	15
T107				10.71		
T108		23.81	23.81		69.05	69.05
T110	22.12			64.16		
T111	9.52	9.52	9.52	9.52	9.52	23.81
T113	16.55		33.1			
T114	31.25	14.58	31.25	31.25	14.58	56.25
T115	18.75	38.28	19.53	51.95	51.95	28.52
T116	14.29	14.29	14.29	14.29	14.29	14.29
T117		13.99			13.99	
T118		16.55				
T119			9.03			12.9
T120	12.66	12.66		12.66	12.66	
T121	10	10	10	10	10	10
T122	8.33	8.33	8.33	8.33	8.33	8.33
T124	36.99	57.53	36.99		10.27	
T125	42.86	14.29	42.86	28.57	14.29	28.57
T126	20.83	20.83	20.83	20.83	20.83	20.83
T129	9.77	9.77	9.77	9.77	9.77	9.77
T131	71.74	71.74		16.3	16.3	
T132	20.83	20.83	50	10.42	10.42	25
T133	81.82	54.55	88.18	81.82	54.55	93.18
T134	44.64	71.43	71.43	22.32	49.11	44.64
T135	72.88	72.88	42.37	21.19	21.19	
T136	60	60	96			91.5
T137	51.43	51.43		48.21	48.21	
T138	70.48	70.48	91.43	46.66	46.67	23.81
T139	50	50	91.66			
T140	53.1	53.1	53.1			
T141	19.05	19.05	19.05	19.05	19.05	19.05
T142						
T143	13.79	13.79		21.19	13.79	
T144			58.33			37.5
T145	41.67	41.66		19.53	19.53	
T146	14.29	14.29		14.29	14.29	
T147			13.99			
T148			11.03			24.83
T149	10.32	10.32		10.32	10.32	
T153		9.38	9.38		9.38	9.38
T154	8.22		13.7	8.22		
T155	36.19	19.05	36.19	36.19	19.05	36.19
T156		16.67			16.67	
T157	15.63	15.63		15.63	15.63	15.63
T158		20.55			10.27	
T159	23.44		23.44	11.72		11.72
T160	21.43	21.43	21.43	10.71	10.71	10.71

Table A3-72

3-Resource Scenario, ITSF						
Schedule Performance	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Operation Tool Flexibility First	Highest Operation Tool Flexibility First	Minimum Tool Index First	Maximum Tool Index First
% Late Orders	66.66	83.33	83.33	66.66	83.33	66.66
Total Late Time	11D 11:07	45D 11:03	21D 6:58	11D 0:03	19D 13:58	11D 11:07
Total Lead Time	39D 15:03	47D 7:01	44D 13:04	39D 9:53	33D 19:49	37D 13:55
Minimum Added Value	28.93	14.9	25.34	28.45	25.82	28.93
Average Added Value	36.62	20.36	37.46	33.18	30.06	35.41
Maximum Added Value	68.12	23.39	71.13	45.68	37.41	60.37
Resource Min. Working %	14.89	14.32	14.95	14.98	14.89	14.89
Resource Avg. Working %	15.98	14.79	16.94	16.07	15.36	15.98
Resource Max. Working %	17.39	15.06	20.16	17.49	15.66	17.39
Resource Min. Idle %	18.92	20.43	15.92	18.48	20.47	18.36
Resource Avg. Idle %	20.25	20.61	19.05	19.8	20.87	19.31
Resource Max. Idle %	21.38	20.91	21.09	20.94	21.39	20.66
Resource Min. Utils %	40.91	40.25	41.33	41.54	40.87	40.91
Resource Avg. Utils %	43.9	41.58	46.84	44.58	42.22	43.9
Resource Max. Utils	47.76	42.34	55.73	48.5	42.99	47.76
Schedule Duration	19D 7:53	20D 2:24	19D 6:10	19D 5:19	19D 8:01	19D 7:53

Schedule Performance	Minimum Operation Time First	Maximum Operation Time First	Maximum Cost Of Operation First	Lowest Position Of Operation First	Highest Position Of Operation First
% Late Orders	83.33	83.33	66.66	83.33	66.66
Total Late Time	19D 17:09	23D 13:00	11D 0:03	19D 13:58	11D 11:07
Total Lead Time	42D 5:24	46D 2:58	39D 9:53	33D 19:49	37D 13:55
Minimum Added Value	19.1	25.32	28.45	25.82	28.93
Average Added Value	29.77	36.19	33.18	30.06	35.41
Maximum Added Value	36.89	71.13	45.68	37.41	60.37
Resource Min. Working %	14.38	14.95	14.98	14.89	14.89
Resource Avg. Working %	15.44	16.94	16.07	15.36	15.98
Resource Max. Working %	16.8	20.16	17.49	15.66	17.39
Resource Min. Idle %	18.62	15.92	18.48	20.47	18.36
Resource Avg. Idle %	19.97	19.05	19.8	20.87	19.31
Resource Max. Idle %	21	21.08	20.94	21.39	20.66
Resource Min. Utils %	40.5	41.32	41.54	40.87	40.91
Resource Avg. Utils %	43.47	46.83	44.58	42.22	43.9
Resource Max. Utils	47.29	55.72	48.5	42.99	47.76
Schedule Duration	20D 0:18	19D 6:12	19D 5:19	19D 8:01	19D 7:53

Table A3-73

6-Resource Scenario, 1TSF						
Schedule Performance	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Operation Tool Flexibility First	Highest Operation Tool Flexibility First	Minimum Tool Index First	Maximum Tool Index First
% Late Orders	50	66.6	66.66	66.66	66.6	50
Total Late Time	7D 18:26	18D 1:22	8D 20:29	13D 23:48	17D 0:22	8D 15:23
Total Lead Time	32D 3:58	41D 12:33	32D 9:07	39D 7:37	41D 16:03	33D 0:55
Minimum Added Value	29.81	26.35	30.72	25.1	27.56	29.81
Average Added Value	42.76	31.46	39.11	34.95	31.88	42
Maximum Added Value	79.66	47.98	57.31	74.48	47.98	79.66
Resource Min. Working %	1.88	1.97	1.99	1.99	1.97	1.88
Resource Avg. Working %	7.62	7.99	8.04	7.7	7.99	7.62
Resource Max. Working %	24.28	25.46	25.64	23.52	25.46	24.28
Resource Min. Idle %	11.24	10.91	9.84	12.05	10.89	11.24
Resource Avg. Idle %	27.89	28.41	27.82	28.07	28.41	27.89
Resource Max. Idle %	33.68	34.45	33.97	33.83	34.45	33.68
Resource Min. Utils %	5.29	5.42	5.53	5.56	5.42	5.29
Resource Avg. Utils %	21.4	21.91	22.35	21.47	21.91	21.4
Resource Max. Utils	68.21	69.84	71.24	65.6	69.84	68.21
Schedule Duration	20D 6:38	19D 8:12	19D 4:52	19D 3:54	19D 8:12	20D 6:38

Schedule Performance	Minimum Operation Time First	Maximum Operation Time First	Maximum Cost Of Operation First	Lowest Position Of Operation First	Highest Position Of Operation First
% Late Orders	66.66	66.66	66.66	66.6	50
Total Late Time	12D 2:28	11D 19:08	13D 23:48	17D 0:22	8D 15:23
Total Lead Time	36D 20:47	36D 3:11	39D 7:37	41D 16:03	33D 0:55
Minimum Added Value	26.61	27.73	25.1	27.56	29.81
Average Added Value	35.4	36.25	34.95	31.88	42
Maximum Added Value	49.8	55.1	74.48	47.98	79.66
Resource Min. Working %	1.97	1.97	1.99	1.97	1.88
Resource Avg. Working %	7.99	7.98	7.7	7.99	7.62
Resource Max. Working %	25.46	25.45	23.52	25.46	24.28
Resource Min. Idle %	10.91	10.92	12.05	10.89	11.24
Resource Avg. Idle %	28.41	28.42	28.07	28.41	27.89
Resource Max. Idle %	34.45	34.45	33.83	34.45	33.68
Resource Min. Utils %	5.42	5.42	5.56	5.42	5.29
Resource Avg. Utils %	21.91	21.9	21.47	21.91	21.4
Resource Max. Utils	69.84	69.82	65.6	69.84	68.21
Schedule Duration	19D 8:12	19D 8:15	19D 3:54	19D 8:12	20D 6:38

Table A3-74

3-Resource Scenario, 2TSF						
Schedule Performance	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Operation Tool Flexibility First	Highest Operation Tool Flexibility First	Minimum Tool Index First	Maximum Tool Index First
% Late Orders	40	100	80	40	60	60
Total Late Time	9D 5:52	26D 19:08	13D 20:48	9D 5:46	10D 13:35	9D 13:13
Total Lead Time	22D 11:03	41D 22:27	31D 2:47	24D 12:18	32D 16:39	29D 23:10
Minimum Added Value	22.94	21.2	24.9	23.04	24.97	24.63
Average Added Value	36.71	27.81	33.38	36.42	36.41	36.63
Maximum Added Value	86.61	31.6	64.68	86.61	80.11	67.82
Resource Min. Working %	12.59	11.8	12.76	12.59	12.77	12.77
Resource Avg. Working %	16.87	15.81	17.1	16.87	17.12	17.12
Resource Max. Working %	20.01	18.76	20.29	20.02	20.31	20.31
Resource Min. Idle %	16.67	14.47	15.86	16.65	15.77	15.79
Resource Avg. Idle %	19.88	18.5	19.11	19.87	19.03	19.04
Resource Max. Idle %	24.19	24.03	23.48	24.18	23.41	23.42
Resource Min. Utils %	34.11	32.82	35.09	34.12	35.18	35.17
Resource Avg. Utils %	45.71	43.98	47.02	45.73	47.15	47.13
Resource Max. Utils	54.23	52.19	55.79	54.26	55.94	55.93
Schedule Duration	12D 5:59	13D 1:38	12D 1:57	12D 5:56	12D 1:40	12D 1:42

Schedule Performance	Minimum Operation Time First	Maximum Operation Time First	Maximum Cost Of Operation First	Lowest Position Of Operation First	Highest Position Of Operation First
% Late Orders	60	60	60	100	60
Total Late Time	9D 17:52	10D 16:10	11D 11:59	19D 6:26	11D 15:52
Total Lead Time	27D 19:00	27D 12:56	27D 2:24	37D 19:18	30D 3:34
Minimum Added Value	25.33	26.37	24.33	26.79	23.34
Average Added Value	36.51	34.75	35.24	30.16	34.02
Maximum Added Value	52.08	66.01	74.72	37.42	78.07
Resource Min. Working %	13.69	12.87	12.83	12.89	12.52
Resource Avg. Working %	18.35	17.24	17.19	17.28	16.78
Resource Max. Working %	21.77	20.46	20.4	20.5	19.91
Resource Min. Idle %	14.91	15.17	15.08	14.97	17.08
Resource Avg. Idle %	18.39	18.45	18.45	18.26	20.27
Resource Max. Idle %	23.07	22.85	22.72	22.68	24.56
Resource Min. Utils %	37.11	35.89	35.61	36.12	33.66
Resource Avg. Utils %	49.72	48.1	47.72	48.41	45.1
Resource Max. Utils	59	57.01	56.62	57.44	53.52
Schedule Duration	11D 6:13	11D 23:35	12D 0:24	11D 22:56	12D 7:26

Table A3-75

6-Resource Scenario, 2TSF						
Schedule Performance	Lowest Remaining Duration First	Highest Remaining Duration First	Lowest Operation Tool Flexibility First	Highest Operation Tool Flexibility First	Minimum Tool Index First	Maximum Tool Index First
% Late Orders	40	60	40	40	40	40
Total Late Time	8D 18:43	12D 9:17	11D 22:31	8D 18:43	11D 20:55	8D 18:43
Total Lead Time	22D 19:39	30D 2:58	24D 20:03	22D 19:39	30D 1:29	22D 19:39
Minimum Added Value	27.24	21	20.69	27.24	21.04	27.24
Average Added Value	39.15	35	35.89	39.15	34.94	39.15
Maximum Added Value	81.79	66.17	74.42	81.79	73.02	81.79
Resource Min. Working %	4.93	4.85	4.87	4.93	4.91	4.93
Resource Avg. Working %	8.63	8.49	8.52	8.63	8.59	8.63
Resource Max. Working %	17.36	17.07	17.14	17.36	17.27	17.36
Resource Min. Idle %	18.27	14.46	19.31	18.27	18.31	18.27
Resource Avg. Idle %	27.03	26.27	27.96	27.03	27.32	27.03
Resource Max. Idle %	30.73	31.52	31.61	30.73	31.06	30.73
Resource Min. Utils %	13.8	13.32	13.32	13.8	13.62	13.8
Resource Avg. Utils %	24.16	23.31	23.32	24.16	23.84	24.16
Resource Max. Utils	48.55	46.85	46.87	48.55	47.92	48.55
Schedule Duration	11D 23:08	12D 3:52	12D 2:49	11D 23:08	12D 0:29	11D 23:08
Schedule Performance	Minimum Operation Time First	Maximum Operation Time First	Maximum Cost Of Operation First	Lowest Position Of Operation First	Highest Position Of Operation First	
% Late Orders	60	40	40	40	40	
Total Late Time	9D 9:25	11D 6:35	8D 18:43	11D 20:55	8D 18:43	
Total Lead Time	26D 7:30	26D 9:46	22D 19:39	30D 1:29	22D 19:39	
Minimum Added Value	27.24	26.2	27.24	21.04	27.24	
Average Added Value	39.82	37.81	39.15	34.94	39.15	
Maximum Added Value	73.94	82.65	81.79	73.02	81.79	
Resource Min. Working %	4.93	4.85	4.93	4.91	4.93	
Resource Avg. Working %	8.63	8.49	8.63	8.59	8.63	
Resource Max. Working %	17.36	17.06	17.36	17.27	17.36	
Resource Min. Idle %	18.27	19.3	18.27	18.31	18.27	
Resource Avg. Idle %	27.03	27.91	27.03	27.32	27.03	
Resource Max. Idle %	30.73	31.55	30.73	31.06	30.73	
Resource Min. Utils %	13.81	13.3	13.8	13.62	13.8	
Resource Avg. Utils %	24.16	23.27	24.16	23.84	24.16	
Resource Max. Utils	48.56	46.78	48.55	47.92	48.55	
Schedule Duration	11D 23:07	12D 4:02	11D 23:08	12D 0:29	11D 23:08	

Table A3-76

APPENDIX 4: THE DEVELOPED SCHEDULING RULES

This appendix presents two programs written in Visual Basic 5 and integrated with Preactor to form the custom-made scheduling rules and the tool selection rules. The first rule gives preference to higher values of "cost of operation" and 10 such rules were written. The second rule is a tool selection rule giving preference to tools with higher degrees of flexibility, that is, to tools that are capable of more operations. 3 such rules were written.

The lines in italics bold declare (define) variables and allocate storage space while those in ordinary italics represent initializations. Some of the lines of commands have been labelled (1 to 12) for easy referral.

Public Function RunP400MaximizeCostOfOperation(db As PreactorObj, opb As OpenPlanningBoard) As Long

Dim EventTime As Double
Dim CurrentOp As Long
Dim PreviousOp As Long
Dim BestChangeStart As Double
Dim ChangeStart As Double
Dim BestRes As Long
Dim BestProcessEnd As Double
Dim ProcessEnd As Double
Dim Ret As Long
Dim Res As Long
Dim TestStartTime As Double
Dim PreviousOpEndTime As Double
Dim ProcessStart As Double
Dim EventType As Long
Dim EventNumber As Long
Dim EventP1 As Long
Dim EventP2 As Long
Dim CurrentRank As Long
Dim QNumber As Long
Dim QName As String
Dim Found As Boolean
Dim Accuracy As Double
Dim StartTime As Double
Dim EndTime As Double
Dim OpTime As Double
Dim OpName As String

```
 EventTime = 0
 EventType = 0
 EventNumber = 0
 EventP1 = 0
 EventP2 = 0

1. While (opb.NextEvent(EventNumber, EventType, EventTime, EventP1,
   EventP2))
2. For Res = 1 To opb.TotalResources
3. If (opb.IsResourceFree(Res, EventTime)) Then
4. QNumber = opb.GetResourceQueue(Res)
5. Ret = opb.GetResourceQueueName(Res, QName)
6. Ret = opb.RankQueueByField(QName, "Cost of Operation", OpbDescending)

Found = False
CurrentRank = 1
CurrentOp = 0

7. While (opb.GetOpInQueue(QName, CurrentRank, CurrentOp)) And Not Found

8. Found = opb.CanResourceProcessOp(Res, CurrentOp)
9. If Found Then

10. Ret = opb.TestOpOnResource(CurrentOp, Res, EventTime, ChangeStart,
    StartTime, EndTime)
Found = (ChangeStart < (EventTime + Accuracy))

If Found Then

11. Ret = opb.PutOpOnResource(CurrentOp, Res, ChangeStart)

End If
End If
   CurrentRank = CurrentRank + 1
   Wend
12. DoEvents

     End If
   Next Res
 Wend

End Function
```

The explanations to the labelled lines of command are as follows.

1. Returns information about the next event. When there are no more events or the user hits the Cancel button this method will return FALSE.

Possible next events include:

OpbOpFinished	A Resource became available.
OpbShiftChange	A Resource Changed shift state
OpbQueueChange	An Operation completed

If more events are available for processing, TRUE is returned

The values returned in EventP1 and EventP2 are dependent on the value of EventType. As an example, if EventType is OpbOpFinished, then
EventP1 is The Operation that finished on the resource and
EventP2 is The Resource that became available

When Preactor processes the NextEvent method the sequencer will automatically determine which operations can start and will place them in any queue for a resource on which they can be processed.

2. Scans all resources
3. Returns the current free state of a resource.

Returns TRUE if resource is available at the specified time. Always returns true for infinite capacity resources.

4. Finds the number of the queue that is used by a particular resource.

If no queues database is defined then the return value will be 0, indicating that the default system queue is in use.

5. Returns the queue name that is used by a particular resource.
6. Ranks a queue by cost of operation (in this case). There are options of selecting the direction of ranking as follows

OpbDescending	The Queue will be ranked with the highest value first.
OpbAscending	The Queue will be ranked with the lowest value first.

In this case therefore, queue is ranked by performing the operations with the highest value of "cost of operation" first.

7. Finds an operation from a given queue at a given rank.
8. Determines if a specific resource is capable of processing an operation.
9. Moves the program to the next stage if the specific resource is capable of processing the operation.
10. Determines an operations setup time and processing times given a earliest start time.

Tests an operation on a resource and returns information on the time at which the operation would start set-up, start processing and end processing. This routine takes into account operations on the resource, secondary constraints and shift patterns.

11. Places an operation on a resource at a given time.

The PutOpOnResource method provides the main mechanism for scheduling operations using the Open Planning Board. The Time parameter is the time at which the operation is to start processing, if there is a set-up time required then this is the time that the setup time will start, otherwise it is the time at which the operation processing will start.

The PutOpOnResource method is the equivalent of picking up an operation with the mouse and droping it on a resource. If other operations are scheduled to the right (later in time) then their time may be changed.

12. Yields execution so that the operating system can process other events.

```
Public Function RunP400MaximizeCostOfOperation(db As PreactorObj, opb As
OpenPlanningBoard) As Long

Dim EventTime As Double
Dim CurrentOp As Long
Dim PreviousOp As Long
Dim BestChangeStart As Double
Dim ChangeStart As Double
Dim BestRes As Long
Dim BestProcessEnd As Double
Dim ProcessEnd As Double
Dim Ret As Long
Dim Qty As Long
Dim Res As Long
Dim TestStartTime As Double
Dim PreviousOpEndTime As Double
Dim ProcessStart As Double
Dim ToolLife As Double
Dim ToolLife1 As Double
Dim ToolLife2 As Double
Dim ToolLife3 As Double
Dim ToolFlex As Double
Dim ToolFlex1 As Double
Dim ToolFlex2 As Double
Dim ToolFlex3 As Double
Dim ToolCost As Double
Dim ToolCost1 As Double
Dim ToolCost2 As Double
Dim ToolCost3 As Double
Dim PrevToolLife As Double
Dim CurrentToolLife As Double
Dim TKitNumber As Long
Dim TRKitNumber As Long
Dim SecResNumber1 As Long
Dim SecResNumber2 As Long
Dim SecResNumber3 As Long
Dim ToolkitRecord As Long
Dim NoOfTools As Long
Dim M As Long
Dim B As Long
Dim i As Long
Dim A As Long
Dim FieldNo As Long
Dim TestRes As Boolean
Dim OpName As String
Dim OpTime As Double
Dim LoadToolOp As Boolean
Dim CurrentTool As Long
Dim EqTool As Long
Dim EventType As Long
```

```
Dim EventNumber As Long
Dim EventP1 As Long
Dim EventP2 As Long
Dim CurrentRank As Long
Dim QNumber As Long
Dim QName As String
Dim Found As Boolean
Dim Accuracy As Double
Dim StartTime As Double
Dim EndTime As Double

  EventTime = 0
  EventType = 0
  EventNumber = 0
  EventP1 = 0
  EventP2 = 0

1. While (opb.NextEvent(EventNumber, EventType, EventTime, EventP1, EventP2))
2. For Res = 1 To opb.TotalResources
3. If (opb.IsResourceFree(Res, EventTime)) Then
4. QNumber = opb.GetResourceQueue(Res)
5. Ret = opb.GetResourceQueueName(Res, QName)
6. Ret = opb.RankQueueByField(QName, "Cost of Operation", OpbAscending)

   Found = False
   CurrentRank = 1
   CurrentOp = 0

7. While (opb.GetOpInQueue(QName, CurrentRank, CurrentOp)) And Not Found
8. Found = opb.CanResourceProcessOp(Res, CurrentOp)
9. If Found Then
10. Ret = opb.TestOpOnResource(CurrentOp, Res, EventTime, ChangeStart, StartTime, EndTime)
   Found = (ChangeStart < (EventTime + Accuracy))
   If Found Then

a) Ret = db.ReadField("Jobs", "Operation Name", CurrentOp, OpName)
b) Ret = db.ReadField("Jobs", "Total Operation Time", CurrentOp, OpTime)
```

i. *ToolLife = 99999*

ii. *ToolFlex = 99999*

iii. *ToolCost = 99999*

ToolkitRecord = 0

TestRes = False

LoadToolOp = False

```
11. If OpName = "Load Tools" Then

    TestRes = True
    LoadToolOp = True
12. Else
        ' add in code to test whether tool kit is on this resource
        Ret = db.ReadField("Jobs", "Tool Constraint1", CurrentOp, SecResNumber1)
        Ret = db.ReadField("Jobs", "Tool Constraint2", CurrentOp, SecResNumber2)
        Ret = db.ReadField("Jobs", "Tool Constraint3", CurrentOp, SecResNumber3)
13. Ret = db.ReadField("Resources", "Tool Kit", Res, TKitNumber)
    Ret = db.FindMatchingRecord("Tool Kit", "Number", ToolkitRecord, TKitNumber)
14. Ret = db.MatrixFieldSize("Tool Kit", "Tools", ToolkitRecord, NoOfTools)
15. For i = 1 To NoOfTools
16. Ret = db.ReadField("Tool Kit", "Tools", ToolkitRecord, M, i)
    Ret = db.FindMatchingRecord("Tools", "Number", EqTool, M)
17. If (M = SecResNumber1) Then
18. Ret = db.ReadField("Tools", "Tool Life", EqTool, ToolLife1)
19. Ret = db.ReadField("Tools", "Tool Flexibility", EqTool, ToolFlex1)
20. Ret = db.ReadField("Tools", "Tool Cost", EqTool, ToolCost1)
    TestRes = True
21. If OpTime <= ToolLife1 Then
        If ToolFlex1 < ToolFlex Then
            ToolFlex = ToolFlex1
        End If
22. Else: GoTo 10
```

```
    End If
23. Else
24. If (M = SecResNumber2) Then
        Ret = db.ReadField("Tools", "Tool Life", EqTool, ToolLife2)
        Ret = db.ReadField("Tools", "Tool Flexibility", EqTool, ToolFlex2)
        Ret = db.ReadField("Tools", "Tool Cost", EqTool, ToolCost2)
        TestRes = True
        If OpTime <= ToolLife2 Then
          If ToolFlex2 < ToolFlex Then
            ToolFlex = ToolFlex2
          End If
        Else: GoTo 10
        End If
25. Else
26. If (M = SecResNumber3) Then
          Ret = db.ReadField("Tools", "Tool Life", EqTool, ToolLife3)
          Ret = db.ReadField("Tools", "Tool Flexibility", EqTool, ToolFlex3)
          Ret = db.ReadField("Tools", "Tool Cost", EqTool, ToolCost3)
          TestRes = True
          If OpTime <= ToolLife3 Then
            If ToolFlex3 < ToolFlex Then
              ToolFlex = ToolFlex3
            End If
          Else: GoTo 10
          End If
          End If
        End If
      End If
10      Next
27. Ret = db.WriteField("Jobs", "Tool Life", CurrentOp, ToolLife)
28. Ret = db.WriteField("Jobs", "Tool Flexibility", CurrentOp, ToolFlex)
29. Ret = db.WriteField("Jobs", "Tool Cost", CurrentOp, ToolCost)

30. Select Case ToolFlex
```

a) Case ToolFlex1: Ret = db.WriteField("Jobs", "Tool", CurrentOp, SecResNumber1)

b) Case ToolFlex2: Ret = db.WriteField("Jobs", "Tool", CurrentOp, SecResNumber2)

c) Case ToolFlex3: Ret = db.WriteField("Jobs", "Tool", CurrentOp, SecResNumber3)

End Select

31. Select Case ToolFlex

a) Case ToolFlex1: Ret = db.WriteField("Jobs", "Tool Life", CurrentOp, ToolLife1)

b) Case ToolFlex2: Ret = db.WriteField("Jobs", "Tool Life", CurrentOp, ToolLife2)

c) Case ToolFlex3: Ret = db.WriteField("Jobs", "Tool Life", CurrentOp, ToolLife3)

End Select

32. Select Case ToolFlex

a) Case ToolFlex1: Ret = db.WriteField("Jobs", "Tool Cost", CurrentOp, ToolCost1)

b) Case ToolFlex2: Ret = db.WriteField("Jobs", "Tool Cost", CurrentOp, ToolCost2)

c) Case ToolFlex3: Ret = db.WriteField("Jobs", "Tool Cost", CurrentOp, ToolCost3)

End Select

33. Ret = db.ReadField("Jobs", "Tool", CurrentOp, M)

34. Ret = db.ReadField("Jobs", "Tool Life", CurrentOp, ToolLife)

35. CurrentToolLife = ToolLife - OpTime

Ret = db.FindMatchingRecord("Tools", "Number", EqTool, M)

36. Ret = db.WriteField("Tools", "Tool Life", M - 1, CurrentToolLife)

End If

37. If TestRes Then

Ret = opb.PutOpOnResource(CurrentOp, Res, ChangeStart)

38. If LoadToolOp Then

Ret = db.ReadField("Jobs", "Tool Kit", CurrentOp, TKitNumber)

Ret = db.WriteField("Resources", "Tool Kit", BestRes, TKitNumber)

```
ToolkitRecord = 0
Ret = db.FindMatchingRecord("Tool Kit", "Number", ToolkitRecord, TKitNumber)
Ret = db.MatrixFieldSize("Tool Kit", "Tools", ToolkitRecord, NoOfTools)
For i = 1 To NoOfTools
   Ret = db.ReadField("Tool Kit", "Tools", ToolkitRecord, M, i)
   FieldNo = i + 13
   Ret = db.WriteField("Resources", FieldNo, BestRes, M)
Next
End of 38. End If

End If
End If

End If

CurrentRank = CurrentRank + 1
Wend
DoEvents

End If
Next Res
Wend

End Function
```

Labels 1 to 9 of the tool selection rule is exactly the same as that for the operation scheduling rule. This rule decides on the tool to be used for the selected operation selected by the scheduling rule which, in this case, is cost of operation.

10a, 10b. Returns the values in the "Operation Name" and "Total Operation Time" fields of the jobs database into allocation spaces OpName and OpTime respectively.

11. Finds out if, for the operation under investigation, the operation name is "Load Tools". If the returned value is TRUE, then the program activates the instructions in label 38.

12. If the returned value to label 11 is FALSE, then the values of "Tool Constraint1", "Tool Constraint2", "Tool Constraint3", are obtained from the jobs database and stored in allocation spaces SecResNumber1, SecResNumber2, SecResNumber3 respectively.

13. Returns the value (in this case, the name) of the tool kit resident on the resource being considered (the resource that is satisfied in labels 8, 9 and 10)

14. Returns the number of tool s in a tool kit and allocates that value to NoOfTools

15. Scans all tools

16. Determines the ith tool in the tool kit (determined by label 13)

17. Determines whether or not this ith tool is the same as "Tool Constraint1" and if the return value is TRUE, then

18. Determines its tool life value from the tools database and allocates in ToolLife1

19. Determines its tool flexibility value from the tools database and allocates in ToolFlex1

20. Determines its tool cost value from the tools database and allocates in ToolCost1

21. Compares the tool life value of the ith tool with the operation time of the operation under investigation (labels 10a and 10b) and if tool life is greater than or equal to, then compares the tool flexibility value of the ith tool with the present value of ToolFlex (for i = 1, the value is 99999 from label 10ii) and if the ToolFlex value is higher, then the new ToolFlex value becomes the tool flexibility value of the ith tool.

22. Otherwise, the program returns to label 15 and the value of i advances to i + 1

23. If the request in label 17 returns a FALSE value, then

24. Determines whether or not this ith tool is the same as "Tool Constraint2" and if the return value is TRUE, then label 18 to 22 is repeated but with allocations in Tool Life2, ToolFlex2 and ToolCost 2 respectively

25. If both labels 17 and 24 return a FALSE value then

26. Determines whether or not this ith tool is the same as "Tool Constraint3" and if the return value is TRUE, then label 18 to 22 is repeated but with allocations in Tool Life3, ToolFlex3 and ToolCost 3 respectively

27. Writes the tool life value determined from labels 18, 24 or 26 into the tool life field of the jobs database

28. Writes the tool flexibility value determined from labels 19, 24 or 26 into the tool life field of the jobs database

29. Writes the tool cost value determined from labels 20, 24 or 26 into the tool cost field of the jobs database

30a. Writes the name of the tool (to be used for the operation under investigation) allocated to SecResNumber 1 (label 12) in the tool field of the jobs database if the ToolFlex value if ToolFlex1 (label 21)

30b. Writes the name of the tool (to be used for the operation under investigation) allocated to SecResNumber 2 (label 12) in the tool field of the jobs database if the ToolFlex value if ToolFlex2 (label 24)

30c. Writes the name of the tool (to be used for the operation under investigation) allocated to SecResNumber 3 (label 12) in the tool field of the jobs database if the ToolFlex value if ToolFlex3 (label 26)

31a. Writes the value of tool life (for the tool to be used for the operation under investigation) allocated to ToolLife1 (label 18) in the tool life field of the jobs database if the ToolFlex value if ToolFlex1 (label 21)

31b. Writes the value of tool life (for the tool to be used for the operation under investigation) allocated to ToolLife2 (label 24) in the tool life field of the jobs database if the ToolFlex value if ToolFlex2 (label 24)

31c. Writes the value of tool life (for the tool to be used for the operation under investigation) allocated to ToolLife3 (label 26) in the tool life field of the jobs database if the ToolFlex value if ToolFlex3 (label 26)

32a. Writes the value of tool cost (for the tool to be used for the operation under investigation) allocated to ToolCost1 (label 18) in the tool cost field of the jobs database if the ToolFlex value if ToolFlex1 (label 21)

32b. Writes the value of tool cost (for the tool to be used for the operation under investigation) allocated to ToolCost2 (label 24) in the tool cost field of the jobs database if the ToolFlex value if ToolFlex2 (label 24)

32c. Writes the value of tool cost (for the tool to be used for the operation under investigation) allocated to ToolCost3 (label 26) in the tool cost field of the jobs database if the ToolFlex value if ToolFlex3 (label 26)

33. Returns the value (in this case, name) of tool (to be used for the operation under investigation) in the jobs database and allocates in M. This is the value returned from label 30.

34. Returns the value of tool life (for the tool to be used for the operation under investigation) in the jobs database and allocates in ToolLife. This is the value returned from label 31.

35. Determines the new tool life value (for the tool to be used for the operation under investigation) by deducting the operation time of that operation from the tool life (of the tool in use) and allocates this value in CurrentToolLife

36. Returns the value of CurrentToolLife in the tool life field of the tools database

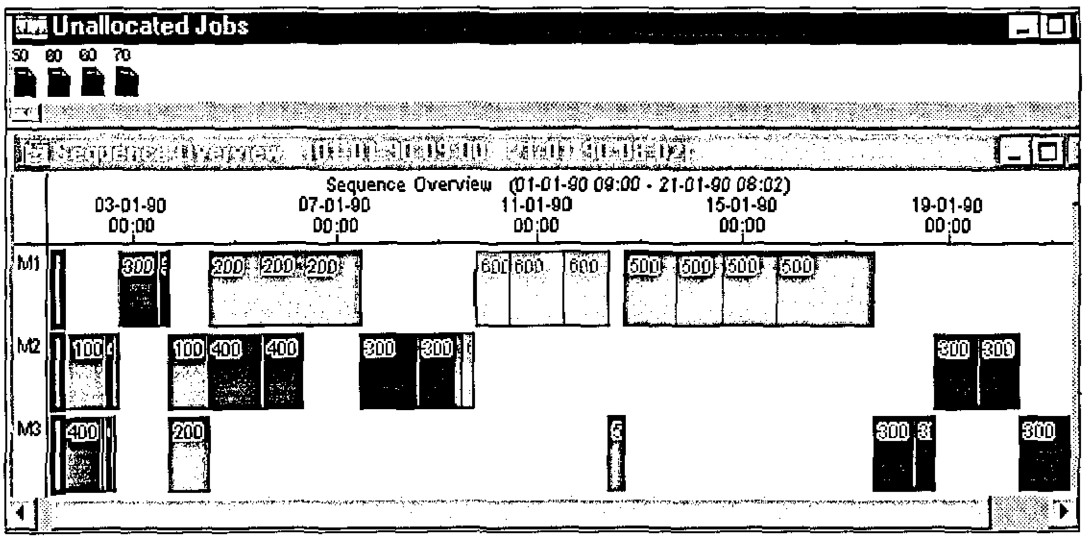
37. Places the operation on the resource

38. Activates the load tool instruction which requests that the tools in a tool kit be loaded on the resource in question

APPENDIX 5: RE-EVALUATION OF SCHEDULE DURATION

In evaluating the new schedule duration, if the next operations were to be done on the resource which was not the last in the schedule, then the last operation's end time is considered. Otherwise, the next operation time is added to the schedule duration. As an example, in the illustration below, for a 3-resource setup, and using the Lowest Setup Time rule, the schedule duration is 20D 4:50 and the last operation is on M3. There are 4 unallocated operations belonging to 1 job as shown.

Orders	Resource	Total Operation Time
Splined Shaft	M3	600
	M3	600
	M3	500
	M3	750



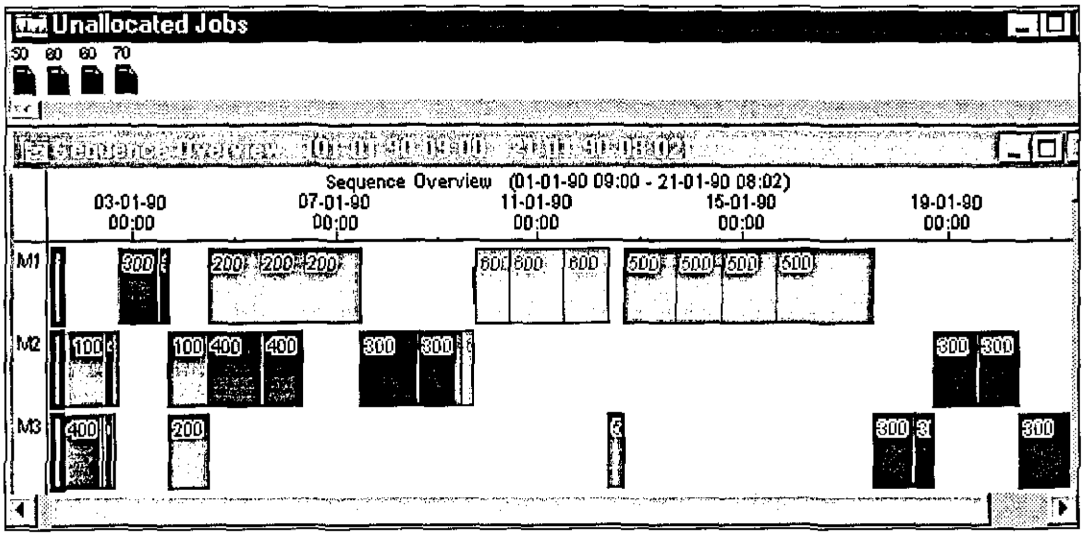
Since the remaining four operations belong to the same job, they need to follow each other and can not be done concurrently. Also, since allocation stopped after the schedule duration, the total duration of the remaining operations can just be added directly to it. If the last operation had been on M2, then if the first of the remaining operations could have been scheduled without the 3-week restriction being broken, it would have had to be scheduled from the last operation on M3 and in this case, the last operation's end time would have had to be used. If the end time of the last operations on M1, M2 and M3 were then compared, the larger value would have to be taken as the schedule duration. If however the last operation before the unallocated ones had been on M2, then the schedule duration would have had to used since if it had been possible to make the operations concurrent, the next operation would not have needed to be unallocated.

There are 540 minutes in a working day so there are (600+600+500+750)/540 days to be added to the schedule duration. Therefore, the new schedule duration is 4 Days and 12 hours + 20D 4:50 = 24D 16:50.

APPENDIX 5: RE-EVALUATION OF SCHEDULE DURATION

In evaluating the new schedule duration, if the next operations were to be done on the resource which was not the last in the schedule, then the last operation's end time is considered. Otherwise, the next operation time is added to the schedule duration. As an example, in the illustration below, for a 3-resource setup, and using the Lowest Setup Time rule, the schedule duration is 20D 4:50 and the last operation is on M3. There are 4 unallocated operations belonging to 1 job as shown.

Orders	Resource	Total Operation Time
Splined Shaft	M3	600
	M3	600
	M3	500
	M3	750



Since the remaining four operations belong to the same job, they need to follow each other and can not be done concurrently. Also, since allocation stopped after the schedule duration, the total duration of the remaining operations can just be added directly to it. If the last operation had been on M2, then if the first of the remaining operations could have been scheduled without the 3-week restriction being broken, it would have had to be scheduled from the last operation on M3 and in this case, the last operation's end time would have had to be used. If the end time of the last operations on M1, M2 and M3 were then compared, the larger value would have to be taken as the schedule duration. If however the last operation before the unallocated ones had been on M2, then the schedule duration would have had to used since if it had been possible to make the operations concurrent, the next operation would not have needed to be unallocated.

There are 540 minutes in a working day so there are (600+600+500+750)/540 days to be added to the schedule duration. Therefore, the new schedule duration is 4 Days and 12 hours + 20D 4:50 = 24D 16:50.

APPENDIX 6: THE PREACTOR CONFIGURATION

This appendix presents the configurations from which Preactor was built. Appendix 6A is the configuration that defines the databases and the associated fields while Appendix 6B defines the visual structure of Preactor.

APPENDIX 6A: PREACTOR Configuration Database File

```
HELP FILE ..\prconfig\PRSP_{COUNTRY}.HLP
;
ICONS ICONS.PDB
;
GANTT_BUCKET_WIDTH 1
;
RECORD_FORMAT
;
;
Jobs,.SCH,0,1000:
      Belongs to Order No.,-1,STRING,
        HELPPOPUPID (201) |
        FAMILY(Order No.) |
        DIALOG ONLY:
      Number,0,INTEGER,
        PRIMARY KEY |
        DIALOG ONLY |
        INHERIT FROM PARENT |
        HIDDEN:
      Show,1,TOGGLE,
        HELPPOPUPID (202) |
        INHERIT FROM PARENT:
      Part No.,-1,STRING,
        HELPPOPUPID (203) |
        DATABASE(Products(Part No.)) |
        INHERIT FROM PARENT |
        LOCATE |
        AUTO EXPAND |
        DbgQueueField1 |
        NO CHILD UPDATE:
      Order No.,-1,STRING,
        HELPPOPUPID (205) |
        FREE FORMAT (10) |
        INHERIT FROM PARENT |
        LOCATE |
        TIP DISPLAY |
        BAR DISPLAY:
      Op. No.,10,INTEGER,
        HELPPOPUPID (208) |
        DATABASE(Products(Operation No.)) |
        UPDATE REFERENCE(Part No.) |
        ICON DISPLAY |
```

```
  TIP DISPLAY |
  OPERATION NUMBER (10) |
  DbgQueueField2 |
  NO TRACK:
Operation,-1,STRING,
  DATABASE(Products(Operation)) |
  UPDATE REFERENCE(Part No.) |
  DIALOG ONLY |
  DIALOG LEVEL -1 |
  ALWAYS UPDATE:
Operation Name,-1,STRING,
  HELPPOPUPID (209) |
  DATABASE(Products(Operation Name)) |
  LOCATE |
  ADDITIONAL REFERENCE(Part No.) |
  SECONDARY PICK |
  DbgQueueField3 |
  TIP DISPLAY:
    Number of Operations,0,REAL,
  DIALOG ONLY |
  DATABASE(Products(Number of Operations) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE |
  INHERIT FROM PARENT |
  ALWAYS UPDATE|
  SORT RECORD:
    Cost of Operation,0,REAL,
  DIALOG ONLY |
  DATABASE(Products(Cost of Operation) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE |
  ALWAYS UPDATE|
  SORT RECORD:
    Positional Factor,0,REAL,
  DIALOG ONLY |
  DATABASE(Products(Positional Factor) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE |
  SORT RECORD|
  ALWAYS UPDATE:
    Penalty Cost,0,REAL,
  DIALOG ONLY |
  INHERIT FROM PARENT |
  INHERIT FROM PARENT |
  SORT RECORD:
    RemWork,0,DURATION,
  DIALOG ONLY |
  DATABASE(Products(RemWork) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE |
  SORT RECORD|
  ALWAYS UPDATE:
Setup Group,-1,STRING,
  HELPPOPUPID (239) |
  DIALOG ONLY |
  DATABASE(Setup Groups(Name)) |
  ALLOW UNSPECIFIED|NEW FIELD:
Resource Group,-1,STRING,
  NO TRACK
  HELPPOPUPID (210) |
```

```
  DATABASE(Resource Group(Name)) |
  SOURCE(Products(Resource Group)) |
  ALLOW UNSPECIFIED |
  DIALOG ONLY |
  READ ONLY |
  DEFAULT ON INSERT |
  UPDATE REFERENCE(Part No.) |
  SUBSTITUTE(-1 -> "All Resources"):
Required Resource,-1,STRING,
  HELPPOPUPID (211) |
  DATABASE(Resource Group(Resources)) |
  ALLOW UNSPECIFIED |
  FORCE WINDOW |
  NO TRACK |
  DEFAULT ON INSERT |
  SOURCE(Products(Required Resource)) |
  UPDATE REFERENCE(Operation) |
  SUBSTITUTE(-1 -> "Select from Group") |
  EXPAND UPDATE |
  DIALOG ONLY:
Resource,-1,STRING,
  HELPPOPUPID (212) |
  DATABASE(Resource Group(Resources)) |
  SOURCE(Products(Resource Data)) |
  ALLOW UNSPECIFIED |
  DEFAULT ON INSERT |
  V AXIS |
  DIALOG ONLY |
  ALWAYS UPDATE:
Quantity,1,INTEGER,
  HELPPOPUPID (215) |
  QUANTITY |
  TIP DISPLAY |
  DbgQueueField4 |
  PARENT UPDATE|
      HIDE WHEN DISABLED:
Routing Options,-1,DIALOG,
  HIDDEN IF 200 |
      HELPPOPUPID (322)
  CALL DIALOG 20:
Alternate Operation?,0,TOGGLE,
  DIALOG LEVEL 20 |
  DIALOG ONLY |
      HELPPOPUPID (304)
  DATABASE(Products(Alternate Operation?)) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE:
Route for This Op.,-1,STRING,
  DIALOG LEVEL 20 |
  READ ONLY | HELPPOPUPID (323)
  EXPAND UPDATE |
  DIALOG ONLY |
  SOURCE(Products(Route for This Op.)) |
  SUBSTITUTE(-1 -> "All Routes") |
  ALLOW UNSPECIFIED |
  UPDATE REFERENCE(Operation) |
  DATABASE(Products(Possible Routes)):
Current Route,-1,STRING,
  DIALOG LEVEL 20 |
  EXPAND UPDATE |
```

```
  DIALOG ONLY | HELPPOPUPID (324)
  SOURCE(Products(Default Route)) |
  UPDATE REFERENCE(Operation) |
  ALLOW UNSPECIFIED |
  INHERIT FROM PARENT |
  DATABASE(Products(Possible Routes)):
Disable Op,0,TOGGLE,
  HIDDEN
  ALWAYS UPDATE
  EVALUATE"(({#Route for This Op.}!={#Current Route})&&
        ({#Route for This Op.}!=-1)&&
        ({#Current Route}!=-1))||
       ({#Alternate Operation?}==1)"
  DISABLE OPERATION:
Process Time Type,0,STRING,
  HELPPOPUPID (213) |
  TABLE(Process Time Type) |
  SOURCE(Products(Process Time Type)) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE |
  FORCE COLUMN BREAK |
  DEFAULT ON INSERT |
  DIALOG ONLY |
  GLOBAL ASSIGN |
  NO TRACK:
Rate Per Hour Toggle,0,TOGGLE,
  DIALOG LEVEL 100 |
  EVALUATE"{#Process Time Type}==-1" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH ON (Quantity per Hour):
Time Per Item Toggle,0,TOGGLE,
  DIALOG LEVEL 100 |
  EVALUATE"{#Process Time Type}==0" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH ON (Op. Time per Item):
Time Per Batch Toggle,0,TOGGLE,
  DIALOG LEVEL 100 |
  EVALUATE"{#Process Time Type}==1" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  TIME PER BATCH |
  SWITCH ON (Batch Time):
Advanced Options,-1,DIALOG,
  HIDDEN IF 200 |
      HELPPOPUPID (302)
  CALL DIALOG 10:
Batching Method,0,STRING,
  TABLE(Batching Method) |
  SOURCE(Products(Batching Method)) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE |
  DEFAULT ON INSERT |
  DIALOG ONLY |
      HELPPOPUPID (303)
  NO TRACK:
Transfer Toggle,0,TOGGLE,
  DIALOG LEVEL 100 |
  EVALUATE"{#Batching Method}==1" |
```

```
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH ON (Transfer Quantity):
Split Togle,0,TOGGLE,
  DIALOG LEVEL 100 |
  EVALUATE"{#Batching Method}==2" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH ON (Lot Size) |
  SWITCH ON (Lot Number):
Transfer Quantity,0,REAL,
  DIALOG ONLY | HELPPOPUPID (319)
  DATABASE(Products(Transfer Quantity)) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE |
  HIDE WHEN DISABLED:
Lot Size,1,REAL,DIALOG ONLY
  DATABASE(Products(Lot Size) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE | HELPPOPUPID (320)
  HIDE WHEN DISABLED |
  OVERWRITE PREVIOUS:
Actual Transfer Quantity,-1,REAL,
  DIALOG ONLY |
  DIALOG LEVEL -1 |
  START OFFSET |
  ALWAYS UPDATE |
  EVALUATE"(({#Batching Method}==1)*{#Transfer Quantity})+
       (({#Batching Method}!=1)*(-1))":
Actual Lot Size,1,REAL,
  DIALOG ONLY |
  DIALOG LEVEL -1 |
  MAX LOT SIZE |
  ALWAYS UPDATE |
  EVALUATE"(({#Batching Method}==2)*{#Lot Size})+
       (({#Batching Method}!=2)*(-1))":
Lot Number,1,REAL,
  DIALOG ONLY | HELPPOPUPID (321)
  HIDE WHEN DISABLED |
  LOT NUMBER:
Op. Time per Item,1,DURATION,
  HELPPOPUPID (214) |
  FORMAT(.4) |
  DIALOG ONLY |
  NO DAYS |
  DATABASE(Products(Op. Time per Item)) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE |
  ALWAYS UPDATE |
  HIDE WHEN DISABLED:
Batch Time,1,DURATION,
  FORMAT(.4) |
  DIALOG ONLY |
  ALLOW OPERATION SPAN |
  DATABASE(Products(Batch Time) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE | HELPPOPUPID (318)
  ALWAYS UPDATE |
  HIDE WHEN DISABLED |
  OVERWRITE PREVIOUS:
```

```
Quantity per Hour,1,REAL,
  FORMAT(.4) | HELPPOPUPID (317)
  DIALOG ONLY |
  DATABASE(Products(Quantity per Hour)) |
  UPDATE REFERENCE(Operation) |
  EXPAND UPDATE |
  ALWAYS UPDATE |
  HIDE WHEN DISABLED |
  OVERWRITE PREVIOUS:
Real Op Time Per Item,0,DURATION,
  ALLOW OPERATION SPAN |
  EVALUATE"(({Op. Time per Item})*({#Process Time Type}==0))+
        (({Batch Time})*({#Process Time Type}==1))+
        ((-1)*({#Process Time Type}==2))+
        (((1/{Quantity per Hour})/24)*({#Process Time Type}==-1)))" |
  PROCESS TIME |
  ALWAYS UPDATE |
  DIALOG LEVEL 100 |
  DIALOG ONLY:
Due Date,-1,TIME,
  HELPPOPUPID (217) |
  REPEAT UPDATE |
  DUE DATE |
  SHOW DATE |
  INHERIT FROM PARENT |
  TIP DISPLAY |
  SORT RECORD LOCATE:
Setup Start,-1,TIME,
  HELPPOPUPID (219) |
  LAUNCH TIME |
  DEFAULT ON INSERT |
  DIALOG ONLY:
Start Time,-1,TIME,
  HELPPOPUPID (220) |
  START TIME |
  DEFAULT ON INSERT |
  H START |
  DIALOG ONLY:
End Time,-1,TIME,
  HELPPOPUPID (221) |
  END TIME |
  DEFAULT ON INSERT |
  H END |
  DIALOG ONLY:
Lock Operation,0,TOGGLE,
  HELPPOPUPID (222) |
  DIALOG ONLY |
  DEFAULT ON INSERT |
  SEQUENCE LOCK|NEW FIELD:
Mid Batch Quantity,0,INTEGER,
  SEQ COMPLETED |
  DIALOG ONLY |
      HELPPOPUPID (305)
  DIALOG LEVEL 10:
Mid Batch Time,-1,TIME,
  SEQ REFERENCE TIME |
  DIALOG ONLY |
      HELPPOPUPID (305)
  DIALOG LEVEL 10:
Effective Op Time,0,DURATION,
```

```
    SEQ EFFECTIVE PROCESS TIME |
    DIALOG ONLY |
    READ ONLY |
        HELPPOPUPID (305)
    DIALOG LEVEL 10:
  Assembly Level,1,REAL,DIALOG ONLY
    DIALOG LEVEL 10 |
    SUB-ASSEMBLY LEVEL |
    DATABASE(Products(Assembly Level)) |
    UPDATE REFERENCE(Operation) |
        HELPPOPUPID (342)
    EXPAND UPDATE:
  Assembly Key,1,REAL,DIALOG ONLY
    DIALOG LEVEL 10 |
    SUB-ASSEMBLY KEY |
    DATABASE(Products(Assembly Key)) |
    UPDATE REFERENCE(Operation) |
        HELPPOPUPID (343)
    EXPAND UPDATE:
  Spare 4,-1,INTEGER,HIDDEN:
  Spare 5,-1,INTEGER,HIDDEN:
  Spare 6,-1,INTEGER,HIDDEN:
  Spare 7,-1,INTEGER,HIDDEN:
  Spare 8,-1,INTEGER,HIDDEN:
  Spare 9,-1,INTEGER,HIDDEN:
  Spare 10,-1,INTEGER,HIDDEN;
;
;
Resource Group,"GROUPS.PDB",0:
  Number,0,INTEGER,
    PRIMARY KEY |
    HIDDEN:
  Name,0,STRING,
    HELPPOPUPID (258) |
    FREE FORMAT (40) |
    UNIQUE |
    GANTT GROUP |
    SEQ GROUP:
  Resources,-1,MATRIX,
    CALENDAR GROUP |
    HELPPOPUPID (259) |
    AUTO LIST(Resources(Name));
;
Resources,"RESOURCE.PDB",0,50:
  Number,0,INTEGER,
    PRIMARY KEY |
    HIDDEN:
  Name,0,STRING,
    FREE FORMAT (35) |
    UNIQUE |
    SEQ WINDOW:
  Sequencer Window State,0,STRING,
    TABLE(Window State) |
    DIALOG ONLY |
    SEQ STATE:
  Bucket Units,1,STRING,
    TABLE(Time Items) |
    DIALOG ONLY |
    SEQ BUCKET UNITS:
  Bucket Size,60,INTEGER,
```

```
      INTEGER |
      DIALOG ONLY |
      SEQ BUCKET DURATION:
    Bucket Capacity,60,INTEGER,
      INTEGER |
      DIALOG ONLY |
      SEQ BUCKET CAPACITY |
      SUBSTITUTE(-1 -> "Infinite"):
    Vertical Bucket Size,60,INTEGER,
      DIALOG ONLY |
      SEQ VERTICAL BUCKET SIZE:
    Waiting Plot Color,7,STRING,
      COLOR |
      TABLE(Colors) |
      WAIT CONTROL |
      DIALOG ONLY:
    Waiting Plot Fill Pattern,16,STRING,
      TABLE(Patterns) |
      PATTERN |
      WAIT CONTROL |
      DIALOG ONLY:
    Secondary Resources,-1,MATRIX,
      AUTO LIST(Secondary Resources(Name))
      HELPPOPUPID (326):
    Constraint Usage,5,MATRIX | STRING,
      CAPACITY TYPE |
      HELPPOPUPID (327) |
      TABLE(Constraint Usage) |
      ASSOCIATE(Secondary Resources) |
      AUTO DIMENSION(Resource,Resources(Name),
               Constraint,Secondary Resources(Name)):
    Constraint Quantity,0,MATRIX | REAL,
      USE CAPACITY |
      HELPPOPUPID (328) |
      REMOTE(Jobs(Quantity)) |
      ASSOCIATE(Secondary Resources) |
      AUTO DIMENSION(Resource,Resources(Name),
               Constraint,Secondary Resources(Name));
;
;
;
Calendar,.CAL,0,50000:
    Primary,1,TOGGLE,
      PRIMARY RESOURCE |
      DIALOG ONLY |
      SWITCH ON (Primary Data) |
      SWITCH OFF (Secondary Data) |
      SWITCH ON (Primary Resource) |
      SWITCH ON (Primary Resource Group) |
      SWITCH OFF (Secondary Resource) |
      SWITCH ON (Status) |
      SWITCH OFF (Max.) |
      SWITCH ON (Efficiency %) |
      SWITCH OFF (Min.) |
      HELPPOPUPID (330) |
      SWITCH ON (Primary Resource Group):
    Primary Data,0,STRING,
      NULL FIELD |
      HELPPOPUPID (331) |
      DIALOG ONLY:
```

```
    Primary Resource,-1,STRING,
      HELPPOPUPID (223) |
      DATABASE(Resources(Name)) |
      SEQ WINDOW |
      SUBSTITUTE(-2->"Use Group") |
      ALLOW UNSPECIFIED:
    Primary Resource Toggle,0,TOGGLE,
      DIALOG LEVEL 100 |
      EVALUATE"({#Primary Resource}==-2) && {#Primary}" |
      DIALOG ONLY |
      ALWAYS UPDATE |
      SWITCH OFF (Primary Resource Group):
    Primary Resource Group,-1,STRING,
      DATABASE(Resource Group(Name)) |
      ALLOW UNSPECIFIED
      HELPPOPUPID (332):
    Status,1,STRING,
      HELPPOPUPID (224) |
      DATABASE(Calendar States(Name)):
    Efficiency %,100,REAL,
      HELPPOPUPID (225) |
      DATABASE(Calendar States(Efficiency)) |
      UPDATE REFERENCE(Status) |
      EFFICIENCY:
    Secondary Data,0,STRING,
      NULL FIELD |
      HELPPOPUPID (333) |
      DIALOG ONLY:
    Secondary Resource,-1,STRING,
      DATABASE(Secondary Resources(Name)) |
      ALLOW UNSPECIFIED |
      SEQ GRAPH
      HELPPOPUPID (334):
    Max.,0,INTEGER,
      WIDTH OF (*****) |
      HELPPOPUPID (335) |
      GRAPH HIGH VALUE:
    Min.,0,INTEGER,
      WIDTH OF (*****) |
      HELPPOPUPID (336) |
      GRAPH LOW VALUE:
    Time Data,0,STRING,
      NULL FIELD |
      HELPPOPUPID (337) |
      DIALOG ONLY:
    Start Time,-1,TIME,
      HELPPOPUPID (226) |
      START TIME:
    End Time,-1,TIME,
      HELPPOPUPID (227) |
      END TIME;
;
;
Default Calendar,.CAL,0:
    Primary,1,TOGGLE,
      PRIMARY RESOURCE |
      DIALOG ONLY |
      SWITCH ON (Primary Data) |
      SWITCH OFF (Secondary Data) |
      SWITCH ON (Primary Resource) |
```

```
  SWITCH ON (Primary Resource Group) |
  SWITCH OFF (Secondary Resource) |
  SWITCH ON (Status) |
  SWITCH OFF (Max.) |
  SWITCH ON (Efficiency %) |
  SWITCH OFF (Min.) |
  HELPPOPUPID (364) |
  SWITCH ON (Primary Resource Group):
Primary Data,0,STRING,
  NULL FIELD |
  HELPPOPUPID (331) |
  DIALOG ONLY:
Primary Resource,-1,STRING,
  HELPPOPUPID (365) |
  DATABASE(Resources(Name)) |
  SUBSTITUTE(-2->"Use Group") |
  SEQ WINDOW |
  ALLOW UNSPECIFIED:
Primary Resource Toggle,0,TOGGLE,
  DIALOG LEVEL 100 |
  EVALUATE"({#Primary Resource}==-2) && {#Primary}" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH OFF (Primary Resource Group):
Primary Resource Group,-1,STRING,
  DATABASE(Resource Group(Name)) |
  ALLOW UNSPECIFIED
  HELPPOPUPID (366):
Status,1,STRING,
  HELPPOPUPID (229) |
  DATABASE(Calendar States(Name)):
Efficiency %,100,REAL,
  HELPPOPUPID (230) |
  DATABASE(Calendar States(Efficiency)) |
  UPDATE REFERENCE(Status) |
  EFFICIENCY:
Secondary Data,0,STRING,
  NULL FIELD |
  HELPPOPUPID (367) |
  DIALOG ONLY:
Secondary Resource,-1,STRING,
  DATABASE(Secondary Resources(Name)) |
  ALLOW UNSPECIFIED |
  SEQ GRAPH
  HELPPOPUPID (368):
Max.,0,INTEGER,
  WIDTH OF (*****) |
  HELPPOPUPID (335) |
  GRAPH HIGH VALUE:
Min.,0,INTEGER,
  WIDTH OF (*****) |
  HELPPOPUPID (336) |
  GRAPH LOW VALUE:
Time Data,0,STRING,
  NULL FIELD |
  DIALOG ONLY
  HELPPOPUPID (337):
Start Time,-1,TIME,
  HELPPOPUPID (369) |
  SHOW TIME:
```

```
      End Time,-1,TIME,
        HELPPOPUPID (370) |
        SHOW TIME;
;
;
Calendar States,"STATES.PDB",0:
      Number,0,INTEGER,
        PRIMARY KEY |
        HIDDEN:
      Name,1,STRING,
        UNIQUE |
        HELPPOPUPID (338) |
        FREE FORMAT(30):
      Efficiency,100,INTEGER,
        HELPPOPUPID (339):
      Color,-1,STRING,
        HELPPOPUPID (340) |
        TABLE(Colors) |
        COLOR |
        CALENDAR CONTROL:
      Pattern,-1,STRING,
        HELPPOPUPID (341) |
        TABLE(Patterns) |
        PATTERN |
        CALENDAR CONTROL;
;
; Products Definition
;
Products,"PRODUCTS.PDB",0,500:
      Parent Part,-1,STRING,
        HELPPOPUPID (233) |
        FAMILY(Part No.) |
        DIALOG ONLY:
      Number,0,INTEGER,
        PRIMARY KEY |
        HIDDEN:
      Part No.,0,STRING,
        HELPPOPUPID (234) |
        FREE FORMAT (10) |
        LOCATE |
        INHERIT FROM PARENT |
        UNIQUE:
      Setup Group,-1,STRING,
        HELPPOPUPID (239) |
        DIALOG ONLY |
        DATABASE(Setup Groups(Name)) |
        ALLOW UNSPECIFIED:
      Operation No.,10,INTEGER,
        HELPPOPUPID (236) |
        OPERATION NUMBER (10):
      Operation,-1,STRING,
        FREE FORMAT |
        EVALUATE"{Part No.} {Operation Name} {Operation No.}" |
        ALWAYS UPDATE |
        DIALOG ONLY |
        DIALOG LEVEL 99:
      Operation Name," ",STRING,
        HELPPOPUPID (237) |
        FREE FORMAT |
        GANTT LEGEND:
```

```
Additional Op.,0,TOGGLE,
  HELPPOPUPID (307) |
  CONTROL AUTO EXPAND |
  DIALOG ONLY:
    Number of Operations,0,INTEGER,
  DIALOG ONLY|
  INHERIT FROM PARENT:
    Cost of Operation,0,REAL,
  DIALOG ONLY:
Positional Factor,0,REAL,
      DIALOG ONLY:
Penalty Cost,0,REAL,
  DIALOG ONLY|
  INHERIT FROM PARENT:
RemWork,0,DURATION,
  DIALOG ONLY:
Resource Group,-1,STRING,
  NO TRACK
  DATABASE(Resource Group(Name)) |
  ALLOW UNSPECIFIED |
  HELPPOPUPID (239) |
  SUBSTITUTE(-1 -> "All Resources"):
Resource Data,-1,MATRIX,
  HELPPOPUPID (308) |
  AUTO SELECT |
  AUTO LIST(Resource Group(Resources)):
Allow Auto Seq.?,1,MATRIX | TOGGLE,
  HELPPOPUPID (309) |
  AUTO SEQ RESTRICT |
  ASSOCIATE(Resource Data) |
  AUTO DIMENSION(Product,Products(Operation),
          Resource,Resources(Name)):
Res. Specific Op Time,0,MATRIX | DURATION,
  HELPPOPUPID (362) |
  HIDE WHEN DISABLED |
  ASSOCIATE(Resource Data) |
  ALTERNATE PROCESS TIME |
  AUTO DIMENSION(Product,Products(Operation),
          Resource,Resources(Name)):
Res. Specific Sec. Const.,-1,MATRIX | STRING,
  HELPPOPUPID (310) |
  DATABASE(Secondary Resources(Name)) |
  ALLOW UNSPECIFIED |
  ASSOCIATE(Resource Data) |
  AUTO DIMENSION(Product,Products(Operation),
          Resource,Resources(Name)):
Res. Specific Const. Usage,5,MATRIX | STRING,
  HELPPOPUPID (311) |
  CAPACITY TYPE |
  TABLE(Constraint Usage) |
  ASSOCIATE(Resource Data) |
  AUTO DIMENSION(Product,Products(Operation),
          Resource,Resources(Name)):
Res. Specific Const. Qty,0,MATRIX | REAL,
  HELPPOPUPID (312) |
  USE CAPACITY |
  REMOTE(Jobs(Quantity)) |
  ASSOCIATE(Resource Data) |
  AUTO DIMENSION(Product,Products(Operation),
          Resource,Resources(Name)):
```

```
Res. Selection Timeout,-1,MATRIX | DURATION,
  HELPPOPUPID (313) |
  RESOURCE SELECTION TIMEOUT |
  HIDDEN IF 200 |
  ASSOCIATE(Resource Data) |
  AUTO DIMENSION(Product,Products(Operation),
           Resource,Resources(Name)):
Set Subsequent Resource Group,-1,MATRIX | STRING,
  HELPPOPUPID (314) |
  NO TRACK
  SUBSEQUENT RESOURCE CONSTRAINT |
  ALLOW UNSPECIFIED |
  HIDDEN IF 200 |
  DATABASE(Resource Group(Name)) |
  ASSOCIATE(Resource Data) |
  AUTO DIMENSION(Product,Products(Operation),
           Resource,Resources(Name)):
Reset Subsequent Resource Group,-1,MATRIX | STRING,
  HELPPOPUPID (315) |
  NO TRACK
  RESET SUBSEQUENT RESOURCE |
  ALLOW UNSPECIFIED |
  MUST USE NEXT |
  HIDDEN IF 200 |
  DATABASE(Resource Group(Name)) |
  ASSOCIATE(Resource Data) |
  AUTO DIMENSION(Product,Products(Operation),
           Resource,Resources(Name)):
Required Resource,-1,STRING,
  HELPPOPUPID (240) |
  DATABASE(Resource Group(Resources)) |
  ALLOW UNSPECIFIED |
  FORCE WINDOW |
  NO TRACK |
  SUBSTITUTE(-1 -> "Select from Group"):
Advanced Options,-1,DIALOG,
  HELPPOPUPID (316) |
  HIDDEN IF 200 |
  CALL DIALOG 10:
Setup Time,0,DURATION,
  HELPPOPUPID (241) |
  FORCE COLUMN BREAK |
  DIALOG ONLY |
  FORMAT(.2) |
  SEQ SETUP:
Like To Like Setup Time,-1,DURATION,
  HELPPOPUPID (243) |
  DIALOG ONLY |
  FORMAT(.2) |
  LIKE TO LIKE SETUP:
Process Time Type,0,STRING,
  HELPPOPUPID (242) |
  TABLE(Process Time Type) |
  DIALOG ONLY |
  GLOBAL ASSIGN:
Rate Per Hour Toggle,0,TOGGLE,
  EVALUATE"{#Process Time Type}==-1" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH ON (Quantity per Hour) |
```

```
  DIALOG LEVEL 99:
Time Per Item Toggle,0,TOGGLE,
  EVALUATE"{#Process Time Type}==0" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH ON (Op. Time per Item) |
  DIALOG LEVEL 99:
Time Per Batch Toggle,0,TOGGLE,
  EVALUATE"{#Process Time Type}==1" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH ON (Batch Time) |
  DIALOG LEVEL 99:
Res Specific Time Per Item Toggle,0,TOGGLE,
  EVALUATE"{#Process Time Type}==2" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH ON (Res. Specific Op Time) |
  DIALOG LEVEL 99:
Op. Time per Item,0.006944444444445,DURATION,
  FORMAT(.4) |
  DIALOG ONLY |
  NO DAYS |
  HIDE WHEN DISABLED |
  HELPPOPUPID (214):
Batch Time,0.006944444444445,DURATION,
  FORMAT(.4) | HELPPOPUPID (318)
  DIALOG ONLY |
  ALLOW OPERATION SPAN |
  HIDE WHEN DISABLED |
  OVERWRITE PREVIOUS:
Quantity per Hour,1,REAL,
  FORMAT(.4) | HELPPOPUPID (317)
  DIALOG ONLY |
  HIDE WHEN DISABLED |
  OVERWRITE PREVIOUS:
Real Op Time Per Item,0,DURATION,
  EVALUATE"(({Op. Time per Item})*({#Process Time Type}==0))+
        (({Batch Time})*({#Process Time Type}==1))+
        (((1/{Quantity per Hour})/24)*({#Process Time Type}==-1)))" |
  ALWAYS UPDATE |
  DIALOG ONLY |
  DIALOG LEVEL 99:
Batching Method,0,STRING,
  TABLE(Batching Method) |
      HELPPOPUPID (303)
  DIALOG ONLY:
Transfer Toggle,0,TOGGLE,
  EVALUATE"{#Batching Method}==1" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH ON (Transfer Quantity) |
  DIALOG LEVEL 99:
Spilt Toggle,0,TOGGLE,
  EVALUATE"{#Batching Method}==2" |
  DIALOG ONLY |
  ALWAYS UPDATE |
  SWITCH ON (Lot Size) |
  DIALOG LEVEL 99:
Transfer Quantity,0,REAL,
```

```
      HELPPOPUPID (319)
   DIALOG ONLY |
   HIDE WHEN DISABLED:
Lot Size,1,REAL,
      HELPPOPUPID (320)
   DIALOG ONLY |
   HIDE WHEN DISABLED |
   OVERWRITE PREVIOUS:
Product Display Data,-1,DIALOG,
   HELPPOPUPID (244) |
   CALL DIALOG 20:
Icon Name,1,STRING,
   HELPPOPUPID (245) |
   ICON |
   DIALOG ONLY |
   SEQ ICON |
   INHERIT FROM PARENT |
   DIALOG LEVEL 20:
Icon Foreground,15,STRING,
   HELPPOPUPID (246) |
   COLOR |
   TABLE(Colors) |
   DIALOG ONLY |
   SEQ ICON FOREGROUND |
   INHERIT FROM PARENT |
   DIALOG LEVEL 20:
Icon Background,8,STRING,
   HELPPOPUPID (247) |
   COLOR |
   TABLE(Colors) |
   DIALOG ONLY |
   SEQ ICON BACKGROUND |
   GANTT CONTROL |
   INHERIT FROM PARENT |
   DIALOG LEVEL 20:
Pattern,16,STRING,
   HELPPOPUPID (248) |
   TABLE(Patterns) |
   PATTERN |
   GANTT CONTROL |
   DIALOG ONLY |
   INHERIT FROM PARENT |
   DIALOG LEVEL 20:
Secondary Resources,-1,MATRIX,
   AUTO LIST(Secondary Resources(Name))
      HELPPOPUPID (363):
Constraint Usage,5,MATRIX | STRING,
   CAPACITY TYPE |
      HELPPOPUPID (327)
   TABLE(Constraint Usage) |
   ASSOCIATE(Secondary Resources) |
   AUTO DIMENSION(Product,Products(Operation),
         Constraint,Secondary Resources(Name)):
Constraint Quantity,0,MATRIX | REAL,
   USE CAPACITY |
      HELPPOPUPID (328)
   REMOTE(Jobs(Quantity)) |
   ASSOCIATE(Secondary Resources) |
   AUTO DIMENSION(Product,Products(Operation),
         Constraint,Secondary Resources(Name)):
```

```
Assembly Level,1,REAL,
  DIALOG ONLY |
      HELPPOPUPID (342)
  DIALOG LEVEL 10:
Assembly Key,1,REAL,
  DIALOG ONLY |
      HELPPOPUPID (343)
  DIALOG LEVEL 10:
Link Operation By Key?,0,TOGGLE,
  DIALOG ONLY |
  HIDDEN |
  SUBSEQUENT OP KEY MATCH |
  DIALOG LEVEL 10:
Max Time Before Next Op.,-1,DURATION,
  DIALOG ONLY |
      HELPPOPUPID (344)
  DIALOG LEVEL 10 |
  INTER OPERATION INTERVAL:
Interval Type,0,STRING,
  TABLE(Interval Types) |
  DIALOG ONLY |
      HELPPOPUPID (345)
  DIALOG LEVEL 10 |
  INTER OPERATION TYPE:
Maximum Operation Span Increase %,-1,REAL,
  DIALOG ONLY |
      HELPPOPUPID (346)
  DIALOG LEVEL 10 |
  MAX OPERATION SPAN |
  SUBSTITUTE(-1 -> "Infinite"):
Slack Time After Last Operation,0,DURATION,
  DIALOG ONLY |
      HELPPOPUPID (347)
  DIALOG LEVEL 10 |
  SEQ SLACK:
Routing Options,-1,DIALOG,
  HIDDEN IF 200 |
      HELPPOPUPID (322)
  CALL DIALOG 30:
Alternate Operation?,0,TOGGLE,
  DIALOG LEVEL 30 |
      HELPPOPUPID (238)
  DIALOG ONLY:
Possible Routes,-1,MATRIX,
  PARENT ONLY
      HELPPOPUPID (348)
  INHERIT FROM PARENT
  HIDDEN IF 200 |
  DIALOG LEVEL 30 |
  AUTO LIST(Routes(Name)):
Route for This Op.,-1,STRING,
  HIDDEN IF 200 |
      HELPPOPUPID (323)
  DIALOG LEVEL 30 |
  SUBSTITUTE(-1 -> "All Routes") |
  ALLOW UNSPECIFIED |
  DATABASE(Products(Possible Routes)):
Default Route,-1,STRING,
  DIALOG LEVEL 30 |
  INHERIT FROM PARENT |
```

```
    DIALOG ONLY |
        HELPPOPUPID (349)
    ALLOW UNSPECIFIED |
    DATABASE(Products(Possible Routes)):
  Dummy Access,-1,STRING,
    DIALOG ONLY
    DIALOG LEVEL -1
    READ ONLY
    NO TRACK
    EVALUATE"(({#Parent Part}==-1)*{#Number})+
        (({#Parent Part}!=-1)*{#Parent Part})"
    ALWAYS UPDATE
    DATABASE(Products(Part No.)):
  Spare 4,-1,INTEGER,HIDDEN:
  Spare 5,-1,INTEGER,HIDDEN:
  Spare 6,-1,INTEGER,HIDDEN:
  Spare 7,-1,INTEGER,HIDDEN:
  Spare 8,-1,INTEGER,HIDDEN:
  Spare 9,-1,INTEGER,HIDDEN:
  Spare 10,-1,INTEGER,HIDDEN;
;
;
Calendar Set Up,"HORIZON.PDB",0:
  Number,0,INTEGER,
    PRIMARY KEY |
    HIDDEN | READ ONLY:
  Amount of History Days Displayed,7,INTEGER,
    HELPPOPUPID (253):
  Future Days Displayed,100,INTEGER,
    HELPPOPUPID (254):
  Default Earliest Start Date Offset,0,INTEGER,
    HELPPOPUPID (255):
  Default Due Date Offset,21,INTEGER,
    HELPPOPUPID (256):
  Default Terminator Offset,0,DURATION,
    HELPPOPUPID (257):
  Default Start Offset,0,DURATION,
    DIALOG ONLY | HIDDEN;
;
;
Secondary Resources,"CONSTR2.PDB",0:
  Number,0,INTEGER,
    PRIMARY KEY |
    HIDDEN:
  Name,1,STRING,
    UNIQUE |
    HELPPOPUPID (350)
    FREE FORMAT(20) |
    SEQ GRAPH:
  Plot Color,8,STRING,
    HELPPOPUPID (351)
    COLOR |
    TABLE(Colors) |
    GRAPH CONTROL:
  Plot Fill Pattern,1,STRING,
    HELPPOPUPID (352)
    TABLE(Patterns) |
    PATTERN |
    GRAPH CONTROL:
  Max. Value,0,INTEGER,
```

```
    HELPPOPUPID (353)
    SUBSTITUTE(0->"Follow Shift Pattern") |
    GRAPH HIGH VALUE |
    DIALOG ONLY:
  Max. Value Color,8,STRING,
    HELPPOPUPID (354)
    COLOR |
    GRAPH HIGH CONTROL |
    TABLE(Colors) |
    DIALOG ONLY:
  Min. Value,0,INTEGER,
    HELPPOPUPID (355)
    GRAPH LOW VALUE |
    DIALOG ONLY:
  Min. Value Color,8,STRING,
    HELPPOPUPID (356)
    COLOR |
    GRAPH LOW CONTROL |
    TABLE(Colors) |
    DIALOG ONLY :
  Use as a Constraint,0,TOGGLE,
    HELPPOPUPID (357)
    SECONDARY CONSTRAINT |
    CONSTRAINT LIMIT CHECK |
    DIALOG ONLY:
  Calendar Effect,3,STRING,
    HELPPOPUPID (358)
    TABLE(Effects) |
    CAPACITY CALENDAR EFFECT;
;
;
;
Setup Groups,"SETGROUP.PDB",0:
  Number,0,INTEGER,
    PRIMARY KEY |
    HIDDEN:
  Name,1,STRING,
    HELPPOPUPID (359)
    UNIQUE |
    FREE FORMAT(30):
  Sequence Dependent Setup Time,0,MATRIX | DURATION,
    HELPPOPUPID (360)
    AUTO DIMENSION(To,Setup Groups(Name),
          From,Setup Groups(Name)) |
    SEQ SETUP;
;
Routes,"ROUTES.PDB",0:
  Number,0,INTEGER,
    PRIMARY KEY |
    HIDDEN:
  Name,1,STRING,
    UNIQUE |
    HELPPOPUPID (361)
    FREE FORMAT(30);
;
RECORD_END
;
STRING_TABLES
;
Constraint Usage:
```

1, Increment from Start:
2, Increment from End:
3, Decrement from Start:
4, Decrement from End:
5, Increment for Duration:
6, Decrement for Duration:
7, No Change:
8, Increment To End:
9, Decrement To End:
10, Increment Setup Time Only:
11, Decrement Setup Time Only:
12, Increment From Start Of Setup:
13, Decrement From Start Of Setup:
14, Increment For Entire Job:
15, Decrement For Entire Job;

;
Interval Types:
0,No limit:
1,End of Current to Start of Next:
2,End of Current to End of Next:
3,Start of Current to Start of Next:
4,Start of Current to End of Next;

;
Effects:
0, No Effect:
1, Start of Job Efficiency:
2, Follow Efficiency Changes:
3, Use 100% if Greater Than 0%;

;
Process Time Type:
-1, Rate Per Hour:
0, Time Per Item:
1, Time Per Batch:
2, Res. Specific Time Per Item;

;
;
Operation Type:
0, Other:
-1, Load Tools;

;
;
;
Batching Method:
0, None:
1, Transfer:
2, Split;

;
Time Items:
1, Minutes:
2, Hours:
3, Days:
4, Weeks;

;
Finite:
-2, Infinite with Shift Patterns:
-1, Infinite:
1, Finite;

;
Colors:
-2, White:

1, Blue:
2, Red:
3, Pink:
4, Green:
5, Cyan:
6, Yellow:
7, Black:
8, Dark Gray:
9, Dark Blue:
10, Dark Red:
11, Dark Pink:
12, Dark Green:
13, Dark Cyan:
14, Brown:
15, Pale Gray:
-1, None;
;
Patterns:
16, Solid (100%):
1, 90% Fill:
2, 80% Fill:
3, 70% Fill:
4, 60% Fill:
17, Half Tone (50%):
5, 40% Fill:
6, 30% Fill:
7, 20% Fill:
8, 10% Fill:
15, Blank (0%):
9, Vertical Lines:
10, Horizontal Lines:
11, Lt Up Diagonal 1:
21, Dk Up Diagonal 1:
12, Lt Up Diagonal 2:
22, Dk Up Diagonal 2:
25, Lt Up Diagonal 3:
26, Dk Up Diagonal 3:
13, Lt Down Diagonal 1:
23, Dk Down Diagonal 1:
14, Lt Down Diagonal 2:
24, Dk Down Diagonal 2:
27, Lt Down Diagonal 3:
28, Dk Down Diagonal 3:
18, Small Hatch:
20, Large Hatch:
19, Cross Hatch:
29, Horizontal Zig Zag:
30, Vertical Zig Zag:
31, Large Spots:
32, Small Spots:
33, Horizontal Wave:
34, Vertical Wave:
10001,Safe Back Diagonal:
10002,Safe Forward Diagonal:
10003,Safe Horizontal:
10004,Safe Vertical:
10005,Safe Cross Hatch:
10006,Safe Diagonal Hatch:
-1, None;
;

```
Window State:
  0, Visible:
  1, Minimized:
  2, Disabled;
;
;
STRING_TABLES_END
;
REPORTS
;
;
; Report of orders (Parent records only)
;
; Schedule Performance report (Only correct from within the Sequencer)
;
Schedule Performance,Jobs,Portrait,62,100,Time,200:
   Form No. : P300-000,Left,1,1,-1,
   {TIME},Right,1,1,0,
   Schedule Performance Metrics,Center | FONT(Times New Roman) BOLD ITALIC,2,2,1,
   Job Count Data,ABSOLUTE 2,1,1,0,
   Early,ABSOLUTE 24,1,1,-1,
   Late,ABSOLUTE 39,1,1,-1,
   Incomplete,ABSOLUTE 52,1,1,-1,
   Started,ABSOLUTE 68,1,1,1,
   Absolute,ABSOLUTE 3,1,1,-1,
   {PERF_NUMBER_EARLY_JOBS},ABSOLUTE 23,1,1,-1,
   {PERF_NUMBER_LATE_JOBS},ABSOLUTE 38,1,1,-1,
   {PERF_NUMBER_INCOMPLETE_JOBS},ABSOLUTE 53,1,1,-1,
   {PERF_NUMBER_STARTED_JOBS},ABSOLUTE 68,1,1,0,
   Percentage,ABSOLUTE 3,1,1,-1,
   {PERF_PERCENT_EARLY_JOBS},ABSOLUTE 23,1,1,-1,
   {PERF_PERCENT_LATE_JOBS},ABSOLUTE 38,1,1,-1,
   {PERF_PERCENT_INCOMPLETE_JOBS},ABSOLUTE 53,1,1,-1,
   {PERF_PERCENT_STARTED_JOBS},ABSOLUTE 68,1,1,1,
   Job Completion Data,ABSOLUTE 2,1,1,0,
   Total,ABSOLUTE 24,1,1,-1,
   Minimum,ABSOLUTE 38,1,1,-1,
   Average,ABSOLUTE 53,1,1,-1,
   Maximum,ABSOLUTE 67,1,1,1,
   Early Time,ABSOLUTE 3,1,1,-1,
   {PERF_TOTAL_EARLY_TIME},ABSOLUTE 19.5,1,1,-1,
   {PERF_MIN_EARLY_TIME},ABSOLUTE 34.5,1,1,-1,
   {PERF_AVG_EARLY_TIME},ABSOLUTE 49.5,1,1,-1,
   {PERF_MAX_EARLY_TIME},ABSOLUTE 64.5,1,1,0,
   Late Time,ABSOLUTE 3,1,1,-1,
   {PERF_TOTAL_LATE_TIME},ABSOLUTE 19.5,1,1,-1,
   {PERF_MIN_LATE_TIME},ABSOLUTE 34.5,1,1,-1,
   {PERF_AVG_LATE_TIME},ABSOLUTE 49.5,1,1,-1,
   {PERF_MAX_LATE_TIME},ABSOLUTE 64.5,1,1,0,
   Setup Time,ABSOLUTE 3,1,1,-1,
   {PERF_TOTAL_SETUP_TIME},ABSOLUTE 19.5,1,1,-1,
   {PERF_MIN_SETUP_TIME},ABSOLUTE 34.5,1,1,-1,
   {PERF_AVG_SETUP_TIME},ABSOLUTE 49.5,1,1,-1,
   {PERF_MAX_SETUP_TIME},ABSOLUTE 64.5,1,1,0,
   Lead Time,ABSOLUTE 3,1,1,-1,
   {PERF_TOTAL_LEAD_TIME},ABSOLUTE 19.5,1,1,-1,
   {PERF_MIN_LEAD_TIME},ABSOLUTE 34.5,1,1,-1,
   {PERF_AVG_LEAD_TIME},ABSOLUTE 49.5,1,1,-1,
   {PERF_MAX_LEAD_TIME},ABSOLUTE 64.5,1,1,1,
   Added Value Percentage,ABSOLUTE 3,1,1,-1,
```

{PERF_MIN_ADDED_VALUE},ABSOLUTE 38,1,1,-1,
{PERF_AVG_ADDED_VALUE},ABSOLUTE 53,1,1,-1,
{PERF_MAX_ADDED_VALUE},ABSOLUTE 68,1,1,1,
Resource Data,ABSOLUTE 2,1,1,0,
Minimum,ABSOLUTE 38,1,1,-1,
Average,ABSOLUTE 53,1,1,-1,
Maximum,ABSOLUTE 67,1,1,1,
Working Percentage,ABSOLUTE 3,1,1,-1,
{PERF_MIN_WORKING},ABSOLUTE 38,1,1,-1,
{PERF_AVG_WORKING},ABSOLUTE 53,1,1,-1,
{PERF_MAX_WORKING},ABSOLUTE 68,1,1,0,
Setup Percentage,ABSOLUTE 3,1,1,-1,
{PERF_MIN_RES_SETUP},ABSOLUTE 38,1,1,-1,
{PERF_AVG_RES_SETUP},ABSOLUTE 53,1,1,-1,
{PERF_MAX_RES_SETUP},ABSOLUTE 68,1,1,0,
Unavailable Percentage,ABSOLUTE 3,1,1,-1,
{PERF_MIN_UNAVAILABLE},ABSOLUTE 38,1,1,-1,
{PERF_AVG_UNAVAILABLE},ABSOLUTE 53,1,1,-1,
{PERF_MAX_UNAVAILABLE},ABSOLUTE 68,1,1,0,
Idle Percentage,ABSOLUTE 3,1,1,-1,
{PERF_MIN_IDLE},ABSOLUTE 38,1,1,-1,
{PERF_AVG_IDLE},ABSOLUTE 53,1,1,-1,
{PERF_MAX_IDLE},ABSOLUTE 68,1,1,0,
Utilization Percentage,ABSOLUTE 3,1,1,-1,
{PERF_MIN_UTIL},ABSOLUTE 38,1,1,-1,
{PERF_AVG_UTIL},ABSOLUTE 53,1,1,-1,
{PERF_MAX_UTIL},ABSOLUTE 68,1,1,1,
Schedule Span,ABSOLUTE 3,1,1,-1,
{PERF_SCHEDULE_START} to {PERF_SCHEDULE_END},ABSOLUTE 19,1,1,-1,
Schedule Duration,ABSOLUTE 49,1,1,-1,
{PERF_SCHEDULE_SPAN},ABSOLUTE 64,1,1,1,
1.5:5.7 1:5.7 1:10.5 -1:10.5 -1:5.7 14:5.7,LINE,
1.5:5.6 0.8:5.6 0.8:10.6 -0.8:10.6 -0.8:5.6 14:5.6,LINE,
1:7.7 -1:7.7,LINE,
1:7.8 -1:7.8,LINE,
18.7:5.7 18.7:10.5,LINE,
18.9:5.7 18.9:10.5,LINE,
33.7:5.7 33.7:10.5,LINE,
48.7:5.7 48.7:10.5,LINE,
63.7:5.7 63.7:10.5,LINE,
1:9.2 -1:9.2,LINE,
1.5:11.7 1:11.7 1:20.5 -1:20.5 -1:11.7 18:11.7,LINE,
1.5:11.6 0.8:11.6 0.8:20.6 -0.8:20.6 -0.8:11.6 18:11.6,LINE,
1:13.7 -1:13.7,LINE,
1:13.8 -1:13.8,LINE,
18.7:11.7 18.7:18.5,LINE,
18.9:11.7 18.9:18.5,LINE,
33.7:11.7 33.7:20.5,LINE,
33.5:18.6 33.5:20.5,LINE,
48.7:11.7 48.7:20.5,LINE,
63.7:11.7 63.7:20.5,LINE,
1:15.2 -1:15.2,LINE,
1:16.2 -1:16.2,LINE,
1:17.2 -1:17.2,LINE,
1:18.5 -1:18.5,LINE,
1:18.6 -1:18.6,LINE,
1.5:21.7 1:21.7 1:29.5 -1:29.5 -1:21.7 14:21.7,LINE,
1.5:21.6 0.8:21.6 0.8:29.6 -0.8:29.6 -0.8:21.6 14:21.6,LINE,
1:23.7 -1:23.7,LINE,
1:23.8 -1:23.8,LINE,

```
   33.5:21.7 33.5:29.5,LINE,
   33.7:21.7 33.7:29.5,LINE,
   48.7:21.7 48.7:29.5,LINE,
   63.7:21.7 63.7:29.5,LINE,
   1:25.2 -1:25.2,LINE,
   1:26.2 -1:26.2,LINE,
   1:27.2 -1:27.2,LINE,
   1:28.2 -1:28.2,LINE:
  Number:HEADERS ONLY;
;
Or~ders,Jobs,Portrait,60,AUTO,Time:
   Form No. : Preactor {MODE}-001,Left,1,1,-1,
   {TIME},Right,1,1,0,
   Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Order List Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1;
  Belongs to Order No.,
    "ENTRY < 0":
   Order No.,
   Part No.,
   Quantity,
   Due Date;
;
; Work-to list (Sorted by resource)
;
~Work-to List,Jobs,Portrait,80,55,Field:
   Form No. : Preactor Report-002,Left,1,1,-1,
   {TIME},Right,1,1,0,
   Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Work to List,Center,2,2,1,
   For {KEY},Center,2,2,1:
  Resource:PAGE BREAK ON KEY CHANGE  | NEW LINE ON KEY CHANGE(Part No.)
      | NO SECONDARY KEY SORT,
    "({Complete} == 0)&&({Disable Op}==0)":
   Order No.,
   Part No.,
   Quantity,
   Op. No.,
   Operation Name,
   Start Time,
   End Time;
;
; Report of route cards (Sort by order number, new page for each order)
;
~Route Cards,Jobs,Portrait,60,45,Field:
   Form No. : Preactor {MODE}-003,Left,1,1,-1,
   {TIME},Right,1,1,0,
   Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Route Card for Order No. : {Order No.},Center,2,2,1,
   Product,Left,1,1,-1,
   - {Product},ABSOLUTE 20,1,1,0,
   Part Number,Left,1,1,-1,
   - {Part No.},ABSOLUTE 20,1,1,1:
  Order No.:PAGE BREAK ON KEY CHANGE,
    "({Disable Op}==0)":
   Op. No.,
   Quantity,
   Operation Name,
   Resource,
   Start Time,
   End Time;
```

```
;
;
; Report of jobs (Sort by start time, new page for each day)
;
~Job List:By ~Day,Jobs,Portrait,80,55,Time:
  Form No. : Preactor {MODE}-004,Left,1,1,-1,
  {TIME},Right,1,1,0,
  Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
  Job List Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1,
  {DATE},Center,2,2,1:
 Start Time:PAGE BREAK ON DAY CHANGE,
   "({Disable Op}==0)":
  Order No.,
  Part No.,
  Quantity,
  Op. No.,
  Operation Name,
  Resource,
  Start Time,
  End Time,
  Due Date;
;
;
; Report of jobs (Sort by start time)
;
~Job List:~All Jobs,Jobs,Portrait,80,55,Time:
  Form No. : Preactor {MODE}-005,Left,1,1,-1,
  {TIME},Right,1,1,0,
  Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
  Job List Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1;
 Start Time,
   "ALL":
  Order No.,
  Part No.,
  Quantity,
  Op. No.,
  Operation Name,
  Resource,
  Start Time,
  End Time,
  Due Date;
;
;
; Report of Late jobs (only records where due date is less than end time)
;
~Late Jobs:~All Operations,Jobs,Portrait,80,55,Field:
  Form No. : Preactor {MODE}-006,Left,1,1,-1,
  {TIME},Right,1,1,0,
  Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
  Late Operations List Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
 Number:NEW LINE ON KEY CHANGE,
   "(({Due Date}+1)<{End Time})":
  Order No.,
  Part No.,
  Quantity,
  Op. No.,
  Operation Name,
  Resource,
  Start Time,
  End Time,
```

```
  Due Date;
;
~Late Jobs:~Orders,Jobs,Portrait,80,55,Time:
  Form No. : Preactor {MODE}-007,Left,1,1,-1,
  {TIME},Right,1,1,0,
  Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
  Late Orders List Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
 Number:NEW LINE ON KEY CHANGE,
   "({Due Date}+1)<{End Time})",ALL BUT LAST {Op. No.} FOR EACH {Order No.}:
  Order No.,
  Part No.,
  Quantity,
  Op. No.,
  Operation Name,
  Resource,
  Start Time,
  End Time,
  Due Date;
;
~Shift Patterns:~Primary Resources,Jobs:Calendar,Portrait,45,55,Time:
  Form No. : Preactor {MODE}-008,Left,1,1,-1,
  {TIME},Right,1,1,0,
  Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
  Shift Pattern for {DATE} Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Start Time:PAGE BREAK ON DAY CHANGE | NEW LINE ON KEY CHANGE(Primary
Resource),
   "{Primary}==1":
  Status,
  Primary Resource,
  Efficiency %,
  Start Time,
  End Time;
;
~Shift Patterns:~Secondary Resources,Jobs:Calendar,Portrait,45,55,Time:
  Form No. : Preactor {MODE}-008,Left,1,1,-1,
  {TIME},Right,1,1,0,
  Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
  Shift Pattern for {DATE} Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Start Time:PAGE BREAK ON DAY CHANGE | NEW LINE ON KEY CHANGE(Secondary
Resource),
   "{Primary}!=1":
  Secondary Resource,
  Min.,
  Max.,
  Start Time,
  End Time;
;
;
; ---------------------------------------------------------------------------
; Products database report
;
~Basic Data,Products,Landscape,70,70,Time:
  Form No. : Preactor {MODE}-101,Left,1,1,-1,
  {TIME},Right,1,1,0,
  Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
  Product List : Basic Data,Center,2,2,1,
  Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
 Number:DRAW LINES | NEW LINE ON KEY CHANGE(Part No.)
     | NO SORT,
   "ALL":
```

```
  Part No.:PARENT ONLY,
  Operation No.,
  Operation Name,
  Process Time Type,
  Op. Time per Item: HIDE WHEN "{#Process Time Type}!=0",
  Batch Time: HIDE WHEN "{#Process Time Type}!=1",
  Quantity per Hour: HIDE WHEN "{#Process Time Type}!=-1",
  Icon Name,
  Icon Foreground,
  Icon Background,
  Pattern;
;
~Additional Data,Products,Landscape,60,70,Time:
  Form No. : Preactor {MODE}-102,Left,1,1,-1,
  {TIME},Right,1,1,0,
  Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
  Product List : Additional Data,Center,2,2,1,
  Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
 Number:DRAW LINES | NEW LINE ON KEY CHANGE(Part No.)
     | NO SORT,
   "ALL":
  Part No.:PARENT ONLY,
  Operation No.,
  Operation Name,
  Setup Time,
  Like To Like Setup Time;
;
~Resource Data,Products,Landscape,70,70,Time:
  Form No. : Preactor {MODE}-103,Left,1,1,-1,
  {TIME},Right,1,1,0,
  Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
  Product List : Resource Data,Center,2,2,1,
  Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
 Number:DRAW LINES | NEW LINE ON KEY CHANGE(Part No.)
     | NO SORT,
   "ALL":
  Part No.:PARENT ONLY,
  Operation Name,
  Resource Data,
  Allow Auto Seq.?,
  Res. Specific Op Time,
  Res. Selection Timeout,
  Set Subsequent Resource Group,
  Reset Subsequent Resource Group;
;
R~esource Specific Secondary Resource Data,Products,Landscape,60,70,Time:
  Form No. : Preactor {MODE}-104,Left,1,1,-1,
  {TIME},Right,1,1,0,
  Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
  Product List : Resource Specific Secondary Resource Data,Center,2,2,1,
  Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
 Number:DRAW LINES | NEW LINE ON KEY CHANGE(Part No.)
     | NO SORT,
   "ALL":
  Part No.:PARENT ONLY,
  Operation Name,
  Resource Data,
  Res. Specific Sec. Const.,
  Res. Specific Const. Usage,
  Res. Specific Const. Qty;
```

```
;
~Secondary Resource Data,Products,Landscape,50,70,Time:
   Form No. : Preactor {MODE}-105,Left,1,1,-1,
   {TIME},Right,1,1,0,
   Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Product List : Secondary Resource Data,Center,2,2,1,
   Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Number:DRAW LINES | NEW LINE ON KEY CHANGE(Part No.)
       | NO SORT,
    "ALL":
   Part No.:PARENT ONLY,
   Operation Name,
   Secondary Resources,
   Constraint Usage,
   Constraint Quantity;
;
; ------------------------------------------------------------------------
; Resources database report
;
~Resources,Resources,Portrait,60,55,Time:
   Form No. : Preactor {MODE}-201,Left,1,1,-1,
   {TIME},Right,1,1,0,
   PREACTOR {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Resource List,Center,2,2,1,
   Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Number,
    "ALL":
   Name;
;
; ------------------------------------------------------------------------
; Resource Groups database report
;
~Resource Groups,Resource Group,Portrait,45,45,Time:
   Form No. : Preactor {MODE}-301,Left,1,1,-1,
   {TIME},Right,1,1,0,
   PREACTOR {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Resource Group List,Center,2,2,1,
   Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Number:DRAW LINES,
    "ALL":
   Name,
   Resources;
;
; ------------------------------------------------------------------------
; Calendar States database report
;
~Calendar States,Calendar States,Portrait,60,45,Time:
   Form No. : Preactor {MODE}-401,Left,1,1,-1,
   {TIME},Right,1,1,0,
   PREACTOR {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Calendar State List,Center,2,2,1,
   Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Number,
    "ALL":
   Name,
   Efficiency,
   Color,
   Pattern;
;
;
```

```
; -----------------------------------------------------------------------
; Primary Resource  Calendar Exceptions file report
;
~Primary Resources,Calendar,Portrait,60,110,Time:
   Form No. : Preactor {MODE}-501,Left,1,1,-1,
   {TIME},Right,1,1,0,
   Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Primary Resource Calendar Exceptions List,Center,2,2,1,
   for {USER STRING 1},Center,2,2,1,
   Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Primary Resource,
    "{Primary} == 1":
   Primary Resource,
   Primary Resource Group,
   Status,
   Efficiency %,
   Start Time,
   End Time;
;
; -----------------------------------------------------------------------
; Secondary Resource Calendar Exceptions file report
;
~Secondary Resources,Calendar,Portrait,60,110,Time:
   Form No. : Preactor {MODE}-502,Left,1,1,-1,
   {TIME},Right,1,1,0,
   Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Secondary Resource Calendar Exceptions List,Center,2,2,1,
   for {USER STRING 1},Center,2,2,1,
   Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Secondary Resource,
    "{Primary} == 0":
   Secondary Resource,
   Min.,
   Max.,
   Start Time,
   End Time;
;
;
; -----------------------------------------------------------------------
; Primary Resource  Calendar file report
;
~Primary Resources,Default Calendar,Portrait,60,110,Time:
   Form No. : Preactor {MODE}-601,Left,1,1,-1,
   {TIME},Right,1,1,0,
   Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Primary Resource Calendar Exceptions List,Center,2,2,1,
   for {USER STRING 1},Center,2,2,1,
   Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Primary Resource,
    "{Primary} == 1":
   Primary Resource,
   Primary Resource Group,
   Status,
   Efficiency %,
   Start Time,
   End Time;
;
; -----------------------------------------------------------------------
; Secondary Resource Calendar Exceptions file report
;
```

```
~Secondary Resources,Default Calendar,Portrait,60,110,Time:
   Form No. : Preactor {MODE}-602,Left,1,1,-1,
   {TIME},Right,1,1,0,
   Preactor {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Secondary Resource Calendar Exceptions List,Center,2,2,1,
   for {USER STRING 1},Center,2,2,1,
   Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Secondary Resource,
    "{Primary} == 0":
   Secondary Resource,
   Min.,
   Max.,
   Start Time,
   End Time;
;
; ------------------------------------------------------------------------
; Resources database report
;
~Secondary Resources,Secondary Resources,Landscape,60,55,Time:
   Form No. : Preactor {MODE}-701,Left,1,1,-1,
   {TIME},Right,1,1,0,
   PREACTOR {MODE},Center | FONT(Times New Roman) BOLD ITALIC,3,3,1,
   Secondary Resource List,Center,2,2,1,
   Page {CURRENT_PAGE} of {TOTAL_PAGES},Center,2,2,1:
  Number,
    "ALL":
   Name,
   Plot Color,
   Plot Fill Pattern,
   Max. Value,
   Max. Value Color,
   Min. Value,
   Min. Value Color,
   Use as a Constraint,
   Calendar Effect;
;
; ------------------------------------------------------------------------
;
REPORTS_END
```

APPENDIX 6B: PREACTOR Command File

```
; Defines the message to be displayed in the main window.
;
TITLE
Standard Configuration
;
HELP FILE
..\prconfig\PRSP_{COUNTRY}.HLP
;
PROGRAMS
;
{CONDITIONAL},
  {MODE} != 400,MainMenu:
  {SYSTEM}==1:RegServer16:
  ELSE:RegServer32;
;
RegServer16 : MANIP.EXE,
  /A ..\prconfig\VBPROJ.EXE,
  Processing Data,
  Manipulate,
  Background,
  0:{NEXT}:
  1:MainMenu;
;
..\prconfig\VBPROJ.EXE,
  ,
  Register the P400 rule server,
  ,
  Detached,
  0,MainMenu:
  ALWAYS,RegError16;
;
RegServer32 : MANIP.EXE,
  /A ..\prconfig\VBPROJ.DLL,
  Processing Data,
  Manipulate,
  Background,
  0:{NEXT}:
  1:MainMenu;
;
{REGISTER SERVER},
  ..\prconfig\VBPROJ.DLL,
  Register the P400 rule server,
  ,
  Foreground,
  0,MainMenu:
  ALWAYS,RegError32;
;
RegError16 : {DIALOG},
  Error Regestering ActiveX Rule Server,
  REGSVR32 Error,
  CTEXT,The P400 Rule server, ..\prconfig\VBPROJ.EXE failed to
  CTEXT,register,  Please contact your system supplier who
  CTEXT,will help you correct this problem.
  CTEXT,--
  CTEXT,You will not be able to use the P400 rules
  CTEXT,with this configuration.
```

```
  SMALL | DEFPUSHBUTTON,OK,MainMenu;
;
RegError32 : {DIALOG},
  Error Regestering ActiveX Rule Server,
  REGSVR32 Error,
  CTEXT,The P400 Rule server, ..\prconfig\VBPROJ.DLL failed to
  CTEXT,register,  Please contact your system supplier who
  CTEXT,will help you correct this problem.
  CTEXT,--
  CTEXT,You will not be able to use the P400 rules
  CTEXT,with this configuration.
  SMALL | DEFPUSHBUTTON,OK,MainMenu;
;
MainMenu : {DIALOG},
  Select Scheduling Option from Menu,
  Main Menu:
  PUSHBUTTON | HELPPOPUPID (100),&Help,PR_Help:
  PUSHBUTTON | HELPPOPUPID (101),&View/Edit Current Orders,S_Predit:
  PUSHBUTTON | HELPPOPUPID (102),&Generate Schedule,S_SEQ:
  PUSHBUTTON | HELPPOPUPID (103),View Gantt &Chart,Gantt:
  PUSHBUTTON | HELPPOPUPID (104),View &Order Trace Chart,Trace:
  PUSHBUTTON | HELPPOPUPID (105),Maintain Shift &Patterns,Shifts:
  PUSHBUTTON | HELPPOPUPID (106),&Maintain Database,Maintain:
  DEFPUSHBUTTON | HELPPOPUPID (166),E&xit Preactor {MODE},{END};
;
;
; --------------------------------------------------------------------
; Does Specific language help exist?
; --------------------------------------------------------------------
;
PR_Help : MANIP.EXE,
  /A ..\bin\PRU8_{COUNTRY}.HLP,

  ,
  Manip,
  Foreground,
  0:Country Help:
  1:English Help;
;
; --------------------------------------------------------------------
; Use Specific language help.
; --------------------------------------------------------------------
;
Country Help : winhlp32.exe,
  ..\bin\PRU8_{COUNTRY}.hlp,
  Preactor Help,
  Help,
  Foreground,
  0:MainMenu;
;
; --------------------------------------------------------------------
; Use English Help as default.
; --------------------------------------------------------------------
;
English Help : winhlp32.exe,
  ..\bin\PRU8_ENG.hlp,
  Preactor Help,
  Help,
  Foreground,
  0:MainMenu;
;
```

```
;
; ----------------------------------------------------------------------
; Edit Production Schedule
; ----------------------------------------------------------------------
;
S_Predit : PREDIT.EXE,
  /FMT:Jobs /AS /NEQ  /PS  /FOR:SCHEDULE.SCH /NRE
  "/DueDate:{DATE+{FIND RELATED DB VALUE("Calendar Set Up" "Number" "1" "Default Due
Date Offset")}}"
  "/ES:{DATE+{FIND RELATED DB VALUE("Calendar Set Up" "Number" "1" "Default Earliest
Start Date Offset")}}"
  "/HideExp:Hide Route:1:({#Belongs to Order No.}!=-1)&&({Show}==0)"
  "/HideExp:Hide Alternate Routes:1:({Disable Op}==1)",
  Edit Schedule,
  Preactor Editor,
  Foreground,
  0:MainMenu:
  1:MainMenu:
  250:MainMenu;
;
;
; ----------------------------------------------------------------------
; Edit Production Sequence
; ----------------------------------------------------------------------
;
S_SEQ : PRS.EXE,
  /FMT:Jobs /AS SCHEDULE.DAT /GF /CFMT:Calendar /CP:CALENDAR /CXO
  /SO:{JTIME} /ST:{JTIME} /BT:{JDATE-21} /ET:{JDATE+21}
"/ActiveX400:Lowest Position Of Operation
First:VBPROJ.EntryPoints:RunP400MinimizePositionalFactor"
"/ActiveX400:Highest Position Of Operation
First:VBPROJ.EntryPoints:RunP400MaximizePositionalFactor"
"/ActiveX400:Lowest Remaining Duration Of Operation
First:VBPROJ.EntryPoints:RunP400MinimizeRemWork"
"/ActiveX400:Highest Remaining Duration Of Operation
First:VBPROJ.EntryPoints:RunP400MaximizeRemWork"
"/ActiveX400:Lowest Number of Operations First:VBPROJ.EntryPoints:RunP400MinimizeNoOfOps"
"/ActiveX400:Highest Number of Operations
First:VBPROJ.EntryPoints:RunP400MaximizeNoOfOps"
"/ActiveX400:Highest Cost Of Operation
First:VBPROJ.EntryPoints:RunP400MaximizeCostOfOperation"
"/ActiveX400:Lowest Cost Of Operation
First:VBPROJ.EntryPoints:RunP400MinimizeCostOfOperation"
"/ActiveX400:Critical Ratio:VBPROJ.EntryPoints:RunP400CriticalRatio",
  Sequence Jobs,
  Preactor Sequencer,
  Foreground,
  0:{START}:
  1:{START}:
  2:{START}:
  200:{START}:
  201:{START}:
  202:{START}:
  250:{START};
;
;
; ----------------------------------------------------------------------
; View Gantt Chart
; ----------------------------------------------------------------------
;
```

```
Gantt : GANTT.EXE,
  /FMT:Jobs /NOS /ODT /NEQ SCHEDULE.SCH "/EXC:{Start Time}<0"
  /CFMT:Calendar /CP:CALENDAR,
   View Gantt Chart,
  Preactor Gantt Chart,
  Maximize,
  0:MainMenu;
;
;
; -------------------------------------------------------------------
; View Order Trace Chart
; -------------------------------------------------------------------
;
Trace : GANTT.EXE,
  /FMT:Jobs "/VAO:Order No." /NOS /ODT /NEQ SCHEDULE.SCH
  "/BDO:Operation Name"  /NGG "/LLF:Assembly Key"
 "/EXC:{Start Time}<0",
  View Order Trace Chart,
  Order Trace Chart,
  Maximize,
  0:MainMenu;
;
; -------------------------------------------------------------------
; Maintain Shift Patterns
; -------------------------------------------------------------------
;
Shifts : {DIALOG},
  Select Day Option from Menu,
  Daily Shift Pattern Menu:
  PUSHBUTTON | HELPPOPUPID (108),View/Edit Exceptions for Specific &Day File,Day Shifts:
  PUSHBUTTON | HELPPOPUPID (109),View/Edit &Monday's Shift
Pattern,Daily_Shifts,WEEK_DAY=1:
  PUSHBUTTON | HELPPOPUPID (110),View/Edit &Tuesday's Shift
Pattern,Daily_Shifts,WEEK_DAY=2:
  PUSHBUTTON | HELPPOPUPID (111),View/Edit &Wednesday's Shift
Pattern,Daily_Shifts,WEEK_DAY=3:
  PUSHBUTTON | HELPPOPUPID (112),View/Edit T&hursday's Shift
Pattern,Daily_Shifts,WEEK_DAY=4:
  PUSHBUTTON | HELPPOPUPID (113),View/Edit &Friday's Shift
Pattern,Daily_Shifts,WEEK_DAY=5:
  PUSHBUTTON | HELPPOPUPID (114),View/Edit &Saturday's Shift
Pattern,Daily_Shifts,WEEK_DAY=6:
  PUSHBUTTON | HELPPOPUPID (115),View/Edit S&unday's Shift
Pattern,Daily_Shifts,WEEK_DAY=7:
  PUSHBUTTON | HELPPOPUPID (116),&Copy Monday's Shift Pattern to all
Days,CopyAll,WEEK_DAY=2:
  PUSHBUTTON | HELPPOPUPID (117),&Vacation/Calendar File Deletion,Holiday:
  DEFPUSHBUTTON | HELPPOPUPID (158),Return to Main Menu,MainMenu;
;
; -------------------------------------------------------------------
; Edit Default Day Shift Patterns
; -------------------------------------------------------------------
;
Daily_Shifts : PREDIT.EXE,
  "/FMT:Default Calendar" /AS /NEQ /FOR:{DOW-{NDOW}-{WEEK_DAY}}.CAL
  "/US:1:{TDOW-{NDOW}-{WEEK_DAY}}",
  Edit {TDOW-{NDOW}-{WEEK_DAY}}'s Shift Pattern,
  Preactor Editor,
  Foreground,
  0: Shifts:
```

```
  1: Shifts:
  250: Shifts;
;
; -------------------------------------------------------------------------
; Maintain Specific Day Shift Patterns
; -------------------------------------------------------------------------
;
Day Shifts : {DIALOG},
  Enter Date for the day to Edit,
  Current Date:
  TEXT | HELPPOPUPID (155),Edit Shift Pattern For :
  ENTRYFIELD | HELPPOPUPID (155),DATE,DATE_NOW,{NOW}:
  SMALL | DEFPUSHBUTTON | HELPPOPUPID (161),OK,{NEXT}:
  SMALL | PUSHBUTTON | HELPPOPUPID (162),Cancel,shifts;
;
PREDIT.EXE,
  /FMT:Calendar /AS /NEQ /FOR:CALENDAR\{DATE@{DATE_NOW}}.CAL,
  Edit Shift Exceptions,
  Preactor Editor,
  Foreground,
  0: Shifts:
  250: Shifts;
;
; -------------------------------------------------------------------------
; Copy Mondays Calendar file to all days
; -------------------------------------------------------------------------
;
CopyAll : MANIP.EXE,
  /CO {DOW-{NDOW}-1}.CAL {DOW-{NDOW}-{WEEK_DAY}}.CAL,
  Copying to {TDOW-{NDOW}-{WEEK_DAY}}'s File,
  Manipulate,
  Background,
  0:Chk_CopyAll,WEEK_DAY={WEEK_DAY}+1:
  1:Generic_Error,ERROR_NUMBER=1:
  2:Generic_Error,ERROR_NUMBER=2:
  3:Generic_Error,ERROR_NUMBER=3;
;
; Check if there are more days to copy
;
Chk_CopyAll : {CONDITIONAL},
  {WEEK_DAY} <= 7,CopyAll:
  ELSE:Shifts;
;
; -------------------------------------------------------------------------
; Vacation \ Deletion Menu
; -------------------------------------------------------------------------
;
Holiday : {DIALOG},
  Select Option from Menu,
  Vacation \ Deletion Menu:
  PUSHBUTTON | HELPPOPUPID (125),&Edit Master Vacation File,Vac_Mast:
  PUSHBUTTON | HELPPOPUPID (126),&Setup Vacation,Set_Vac,ERROR_NUMBER=201:
  PUSHBUTTON | HELPPOPUPID (127),&Delete Calendar Files,Delete,ERROR_NUMBER=301:
  DEFPUSHBUTTON | HELPPOPUPID (162),&Return to Shifts Menu,Shifts;
;
;
Vac_Mast : PREDIT.EXE,
  "/FMT:Default Calendar" /AS /NEQ /FOR:VACATION.CAL
  "/US:1:Holiday",
  Edit Vacation Shift Pattern,
```

```
  Preactor Editor,
  Foreground,
  0: Holiday:
  1: Holiday:
  250: Holiday;
;
; Prompt user for start and end of vacation. Previously entered
; dates are retained if the routine is entered again.
;
Set_Vac : {DIALOG},
  Enter Vacation,
  Vacation Dates:
  TEXT | HELPPOPUPID (151),Vacation Start:
  ENTRYFIELD | HELPPOPUPID
(151),DATE,Vac_Start,(({Vac_Start}==0)*{JDATE})+{Vac_Start}:
  TEXT | HELPPOPUPID (152),Vacation End:
  ENTRYFIELD | HELPPOPUPID (152),DATE,Vac_End,(({Vac_End}==0)*{JDATE})+{Vac_End}:
  SMALL | DEFPUSHBUTTON | HELPPOPUPID (163),OK,Chk_Order,Current_Date={Vac_Start}:
  SMALL | PUSHBUTTON | HELPPOPUPID (164),Cancel,Holiday;
;
; Test to see if the dates are in the correct order
;
Chk_Order : {CONDITIONAL},
  {Vac_Start} <= {Vac_End},Make_Vac:
  ELSE:Generic_Error;
;
; Convert the times specified in the master vacation file to dates and times
; in the specific day file.
;
Make_Vac : MANIP.EXE,
  /TTD VACATION.CAL CALENDAR\{DATE@{Current_Date}}.CAL
  {Current_Date} 11 10:11,
  Copying Vacation File for {DATE@{Current_Date}},
  Manip,
  Background,
  0:Chk_End,Current_Date={Current_Date}+1:
  1:Generic_Error,ERROR_NUMBER=202:
  2:Generic_Error,ERROR_NUMBER=203;
;
; Check if there are more days to copy
;
Chk_End : {CONDITIONAL},
  {Current_Date} <= {Vac_End},Make_Vac:
  ELSE:Holiday;
;
;-----------------------------------------------------------------------
;
; Prompt user for start and end of deletion period. Previously
; entered dates are retained if the routine is entered again.
;
Delete : {DIALOG},
  Enter Deletion Date Range,
  Deletion Dates:
  TEXT | HELPPOPUPID (153),Deletion Start:
  ENTRYFIELD | HELPPOPUPID
(153),DATE,Del_Start,(({Del_Start}==0)*{JDATE})+{Del_Start}:
  TEXT | HELPPOPUPID (154),Deletion End:
  ENTRYFIELD | HELPPOPUPID (154),DATE,Del_End,(({Del_End}==0)*{JDATE})+{Del_End}:
  SMALL | DEFPUSHBUTTON | HELPPOPUPID
(165),OK,Chk_DOrder,Current_Date={Del_Start}:
```

```
  SMALL | PUSHBUTTON | HELPPOPUPID (164),Cancel,Holiday;
;
; Test to see if the dates are in the correct order
;
Chk_DOrder : {CONDITIONAL},
  {Del_Start} <= {Del_End},Make_Del:
  ELSE:Generic_Error;
;
; Delete the current specific day file
;
Make_Del : MANIP.EXE,
  /DEL  CALENDAR\{DATE@{Current_Date}}.CAL,
  Deleting Calendar File for {DATE@{Current_Date}},
  Manip,
  Background,
  0:Chk_DEnd,Current_Date={Current_Date}+1:
  1:Chk_DEnd,Current_Date={Current_Date}+1:
  2:Generic_Error,ERROR_NUMBER=101;
;
; Check if there are more days to delete
;
Chk_DEnd : {CONDITIONAL},
  {Current_Date} <= {Del_End},Make_Del:
  ELSE:Holiday;
;
; ------------------------------------------------------------------------
; Maintain Configuration
; ------------------------------------------------------------------------
;
Maintain : {DIALOG},
  Select Maintenance Option from Menu,
  Maintenance Menu:
  PUSHBUTTON,View/Edit Live &Products,M_Products:
  PUSHBUTTON,View/Edit Resource &Groups,M_Groups:
  PUSHBUTTON,View/Edit S&etup Groups,Setup_Groups:
  PUSHBUTTON,View/Edit &Secondary Resources,Sec_Res:
  PUSHBUTTON,View/Edit &Resources,Resources:
  PUSHBUTTON | HELPPOPUPID (183),View/Edit Ro&utes,M_Routes:
  PUSHBUTTON | HELPPOPUPID (184),View/Edit &Calendar States,States:
  DEFPUSHBUTTON | HELPPOPUPID (158),Return to Main Menu,MainMenu;
;
;  PUSHBUTTON,&Make Backup,M_Backup:
;------------------------------------------------------------------------
; Make a Backup
;------------------------------------------------------------------------
;
; Try MWBACKUP.EXE, this is the Windows Backup that comes with MS DOS 6.x
;
Backup : MANIP.EXE
  /PA MWBACKUP.EXE,

  ,
  Manipulate,
  Foreground,
  0,M_Backup:
  1,No_M_Backup;
;
M_Backup :MWBACKUP.EXE,
  PREACTOR.SET,
  Make Backup,
  Backup,
```

```
  Foreground,
  0,Maintain:
  2,Maintain:
  3,Maintain:
  4,Maintain;
;
; Try WNBACKUP.EXE, this is the Windows Backup that comes with PC DOS 6.x
;
No_M_Backup : MANIP.EXE
  /PA WNBACKUP.EXE,
  ,
  Manipulate,
  Foreground,
  0,W_Backup:
  1,No_W_Backup;
;
W_Backup :WNBACKUP.EXE,
  ,
  Make Backup,
  Backup,
  Foreground,
  0,Maintain:
  2,Maintain:
  3,Maintain:
  4,Maintain;
;
; Try BACKUP.EXE, this is the DOS Backup that comes with DOS 4.x, 5.x and 6.x
;
No_W_Backup : MANIP.EXE
  /PA BACKUP.EXE,
  ,
  Manipulate,
  Foreground,
  0,E_Backup:
  1,No_E_Backup;
;
E_Backup :BACKUP.EXE,
  *.* A: /S,
  Make Backup,
  Backup,
  Foreground,
  0,Maintain:
  2,Maintain:
  3,Maintain:
  4,Maintain;
;
; Try BACKUP.COM, this is the DOS Backup that comes with DOS 3.x
;
No_E_Backup : MANIP.EXE
  /PA BACKUP.COM,
  ,
  Manipulate,
  Foreground,
  0,C_Backup:
  1: Generic_Error,ERROR_NUMBER=401;
;
C_Backup :BACKUP.COM,
  *.* A: /S,
  Make Backup,
  Backup,
```

```
  Foreground,
  0,Maintain:
  2,Maintain:
  3,Maintain:
  4,Maintain;
;
; ----------------------------------------------------------------------
; View & Edit Live Products
; ----------------------------------------------------------------------
;
L_Products : PREDIT.EXE,
  /FMT:Products,
  Edit Live Products,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; ----------------------------------------------------------------------
; View & Edit Operation Types
; ----------------------------------------------------------------------
;
Op_Types : PREDIT.EXE,
  /FMT:Operations,
  Edit Operation Types,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; ----------------------------------------------------------------------
; View & Edit Resources
; ----------------------------------------------------------------------
;
Resources : PREDIT.EXE,
  /FMT:Resources,
  Edit Resources,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; ----------------------------------------------------------------------
; View & Edit Routes
; ----------------------------------------------------------------------
;
M_Routes : PREDIT.EXE,
  "/FMT:Routes",
  Edit Routes,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; ----------------------------------------------------------------------
; View & Edit Resource Groups
; ----------------------------------------------------------------------
;
M_Groups : PREDIT.EXE,
  "/FMT:Resource Group",
```

```
  Edit Resource Groups,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
;
; ----------------------------------------------------------------------
; View & Edit Tools
; ----------------------------------------------------------------------
;
Tools : PREDIT.EXE,
  /FMT:Tools,
  Edit Tools,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; ----------------------------------------------------------------------
; View & Edit Resource Groups
; ----------------------------------------------------------------------
;
M_Groups : PREDIT.EXE,
  "/FMT:Resource Group",
  Edit Resource Groups,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
;
;
; ----------------------------------------------------------------------
; View & Edit Secondary Resource Groups
; ----------------------------------------------------------------------
;
SECRes_Groups : PREDIT.EXE,
  "/FMT:Secondary Resource Group",
  Edit Secondary Resource Groups,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; ----------------------------------------------------------------------
; View & Edit Tool Kits
; ----------------------------------------------------------------------
;
T_Groups : PREDIT.EXE,
  "/FMT:Tool Kit",
  Edit Tool Kits,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; ----------------------------------------------------------------------
; View & Edit Secondary Resources
; ----------------------------------------------------------------------
```

```
;
Sec_Res : PREDIT.EXE,
  "/FMT:Secondary Resources",
  Edit Secondary Resources,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; -----------------------------------------------------------------------
; View & Edit Products
; -----------------------------------------------------------------------
;
M_Products : PREDIT.EXE,
  "/FMT:Products",
  Edit Products,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; -----------------------------------------------------------------------
; View & Edit Product Types
; -----------------------------------------------------------------------
;
Setup_Groups : PREDIT.EXE,
  "/FMT:Setup Groups",
  Edit Setup Groups,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; -----------------------------------------------------------------------
; View & Edit Calendar States
; -----------------------------------------------------------------------
;
States : PREDIT.EXE,
  "/FMT:Calendar States",
  Edit Calendar States,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; -----------------------------------------------------------------------
; View & Edit Calendar Set Up
; -----------------------------------------------------------------------
;
Horizon : PREDIT.EXE,
  "/FMT:Calendar Set Up" /ER:0,
  Edit Calendar Set Up,
  Preactor Database Editor,
  Foreground,
  0: Maintain:
  250: Maintain;
;
; -----------------------------------------------------------------------
; Aditional Options Menu
; -----------------------------------------------------------------------
```

```
;
AddOptions : {DIALOG},
  Select Additional Option from Menu,
  Options Menu:
  PUSHBUTTON | HELPPOPUPID (123),&Training Menu,Training,INTRO_DONE=0:
  PUSHBUTTON | HELPPOPUPID (124),&Support Menu,Support:
  DEFPUSHBUTTON | HELPPOPUPID (158),&Return to Main Menu,MainMenu;
;
;
; ----------------------------------------------------------------------
; Training Menu
; ----------------------------------------------------------------------
;
Training : {DIALOG},
  Select Training Option from Menu,
  Training Menu:
  PUSHBUTTON | HELPPOPUPID (131),&Quick Tour,SC_INIT,SCM_NUMBER=0:
  PUSHBUTTON | HELPPOPUPID (132),&Menu Overview,SC_INIT,SCM_NUMBER=1:
  PUSHBUTTON | HELPPOPUPID (133),&Setting up the Database,Dbase:
  PUSHBUTTON | HELPPOPUPID (134),Entering &Orders,SC_INIT,SCM_NUMBER=4:
  PUSHBUTTON | HELPPOPUPID (135),The Preactor Se&quencer,SchedMen:
  PUSHBUTTON | HELPPOPUPID (136),&Gantt Charts and Order
Tracing,SC_INIT,SCM_NUMBER=5:
  PUSHBUTTON | HELPPOPUPID (137),Preactor &Reports,SC_INIT,SCM_NUMBER=6:
  PUSHBUTTON | HELPPOPUPID (138),C&hanging Process Routes,Routes:
  PUSHBUTTON | HELPPOPUPID (139),Dealing with &Completions,SC_INIT,SCM_NUMBER=9:
  PUSHBUTTON | HELPPOPUPID (140),&Late Operations and
Orders,SC_INIT,SCM_NUMBER=11:
  PUSHBUTTON | HELPPOPUPID (167),&Assembly,SC_INIT,SCM_NUMBER=30:
  PUSHBUTTON | HELPPOPUPID (168),&Process Batch,Process:
  PUSHBUTTON | HELPPOPUPID (169),&Preactor 400,P400:
  DEFPUSHBUTTON | HELPPOPUPID (159),Return to Previous Menu,AddOptions;
;
; ----------------------------------------------------------------------
; Database Training Menu
; ----------------------------------------------------------------------
;
Dbase : {DIALOG},
  Select Database Training Option from Menu,
  Database Training Menu:
  PUSHBUTTON | HELPPOPUPID (143),Setting up the &Calendar,SC_INIT,SCM_NUMBER=7:
  PUSHBUTTON | HELPPOPUPID (144),&Resources and Resource
Groups,SC_INIT,SCM_NUMBER=2:
  PUSHBUTTON | HELPPOPUPID (170),Setup &Matrix,SC_INIT,SCM_NUMBER=12:
  PUSHBUTTON | HELPPOPUPID (145),&Shift Patterns and
Vacations,SC_INIT,SCM_NUMBER=3:
  PUSHBUTTON | HELPPOPUPID (146),Entering &Products,SC_INIT,SCM_NUMBER=8:
  DEFPUSHBUTTON | HELPPOPUPID (160),Return to Previous Menu,Training;
;
; ----------------------------------------------------------------------
; Scheduling Training Menu
; ----------------------------------------------------------------------
;
SchedMen : {DIALOG},
  Select Scheduling Training Option from Menu,
  Sequencer Training Menu:
  PUSHBUTTON | HELPPOPUPID (147),The Electronic &Planning
Board,SC_INIT,SCM_NUMBER=20:
  PUSHBUTTON | HELPPOPUPID (148),Resource &Utilization and Status
Update,SC_INIT,SCM_NUMBER=21:
```

```
  PUSHBUTTON | HELPPOPUPID (149),&Re-scheduling and Batch
Splitting,SC_INIT,SCM_NUMBER=22:
  PUSHBUTTON | HELPPOPUPID (150),&Bi-directional Sequencing and
Priority,SC_INIT,SCM_NUMBER=23:
  DEFPUSHBUTTON | HELPPOPUPID (160),Return to &Training Menu,Training;
;
; -----------------------------------------------------------------------
; Process Routes Training Menu
; -----------------------------------------------------------------------
;
Routes : {DIALOG},
  Select Process Routes Option from Menu,
  Process Routes Menu:
  PUSHBUTTON | HELPPOPUPID (174),Over&view,SC_INIT,SCM_NUMBER=62:
  PUSHBUTTON | HELPPOPUPID (175),Additional &Operations,SC_INIT,SCM_NUMBER=10:
  PUSHBUTTON | HELPPOPUPID (176),&Alternate Operations,SC_INIT,SCM_NUMBER=60:
  PUSHBUTTON | HELPPOPUPID (177),Alternate &Routes,SC_INIT,SCM_NUMBER=61:
  DEFPUSHBUTTON | HELPPOPUPID (160),Return to Previous Menu,Training;
;
; -----------------------------------------------------------------------
; Process Batch Training Menu
; -----------------------------------------------------------------------
;
Process : {DIALOG},
  Select Process Batch Option from Menu,
  Process Batch Menu:
  PUSHBUTTON | HELPPOPUPID (171),&Example Description,SC_INIT,SCM_NUMBER=31:
  PUSHBUTTON | HELPPOPUPID (172),&Base Data,SC_INIT,SCM_NUMBER=32:
  PUSHBUTTON | HELPPOPUPID (173),Operations Database,SC_INIT,SCM_NUMBER=33:
  DEFPUSHBUTTON | HELPPOPUPID (160),Return to Previous Menu,Training;
;
; -----------------------------------------------------------------------
; Preactor 400 Training Menu
; -----------------------------------------------------------------------
;
P400 : {DIALOG},
  Select P400 Option from Menu,
  P400 Menu:
  PUSHBUTTON | HELPPOPUPID (178),Over&view,SC_INIT,SCM_NUMBER=63:
  PUSHBUTTON | HELPPOPUPID (179),Simple Example,SC_INIT,SCM_NUMBER=64:
  PUSHBUTTON | HELPPOPUPID (180),Complex Example,SC_INIT,SCM_NUMBER=65:
  DEFPUSHBUTTON | HELPPOPUPID (160),Return to Previous Menu,Training;
;
; -----------------------------------------------------------------------
; Standard ScreenCam Entry Point
; -----------------------------------------------------------------------
;
SC_INIT : {CONDITIONAL},
  {INTRO_DONE} <= 0,{NEXT}:
  ELSE:SC{SCM_NUMBER};
;
; -----------------------------------------------------------------------
; Initial ScreenCam message
; -----------------------------------------------------------------------
;
{MESSAGE},
  ..\prconfig\PREACTOR.MSG : 701,
  ,
  Welcome to the Preactor Trainer,
  Always,
```

```
  0,{NEXT},INTRO_DONE=1;
;
; ----------------------------------------------------------------------
; Initial ScreenCam splash screen, required by Lotus
; ----------------------------------------------------------------------
;
  {SPLASH},
  3000 ..\scrncam\sc.bmp,
  ,
  Screencam,
  Foreground,
  ALWAYS,SC{SCM_NUMBER};
;
; ----------------------------------------------------------------------
; ScreenCam Quick Tour
; ----------------------------------------------------------------------
;
SC0 : SCPLAYER.EXE,
  ..\scrncam\quick8.scm /SCH,
  Quick Tour,
  Screencam,
  Foreground | Minimize Shell,
  0,Training;
;
; ----------------------------------------------------------------------
; ScreenCam Menu Overview
; ----------------------------------------------------------------------
;
SC1 : SCPLAYER.EXE,
  ..\scrncam\Menu.scm /SCH,
  Menu Overview,
  Screencam,
  Foreground | Minimize Shell,
  0,Training;
;
; ----------------------------------------------------------------------
; ScreenCam Resources and Resource Groups
; ----------------------------------------------------------------------
;
SC2 : SCPLAYER.EXE,
  ..\scrncam\resource.scm /SCH,
  Resources and Resource Groups,
  Screencam,
  Foreground | Minimize Shell,
  0,Dbase;
;
; ----------------------------------------------------------------------
; ScreenCam shift Patterns and Vacations
; ----------------------------------------------------------------------
;
SC3 : SCPLAYER.EXE,
  ..\scrncam\shifts.scm /SCH,
  Shift Patterns and Vacations,
  Screencam,
  Foreground | Minimize Shell,
  0,Dbase;
;
; ----------------------------------------------------------------------
; ScreenCam Entering Orders
; ----------------------------------------------------------------------
```

```
;
SC4 : SCPLAYER.EXE,
  ..\scrncam\orders.scm /SCH,
  Entering Orders,
  Screencam,
  Foreground | Minimize Shell,
  0,Training;
;
; ----------------------------------------------------------------------
; ScreenCam Gantt Chart and Order Tracing
; ----------------------------------------------------------------------
;
SC5 : SCPLAYER.EXE,
  ..\scrncam\gantt.scm /SCH,
  Gantt Charts and Order Tracing,
  Screencam,
  Foreground | Minimize Shell,
  0,Training;
;
; ----------------------------------------------------------------------
; ScreenCam Reports
; ----------------------------------------------------------------------
;
SC6 : SCPLAYER.EXE,
  ..\scrncam\reports.scm /SCH,
  Preactor Reports,
  Screencam,
  Foreground | Minimize Shell,
  0,Training;
;
; ----------------------------------------------------------------------
; ScreenCam Setting the Calendar
; ----------------------------------------------------------------------
;
SC7 : SCPLAYER.EXE,
  ..\scrncam\cal.scm /SCH,
  Setting the Calendar,
  Screencam,
  Foreground | Minimize Shell,
  0,Dbase;
;
; ----------------------------------------------------------------------
; ScreenCam Products Database
; ----------------------------------------------------------------------
;
SC8 : SCPLAYER.EXE,
  ..\scrncam\products.scm /SCH,
  The Products Database,
  Screencam,
  Foreground | Minimize Shell,
  0,Dbase;
;
; ----------------------------------------------------------------------
; ScreenCam Completions
; ----------------------------------------------------------------------
;
SC9 : SCPLAYER.EXE,
  ..\scrncam\complete.scm /SCH,
  Dealing with Completions,
  Screencam,
```

```
  Foreground | Minimize Shell,
  0,Training;
;
; ----------------------------------------------------------------------------
; ScreenCam Adding Operations
; ----------------------------------------------------------------------------
;
SC10 : SCPLAYER.EXE,
  ..\scrncam\add.scm /SCH,
  Adding Operations,
  Screencam,
  Foreground | Minimize Shell,
  0,Routes;
;
; ----------------------------------------------------------------------------
; ScreenCam Late Orders
; ----------------------------------------------------------------------------
;
SC11 : SCPLAYER.EXE,
  ..\scrncam\late.scm /SCH,
  Late Orders,
  Screencam,
  Foreground | Minimize Shell,
  0,Training;
;
; ----------------------------------------------------------------------------
; ScreenCam sequence dependent setups
; ----------------------------------------------------------------------------
;
SC12 : SCPLAYER.EXE,
  ..\scrncam\setup18.scm /SCH,
  Sequence Dependent Setups,
  Screencam,
  Foreground | Minimize Shell,
  0,Dbase;
;
; ----------------------------------------------------------------------------
; ScreenCam Electronic planning board
; ----------------------------------------------------------------------------
;
SC20 : SCPLAYER.EXE,
  ..\scrncam\planning.scm /SCH,
  The Electronic Planning Board,
  Screencam,
  Foreground | Minimize Shell,
  0,SchedMen;
;
; ----------------------------------------------------------------------------
; ScreenCam Resource Utilization and Status
; ----------------------------------------------------------------------------
;
SC21 : SCPLAYER.EXE,
  ..\scrncam\status.scm /SCH,
  Resource Utilizations & Status,
  Screencam,
  Foreground | Minimize Shell,
  0,SchedMen;
;
; ----------------------------------------------------------------------------
; ScreenCam Re-Scheduling and Batch Splitting
```

```
; -----------------------------------------------------------------------
;
SC22 : SCPLAYER.EXE,
  ..\scrncam\resched.scm /SCH,
  Re-scheduling and Batch Splitting,
  Screencam,
  Foreground | Minimize Shell,
  0,SchedMen;
;
; -----------------------------------------------------------------------
; ScreenCam Bi-directional Sequencing and Priority
; -----------------------------------------------------------------------
;
SC23 : SCPLAYER.EXE,
  ..\scrncam\priority.scm /SCH,
  Bi-directional Sequencing and Priority,
  Screencam,
  Foreground | Minimize Shell,
  0,SchedMen;
;
; -----------------------------------------------------------------------
; ScreenCam Assembly
; -----------------------------------------------------------------------
;
SC30 : SCPLAYER.EXE,
  ..\scrncam\assy.scm /SCH,
  Assembly,
  Screencam,
  Foreground | Minimize Shell,
  0,Training;
;
; -----------------------------------------------------------------------
; ScreenCam Process Batch Description
; -----------------------------------------------------------------------
;
SC31 : SCPLAYER.EXE,
  ..\scrncam\proc_exp.scm /SCH,
  Process Batch Example Description,
  Screencam,
  Foreground | Minimize Shell,
  0,Process;
;
; -----------------------------------------------------------------------
; ScreenCam Process Batch Data
; -----------------------------------------------------------------------
;
SC32 : SCPLAYER.EXE,
  ..\scrncam\proc_dat.scm /SCH,
  Process Batch Base Data,
  Screencam,
  Foreground | Minimize Shell,
  0,Process;
;
; -----------------------------------------------------------------------
; ScreenCam Process Batch Operations
; -----------------------------------------------------------------------
;
SC33 : SCPLAYER.EXE,
  ..\scrncam\pr_ops01.scm ..\scrncam\pr_ops10.scm ..\scrncam\pr_ops31.scm /SCH,
  Process Batch Operations,
```

```
  Screencam,
  Foreground | Minimize Shell,
  0,Process;
;
; ----------------------------------------------------------------------
; ScreenCam Routing Overview
; ----------------------------------------------------------------------
;
SC62 : SCPLAYER.EXE,
  ..\scrncam\routes.scm /SCH,
  Routing Overview,
  Screencam,
  Foreground | Minimize Shell,
  0,Routes;
;
; ----------------------------------------------------------------------
; ScreenCam Alternate Operations
; ----------------------------------------------------------------------
;
SC60 : SCPLAYER.EXE,
  ..\scrncam\alt.scm /SCH,
  Alternate Operations,
  Screencam,
  Foreground | Minimize Shell,
  0,Routes;
;
; ----------------------------------------------------------------------
; ScreenCam Process Routes
; ----------------------------------------------------------------------
;
SC61 : SCPLAYER.EXE,
  ..\scrncam\RData.scm /SCH,
  Process Routes,
  Screencam,
  Foreground | Minimize Shell,
  0,Routes;
;
; ----------------------------------------------------------------------
; ScreenCam P400 Overview 1
; ----------------------------------------------------------------------
;
SC63 : SCPLAYER.EXE,
  ..\scrncam\P400-1.scm /SCH,
  P400 Overview 1,
  Screencam,
  Foreground | Minimize Shell,
  0,P400;
;
; ----------------------------------------------------------------------
; ScreenCam P400 Overview 2
; ----------------------------------------------------------------------
;
SC64 : SCPLAYER.EXE,
  ..\scrncam\P400E1.scm /SCH,
  P400 Overview 2,
  Screencam,
  Foreground | Minimize Shell,
  0,P400;
;
; ----------------------------------------------------------------------
```

```
; ScreenCam P400 Overview 3
; ----------------------------------------------------------------------
;
SC65 : SCPLAYER.EXE,
  ..\scrncam\P400E2.scm /SCH,
  P400 Overview 3,
  Screencam,
  Foreground | Minimize Shell,
  0,P400;
;
; ----------------------------------------------------------------------
; Support menu
; ----------------------------------------------------------------------
;
Support : {DIALOG},
  Select Support Option from Menu,
  Support Menu:
  PUSHBUTTON | HELPPOPUPID (142),Generate Support File,Support1:
  PUSHBUTTON | HELPPOPUPID (142),Generate Support E-Mail,Support2:
  DEFPUSHBUTTON | HELPPOPUPID (159),&Return to Previous Menu,AddOptions;
;
; ----------------------------------------------------------------------
; Create Support ZIP file
; ----------------------------------------------------------------------
;
Support1 : MANIP.EXE,
  /CZF pre_ts.zip "*.PDB *.CAL PREACTOR.* *.SCH *.CSV"
     "*.zip *.BAK" /r,
  Creating Support ZIP File,
  Mainp,
  Forground,
  0:{NEXT};
;
{MESSAGE},
  ..\prconfig\PREACTOR.MSG : 801,
  ,
  Support File Generated,
  Always,
  0,Support;
;
; ----------------------------------------------------------------------
; Create Support ZIP file and E-Mail
; ----------------------------------------------------------------------
;
Support2 : MANIP.EXE,
  /CZF pre_ts.zip "*.PDB *.CAL PREACTOR.* *.SCH *.CSV"
     "*.zip *.BAK" /r,
  Creating Support ZIP File,
  Mainp,
  Forground,
  0:{NEXT};
;
MANIP.EXE,
  /CEM support@preactor.com "Preactor Automated Technical Support" pre_ts.zip,
  Generate Support E-Mail,
  Manip,
  Foreground,
  0:Support;
;
; ----------------------------------------------------------------------
```

```
; Error Messages
; -----------------------------------------------------------------------------
;
; Generic Error will return to the correct menu as determined by the value
; of the ERROR_NUMBER variable.
;
Generic_Error : {MESSAGE},
  ..\prconfig\PREACTOR.MSG : {ERROR_NUMBER},
  ,
  Preactor Message,
  Always,
  1-ERROR_NUMBER:Shifts:
  2-ERROR_NUMBER:Shifts:
  3-ERROR_NUMBER:Shifts:
  101-ERROR_NUMBER:Shifts:
  201-ERROR_NUMBER:Set_Vac:
  202-ERROR_NUMBER:Holiday:
  203-ERROR_NUMBER:Holiday:
  301-ERROR_NUMBER:Delete:
  401-ERROR_NUMBER:Maintain:
  0:MainMenu;
;
PROGRAMS_END
```

APPENDIX 7: REVIEW PAPER BY THE AUTHOR

Toward the integration of flexible manufacturing system scheduling.

O. O. Balogun† and K. Popplewell†*.

A substantial body of research into the problems of manufacturing scheduling has been reported. Given the diversity of scheduling problems and their inherent intractability, this is not surprising. In more recent years there has been a concentration of effort on scheduling of flexible manufacturing systems (FMS) as these offer a more controlled and predictable environment, even though the complexity of the problem is not reduced. This paper reviews reported research on FMS scheduling, from which it is apparent that individual contributions concentrate on application of one or two of a range of methodologies in the solution of particular sub-problems of the general FMS scheduling problem. Research is categorised in terms both of the scheduling sub-problems considered, and of the methodologies applied. Finally it is proposed that knowledge based simulation methods may be expected to yield integrated solutions to a broader range of FMS scheduling sub-problems than has hitherto been possible.

1. Introduction

Investment in and installation of a flexible manufacturing system (FMS) is very capital intensive. It is therefore important that its potential benefits, some of which are illustrated in table 1, are fully realized to ensure that the system is economically justified. Few, if any, of these benefits can be achieved without efficient scheduling of work through the FMS, and so it is not surprising that there is a large body of reported research on FMS scheduling.

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This paper will attempt to categorize the reported research, identifying the aspects that have received attention in the past, and those yet to be investigated. Two independent taxonomies are applied. The first distinguishes the sub-problems of the general scheduling problem, whilst the second is based on the range of alternative scheduling methodologies applied.

Several of the identified methodologies have been, and still are being applied individually and in combinations, to subsets of FMS scheduling problems. However, the prospect of handling larger subsets and indeed, the global scheduling problem is challenging to FMS scheduling researchers. Fortunately, the reviews and analyses of the individual methodologies and the results of some of the combined methodologies have shown that, with the recent advances in computer technology, combined methodologies can be applied to more complex, real-time scheduling problems.

Several objectives, assumptions and resource constraints in FMS scheduling are presented in Sections 4, 5 and 6 and emphasis is laid on conflicting objectives and restrictive assumptions. Such restrictive assumptions lead to the advantages of the FMS over conventional systems being lost to FMS potential users. Making independent schedules, for example, for each of the resources does not always synchronize their availability and the associated costs are too significant to be ignored. Most works also ignore the dynamic and stochastic behavior of FMSs in their analysis but these are features that distinguish the FMS from conventional systems.

We are led to the conclusion that there is now a real opportunity to apply a combined scheduling methodology to dynamic, stochastic scheduling problems with the objective of reducing the overall manufacturing cost.

[Insert Table 1 About Here]

2. The FMS Scheduling Problem

The overall objective in FMS scheduling is to minimize its overhead and operating costs, subject to satisfying demand for the enterprise's products. However this overall objective presents a set of subsidiary objectives, as depicted in Table 2. These subsidiary objectives conflict to some extent, and it is interesting to note the contrast between researchers' concentration on utilization and the practical schedulers' interest in meeting due dates.

[Insert Table 2 About Here]

In the context of FMS scheduling, demand is manifest as *production orders* which the enterprise must deliver in the correct quantity at the correct time, and implicitly at the correct quality. We will consider that a production order is for a quantity of a specified *part*, and that it may be necessary to split each production order into *batches* for manufacture.

The FMS itself may consist of several *cells*, each containing one or more related *machines*. Each machine is capable of a range of *operations*, using *tools* from its own *tool magazine*, although tools can be transferred between machines and a tool store. Another FMS configuration, the flexible flow line, consists of serial processing stages, where each stage has parallel machines and different part types can be manufactured simultaneously in every stage. Flexible Assembly systems also exist to accommodate assembly and operation precedence constraints. The FMS will require *transport* both between cells and within cells, and whilst some researchers consider the use of cranes, monorails, conveyor networks, industrial robots or trucks (powered or pushed), more than 80% of reported research considers the use of automatic guided vehicles (AGVs). The process of FMS scheduling begins for each production order by deciding on whether it is appropriate to manufacture the order in an FMS, and leads ultimately to the determination of a manufacturing sequence for each machine and transport routings between cells and machines.

2.1 Sub-Problems Of The Scheduling Problem

Part and Machine Family Selection

When production orders are too large to be handled by the resources in a manufacturing system, they are divided into batches. This has the objective of ensuring that system utilization is maximized and that the number of trips taken by automated material handling devices is optimal. Also, having machine groups or cells ensures that the system has a transfer-line-like efficiency and a job-shop-like flexibility (Moodie et al 1994).

Objectives of part selection include those directly associated with the progress of production orders (minimization of total production time, the time between two successive batches and the time within each batch) and those associated with the cost of operating the manufacturing system (minimization of the total throughput time of parts, the minimization of the number of batches required to process all parts and the maximization of the average machine utilization over all batches (Suri and Whitney, 1984)).

Objectives of machine grouping are associated with the reduction of operating costs and include the minimization of total cell load variation among machines (Venugopal and Narendran 1992), minimization of cost or distance of intercellular moves and the minimization of cost of duplicating machines (Seiffodini 1989), maximization of the sum of machine similarities within the cells (Chen and Srivastava 1994), minimization of the amount of intercellular moves (Sofianopoulou 1997) and the maximization of the association of part operations with machines (Shanker and Agrawal 1997). As in all scheduling tasks there is a clear tension between objectives, and in particular between the two categories of objective.

Approaches such as the Production Flow Analysis (Burbridge 1975, 1989), Component Flow Analysis (EL-Essawy and Torrance 1972) and algorithms like ZODIAC (Chandrasekharan and Rajagopalan 1987) and GRAFICS (Srinivasan and Narendran 1991) have been employed. A major approach to the part and machine family selection problem is the Group Technology (GT) technique which identifies families of parts having similar processing requirements and machine families. Kusiak (1983, 1984) proposed a coding system based on the geometrical shape and the type of operations required and their sequences. Matrix formulation, mathematical programming formulation and graph formulation have been used to model the GT problem. To solve the matrix, Similarity Coefficient Methods (McAuley, 1972, Seiffodini and Wolfe, 1986), Sorting Based Algorithms (King, 1980, King and Nakornchai, 1982, Chan and Milner 1982, and Chandrasekharan and Rajagopalan, 1986), Bond Energy Algorithm (McCormick et al 1972), Cost Based Method (Askin and Subramanian 1987), and Cluster Identification Algorithm (Kusiak and Chow 1987) have been developed. Mathematical programming models developed include those by Rajagopalan and Batra (1975), Kusiak (1985), Kusiak et al (1986), Kusiak (1987), Kusiak (1987b), Gunasingh and Lashkari (1989), Bruyand et al (1989), and Shtub (1989). The weakness of these conventional approaches is their implication that a part can only belong to one part family and families are static (Chu and Hayya 1991). Artificial Intelligence tools employed include the knowledge-based approach presented by Stecke et al (1988) under constraints on due dates and tool magazine capacity and studies by Chu and Hayya (1991) that suggest that fuzzy logic approaches offer a special advantage over conventional clustering. Artificial neural networks have been employed by Moon (1990), Moon and Chi (1992) and Moon and Kao (1993). Hwang (1986) however noted that the Group Technology approach did not consider due date interactions among parts or tool magazine capacity constraints. Chakravarty and Shtub (1984), Kusiak (1985), Carrie and Perera (1986), Rajagopalan (1986), and Hwang (1986) also noted the tooling constraint. Stecke and Kim (1991) adapted an existing mathematical programming procedure to solve the part selection problem. The objective was to achieve a higher system utilization through balancing workloads among different machine types in an FMS and results indicated that the flexible approach presented led to better system utilization and makespan than batching.

More recent approaches include the works of Chen and Srivastava (1994), Chen et al (1995), Denizel and Erenguc (1997) and Sofianopoulou (1997) using mathematical programming, Akturk and Balkose (1996) using heuristics, Wang and Roze (1997) using p-median modelling, Shanker and Agrawal (1997) using graph partitioning models, Nayak and Acharya (1998) using a heuristic and mathematical programs, and Lee and Kim (1998) using iterative procedures.

Resource Allocation

The primary resources of an FMS include tooling, machines and transport, and it is the efficient allocation of these resources in meeting production orders which provides an FMS with the flexibility which allows a manufacturing system to respond quickly to dynamic changes. However Stecke and Browne (1985) and Kulatilaka (1988) observed that most

FMS scheduling researchers ignore this, most probably to ease analysis. The effective allocation of resources lowers the total cost of a project and often frees resources for projects that might not have been undertaken otherwise. Were resources unlimited, then scheduling difficulty would be trivial as all jobs can then be set to start at their earliest starting times.

Typical objectives in allocating resources include obtaining minimum total machining time, minimum total machining cost, minimum makespan and minimum disparity in utilization of different machines (Ram et al 1990).

Tool Loading

The tool loading problem involves both the ordering jobs such that total production time is minimized, and the ordering of tool changes to accommodate the job schedule and minimize tool switches. The concurrent scheduling of tools and operations minimizes the amount of unproductive time. Choosing the tool set for each tool magazine, to minimize the total number of part transfers, assigning the chosen tool sets to the machines to minimize the transportation times, and ordering the tool set in each tool magazine to minimize the time for substituting a tool on a machine (switching time) for each machine are steps recommended by Arbib et al (1989).

Approaches to tool loading problems include simulation by Stecke and Solberg (1981), Ben-Ariech (1986) and Mishra et al (1986). Bard (1988) formulated a mathematical program to minimize the makespan by minimizing the number of tool switches and by using a heuristic. Han et al (1989) analyzed the effects of tool loading methods, tool return policies, and job dispatching rules with a tool movement policy, to minimize total processing time. Rajagopalan (1986) and O'Grady and Menon (1987) considered the limitations imposed by the tool magazine capacity and Sarin and Chen (1987) considered the single-period tool allocation problem with the assumption that a tool is loaded only once.

More recent approaches include the works of Mukhopadhyay and Sahu (1996) who presented a heuristic approach using concepts of fuzzy set theory and a potency index to prioritize parts to loading a set of tools to different machining centres in variable machining time. A modified greedy procedure was presented by Rupe and Kuo (1997) where, when an initial tool set is chosen for early scheduled jobs, a heuristic was used to find the number of tool changes required to complete the jobs that potentially follow. This proposed algorithm provided a unique solution involving job splitting, providing better solutions to a generalized tool loading problem.

Machine Allocation

This involves assigning operations, and implicitly parts, to machines. A part in an FMS can have alternative machines for its operations, with different degrees of preference for different machines (Chandra and Talavage 1991). Maximization of work progress rate can be achieved by loading parts on their most preferred machines as often as possible.

Chandra and Talavage (1991) considered machine loading decisions for dynamically scheduled parts, as routing decisions were made progressively as the part completed its operations. The idea was to preserve the routing options for as long as possible in order to judiciously utilize the system's routing flexibility. They did not however assume a parts flow that met the demand requirements of downstream fabrication or assembly activities.

Stecke (1983, 1986) proposed six objectives in formulating a loading problem: balancing the assigned machine processing time, minimizing the number of movements from machine to machine, balancing the workload per machine for a system of groups of pooled machines of equal sizes, unbalancing the workload per machine for a system of groups of pooled machines of unequal sizes, filling the tool magazines as densely as possible, and maximizing the number of operation assignments. Other objectives include maximization of the utilization of resources, minimization of tooling and processing costs, and the maximization of throughput rates (Rajamani and Adil 1996). Most researchers have considered one or some of these objectives. Stecke (1983, 1986) and Shanker and Tzen (1985) used the objective of machine workload balance, Chakravarty and Shtub (1984), the objective of machine's processing time, Kusiak (1986), the objective of production costs and Ammons et al (1985) studied a work-centre loading problem in flexible assembly with the double objective of workload balance and reduction of part movements.

Approaches to solving machine loading problems have included cluster modeling using a machine-part incidence matrix (King 1980, King and Nakornchai 1982, and Chandrasekharan and Rajagopalan 1986), mathematical programming formulations (Stecke and Solberg 1981, and Stecke 1983, Berrada and Stecke 1986, Shanker and Tzen 1985 and Lashkari et al 1987, Kusiak 1987b, Srinivasan et al 1990) and graph partitioning formulations (Hadley 1996). Heuristic approaches include presentations by Denzler and Boe (1987), Stecke (1989), Shanker and Srinivasalu (1989), Mukhopadhyay and Sahu (1992) and Moreno and Ding (1993).

More recent works include those of Hertz et al (1994), Hadley (1996), Atan and Pandit (1996), Tiwari et al (1997), Beaulieu et al (1997) and Nayak and Acharya (1998).

AGV Allocation And Routing

An AGV system with limited vehicles needs to be scheduled so that idle times and collisions are minimized. Reported objectives in AGV routing include the determination of the optimal flow path and minimization of total travel of loaded and empty vehicles (Gaskins and Tanchoco 1987, Gaskins et al 1989, Kaspi and Tanchoco 1990, Kim and Tanchoco 1993, Kouvelis et al 1992, Sinriech and Tanchoco 1991), the determination of an optimal single loop guide path (Egbelu 1993, Sinriech and Tanchoco 1992, Sinriech and Tanchoco 1993, Tanchoco and Sinriech 1992), and the minimization of fixed and travel cost (Kim and Tanchoco 1993).

The AGV guide path layout problem was first studied by Gaskins and Tanchoco (1987) using a mathematical programming approach. Other mathematical heuristic-based models and optimization approaches include those by Cohen and Stein (1978), Gaskins et al (1989), Kaspi and Tanchoco (1990), Goetz and Egbelu (1990), Riopel and Langevin (1991), and Kim and Tanchoco (1993).

More recent works on AGV routing and scheduling include those using heuristics (Kim and Tanchoco 1991, Krishnamurthy et al 1993, and Akturk and Yilmaz 1996), simulation (Taghagboni - Dutta and Tanchoco 1995), knowledge based systems (Kodali et al 1997), and branch and bound algorithms (Sun and Tchernev 1996). Akturk and Yilmaz (1996) developed a new solution procedure for the AGV scheduling problem that considered the interaction of the AGV module with the rest of the decision making hierarchy, the current load of the AGVs and the criticality of the jobs simultaneously.

Sequencing

Batches can be manufactured through alternative sequences of machines and operations, especially in an FMS. Sequencing involves choosing from the options, the sequence that optimizes system's performance. Two main objectives for determining operation sequences are the minimization of transportation of parts between and within cells, and the minimization of set-up and tool changes. Other objectives include minimizing mean flow times, makespan, lateness and the number of tardy jobs (Co et al 1988).

Sequencing approaches include heuristics by Wittrock (1985), McCormick et al (1988), Miltenburg (1989), Escudero (1989), Liu and McCarthy (1991), and Kruth and Detand (1992). Wittrock (1985) studied sequencing a minimal part set (MPS) in a flexible flow system in order to maximize throughput and minimize work-in-process. And McCormick et al (1988) examined a system similar to Wittrock (1985)'s but with finite capacity buffers between machines and proposed a heuristic method based on an equivalent maximum flow problem and using critical path techniques. Silver (1990) considered a problem of sequencing a family of parts on a single machine where the production rate for each part was taken as a control variable. Potential cost savings were identified by slowing down production rate of a key part in the family. Kim et al (1995) proposed a combination of expert system and mathematical programming to produce an optimal operation sequence while minimizing the non-cutting time. Precedence, tolerance and alternatives of operations were taken as constraints. The mathematical method performed grouping of operations and sequencing simultaneously while the expert system preprocessed the procedure by eliminating infeasible solution sets and clustering the operations according to the use of similar tools.

Routing

This involves evaluating the sequence of machines to be visited by each single batch, such that workload is equally divided among the machines and the total number of transfers of parts is minimized.

Conventional approaches such as array-based clustering (King 1980, King and Nakornchai 1982), similarity coefficient-based clustering (McAuley 1972, Seifoddini and Wolfe 1986), and mathematical programming (Kusiak 1987, Gunasingh and Lashkari 1989) can assign a part to only one machine cell (Wen et al, 1996) and do not fully utilize the flexibility of an FMS. Researches on dynamic routing problems include the works of Maimon and Choong (1987), Yao (1985) and Kumar (1987). Yao and Pei (1990) attempted dynamic routing by developing an entropy type of measure incorporating all the job and machine characteristics that contribute to routing flexibility and based on these, the part selection and machine selection rule were established. Sarin and Chen (1987) developed a mathematical model to determine the routing of parts through the machines and allocate cutting tools to each machine to achieve the minimum overall machining cost. Chandra and Talavage (1991) constructed a strategy whereby a part, upon completion of an operation, is sent to a general queue. Their objective was to develop an intelligent job dispatching strategy for FMSs using an opportunistic reasoning approach to provide well-founded assurance of long-term good performance. And Wen et al (1996) developed a fuzzy logic and certainty factor approach, using part-family membership information, taking into consideration dynamic situations.

Integrated Approaches

Some or all the sub-problems of the scheduling problem are interrelated and independent solutions to each may lead to sub-optimal solutions especially where there are conflicts. Because of this, some researchers have attempted solving some of these problems simultaneously. Some of these combined sub-problems are reported as integrated approaches.

Sarin and Chen (1987), O'Grady and Menon (1987) and Chen and Chung (1991) have treated loading and routing concurrently. And Liang and Dutta (1992) considered the part selection, load sharing and machine loading problem. Co et al (1990) also tackled a similar problem. More recent works include :

- heuristics for tool and machine allocation (Kato et al 1993);
- simulation on tool and machine allocation and routing (Gupta et al 1993);
- mathematical formulation for part selection and machine loading (Liang and Dutta 1993);
- heuristics on tool loading and part selection (Sodhi et al 1994);
- heuristics on loading with a graph theoretic approach to routing (Kato 1995);
- integer programming and heuristics for loading and routing (Sawik 1996);
- heuristics for tool and machine loading and sequencing (Roh and Kim 1997).

Kato (1995)'s integrated design approach dealt with machine loading, process routing and production scheduling in FMSs. A GT-based heuristic approach was used in the loading module and a graphic theoretical approach in the routing module to determine the effective process routing that minimizes the number of transfers between machines for each part. Several heuristics were proposed in conjunction with the traditional dispatching rules. And

Sawik (1996) presented an integer programming formulation and an approximate lexicographic approach for a bi-criterion loading and routing problem in a flexible assembly system. Roh and Kim (1997) focused on the part loading, tool loading and part sequencing problem, where each part visits only one machine for its entire processing and where, if required tools were not loaded on the machine, they could be transferred from other machines or a tool crib, all with the objective of minimizing the total tardiness.

3. Modelling Methodology

Considerable research work has been done in the area of job shop scheduling including those by Blackstone et al (1982), French (1987), Foo and Takefuji (1988) and Zhou et al (1991). This is not however directly applicable to FMS scheduling because of the structural complexities of an FMS. The techniques for job shop scheduling usually result in fixed schedules that do not provide for the flexibilities of an FMS (Nauman and Gu, 1997) and the existing general job shop scheduling theory offers exact solutions for only small-sized problems. The proposed use of optimization modeling generates a large number of variables and constraints that lead to non-optimal solutions. In an FMS, the numbers of variables and constraints are even greater. For these reasons coupled with the fact that most manufacturing systems need scheduling for dynamic and unpredictable conditions, artificial intelligence and heuristic-based approaches have been considered in FMS scheduling.

There are five basic approaches to the scheduling problem namely combinatorial optimization, artificial intelligence, simulation-based scheduling with dispatching rules, heuristics-oriented and multi criteria decision making.

3.1 Combinatorial Optimization

The discipline of operational research has contributed a number of techniques to scheduling based on combinatorial optimization methods. The scheduling problem can be handled as sub-problems and each sub-problem can be optimized independently resulting in suboptimization of the global scheduling problem (Section 2.1). Alternatively, the global problem can be presented as a system of mathematical equations. Most of these formulations do not however consider the complexity and unpredictability in an FMS. Also, mathematical programming can be time consuming and very difficult to solve. Stecke (1983) observed that large problem sizes can not be feasibly handled by mathematical programming but recent theoretical advances in integer programming and advances in computer hardware have resulted in commercial software that can handle large integer programs (Jiang and Hsiao, 1994).

Mathematical programming formulations have been proposed by Hitz (1979), Finke and Kusiak (1985), Raman et al (1986), Sawik (1990) and Aanen et al (1993). To date these formulations have been used to evaluate optimal performance measures in scheduling problems, but this is limited to problems with little complications or uncertainties.

3.2 Artificial Intelligence (AI)

Until recently, methods of tackling the scheduling problem were dominated by combinatorial optimization approaches. Their limitations necessitated rapid expansion in the application of AI. AI techniques can, to some extent, handle dynamism and stochastic conditions in manufacturing systems. It is therefore unsurprising that new AI techniques are evolving and established ones are being improved. AI embraces a number of paradigms, and those applied in scheduling are discussed here.

Expert systems (ES)

Expert systems apply a knowledge based approach to schedule decision-making. The most widely reported expert system is the Intelligent Scheduling and Information System (ISIS) described by Fox et al (1982). Other expert systems include OPIS (OPportunistic Intelligent Scheduler) which employs an opportunistic approach to improve ISIS (Ow and Smith, 1988) and selects the most appropriate strategy for scheduling opportunistically. OPAL (Bensana et al 1988) was designed for job shop scheduling and uses production rules and heuristics to determine precedence relations between the operations. ISA (Intelligent Scheduling Assistant) uses approximately 300 rules to construct evolving schedules (Kanet and Adelsberger 1987). PATRIARCH (Lawrence and Morton 1986) incorporates heuristic scheduling algorithms and AI knowledge representation techniques (rule-based production systems) and provides an integrated real-time production support system to plan, schedule and dispatch work in a real-world production setting. MPECS (Multi-Pass Expert Control System), presented by Wu and Wysk (1988), uses multiple criteria coupled with a discrete event simulator to make scheduling decisions. And MADEMA (MAnufacturing DEcision MAking), an expert system described by Chryssolouris et al (1988), supports multi-criteria decision making and scheduling in a shop floor environment.

Other nameless expert systems have been presented and include a manufacturing expert system presented by Kusiak (1986b) to control process planning, programming of robots and machines and production planning. Kim et al (1988) presented an expert system which used decision tables to select alternative resources as opposed to the normal use of priority rules. A knowledge-based scheduler that adopted an hierarchical approach and utilized simulation techniques for FMSs was developed by Doulgeri et al (1993). The knowledge base scheduled the loading of parts in the system based on global knowledge and dispatched parts to workstations based on local knowledge.

Expert systems have been used to generate schedules using experience or expert knowledge. They have thus been able to handle a variety of scheduling problems, and have been especially effective in handling dynamic problems. There has however been little reported on their application to a combination of dynamic and/or stochastic environments.

Neural networks

Neural networks have also been employed in generating schedules. Gulati and Iyengar (1987) developed a neural computing algorithm for a single machine scheduling problem with hard deadlines and task priorities. Arizona et al (1992) also presented a neural network application for a single machine scheduling problem with the total flow time criterion under the JIT production environment. Vaithianathan and Ignizo (1992) developed a neural network to solve resource constrained scheduling models and Liang et al (1992) used computer simulation to collect expert decisions. The data were then optimized using a semi-Markov decision model to remove data redundancies and errors. Finally, the optimized data were used to build an artificial neural network (ANN)-based expert system. Thawonmas et al (1993) proposed a real-time scheduler using neural networks for scheduling independent and non-preemptable tasks with deadlines and resource requirements and a heuristic procedure was embedded into the proposed model to cope with deadlines. Other approaches include those of Kim and Lee (1993), Pierreval (1993), Cho and Wysk (1993), Song et al (1995), Sabuncuoglu and Gurgun (1996), Li et al (1997). Sim et al (1994) used a backpropagation network for a dynamic job-shop scheduling problem. The network was incorporated into an expert system which activated the network to recognize the individual contributions of the dispatching rules according to prevailing shop conditions. Also, Min et al (1998) generated next decision rules based on current decision rules, system status and performance measures and an FMS was simulated to prove the effectiveness of the FMS scheduler. Results showed that the scheduler could successfully satisfy multiple objectives.

Neural networks have been used to generate schedules in various manufacturing systems. They do not however guarantee optimal solutions (Sabuncuoglu 1998). Also, very little has been reported on their application to complicated (unpredictable) FMS scheduling problems.

Genetic Algorithm (GA)

GAs can be used to improve generated behavior or characteristics and have been used to generate schedules. Scheduling researchers who have considered GAs in scheduling include Whitley et al (1989) Cleveland and Smith (1989), Yagiura and Ibaraki (1996), Bolte and Thonemann (1996), Sridhar and Rajendran (1996), Chiu and Fu (1997), and Fleury and Gourgand (1998). Lee et al (1997) developed a combination that implemented the strengths of GAs and induced decision trees for a job-shop scheduling system. Results showed that the approach led to significant improvements compared to conventional approaches.

Other AI techniques

Some fuzzy logic approaches include that by Grabot and Geneste (1994) which combines a number of dispatching rules for conventional job-shop scheduling. Custodio et al (1994) developed an elaborate control and scheduling system which combines two levels of fuzzy logic control, the first level dealing with routing and dispatching decisions, and the second, fuzzy scheduling. Adamapoulos and Pappis (1996) also used a fuzzy approach to a single-machine scheduling problem where the system's variables were defined using fuzzy-linguistic terms. Criteria used were due date, total earliness and tardiness, and the controllable duration of the job's processing times. And Roy and Zhang (1996) advocated a fuzzy logic-based dynamic scheduling algorithm aimed at achieving an optimal solution and validated by simulations.

Other AI approaches include simulated annealing by Brandimarte et al (1987), Sofianopoulou (1991), Van Laarhoven et al (1992) and Aarts et al (1994) and tabu search by Widmer (1991) and Brandimarte (1993).

3.3 Simulation-Based Scheduling With Dispatching Rules

In this approach, relatively simple priority rules are used to generate schedules which are then evaluated by simulation. Such rules include those based on processing time (Shanker and Tzen 1985, Han et al 1989, Stecke and Solberg 1981), number of operations (Stecke and Solberg 1981) and set up time (Vaithianathan 1982).

Simulation studies conducted for the traditional job-shop have proposed numerous simple heuristic (priority) rules for the selection of the next part to be machined at a workstation. These rules are simple, practical and very easy to understand and implement in a large job shop. The tests by Stecke and Solberg (1981) however showed that some rules that performed well in conventional job shops performed poorly in an FMS. Similar tests were performed by Montazeri and Van Wassenhove (1990), showing that although success is very much dependent on the particular FMS, dispatching rules have a large impact on many of the system performance measures. Frese (1987) gave a heuristic-based simulation approach to scheduling an FMS in which the processing times varied as the parts were sequenced in different ways. Cho and Malstrom (1988) performed a physical simulation to test job shop scheduling rules and Park et al (1989) described a pattern-directed scheduler which learns the selection of best dispatching rules from simulation.

Other researchers that applied simulation to evaluate the performance of dispatching rules (heuristics) include Vaithianathan (1982), Kimemia and Gershwin (1983), Lin and Lu (1984), Chang and Sullivan (1984), Chang et al (1986), Chan and Pak (1986), Co et al (1988), Han et al (1989), Jones et al (1995) and Rahimifard and Newman (1997).

Simulation research has been used in conjunction with simple dispatching rules. These rules are somewhat general and were considered inappropriate for FMS scheduling problems as they do not exploit its flexibility (Askin and Subramanyam 1986). Recent research has exploited the use of more modern hardware and simulation software to combine simulation with AI and heuristic methods.

3.4 Heuristics-Oriented

Mathematical solutions are infeasible even for deterministic formulations of the FMS scheduling problem, as the computation time for deriving even a moderate-sized FMS schedule is unacceptable. This has led to the development of heuristic procedures (Tiwari 1997).

Heuristic approaches to scheduling include the presentations by Vaithianathan (1982), Kimemia and Gershwin (1983), Mukhopadhyay et al (1991), Mottete and Widmer (1991), Lee and DiCesare (1992), Lloyd et al (1995), Chen and Jeng (1995) and Xiong et al (1996).

Mukhopadhyay et al (1991) used an integrated heuristic approach to tool allocation, parts, pallets, AGV and machine scheduling. This approach was also adapted by Stecke and Solberg (1981), Shanker and Tzen (1985), and Denzler and Boe (1987). Lee and DiCesare (1992) used Petri net modeling and heuristic search for FMS scheduling, a model that could handle uncertainties and complexities such as routing flexibility, shared resources, rescheduling, and multiple performance criteria. Lloyd et al (1995) also used a similar Petri net modeling and a modified branch and bound search to obtain an optimum makespan. And Stevens and Gemmill (1997) developed heuristics to sequence a set of jobs for an automated 2-machine flowshop with the objective of minimizing maximum lateness.

Heuristics have been used to make dispatching decisions. They are excellent for dynamic problems (Basnet and Mize 1994). They do not however guarantee optimal solutions and very little has been reported on their application to combinations of stochastic and dynamic conditions.

3.5 Multi-Criterion Decision Making (MCDM)

Gupta et al (1991) noted that FMS scheduling problems are very complex and multi-criteria in nature. Multi-criteria approaches were presented by Shanker and Tzen (1985), O'Grady and Menon (1985), Ammons et al (1985) and Kim (1986). Shanker and Tzen (1985) considered a bicriterion scheduling problem in a random FMS, considering a deterministic case, with the criteria of balancing the workload among work centres and meeting due dates of jobs. The optimization models were formulated under the constraints on tool slots, unique job routing, non-splitting of jobs, machine capacity and integrality of the decision and a linearized mixed integer model was proposed. Another bi-criterion problem was handled by Ammons et al (1985) who considered a flexible assembly system with the objectives of balancing workstation utilization and minimizing the total number of workstation-to-workstation job moves, and using an integer goal programming and a heuristic algorithm. O'Grady and Menon (1985) developed a mathematical model, an integer goal programming and an optimization algorithm to select a particular group of orders which would facilitate the satisfactory fulfillment of possibly conflicting multiple performance goals. In order to generate compromise solutions, a set of operating strategies were formulated, each solved as a goal programming problem.

3.6 Hybrids

Hybrid approaches can handle more computationally complex scheduling problems. Nakamura et al (1988), for instance, used simulation and a rule-base to generate appropriate priority rules with the objective of minimizing completion time and reducing the number of setups. Other approaches have been by Kiran and Alptekin (1986), Sarin and Dar-EL (1986), Shaw (1986, 1988), Shaw and Whinston (1989), Rabelo et al (1990), Chaturvedi et al (1990), Wu (1992), Shaw et al (1992), Chaturvedi (1993), Rabelo et al (1993), Gusikhin and Kulinitch (1994), Wang et al (1995), Fujimoto et al (1995) and Jones et al (1995). Shaw (1986, 1988) and Shaw and Whinston (1989) used the combination of A* procedure and scheduling heuristics to facilitate the search for a final schedule. Rabelo et al (1990) presented a hybrid architecture that integrated neural networks (ANNs) and knowledge based (KB) expert systems to generate solutions for real-time scheduling in an FMS. And Chaturvedi et al (1990) used an integrated knowledge-based approach to FMS scheduling using machine learning and simulation. A new learning heuristic based on conceptual clustering which effectively dealt with complex dynamic situations through hierarchical structuring of objectives, was developed. Rabelo et al (1993) presented a hybrid architecture which utilized neural networks for candidate rule selection, parallel Monte Carlo simulation for transient phenomena analysis and genetic algorithm for compromise analysis and induction mechanisms for learning, for FMS schedules. Jones et al (1995) used an approach which integrates neural network, real-time simulation, genetic algorithms and a trace-driven knowledge acquisition technique for scheduling in one-machine and multi-machine scheduling problems. The single performance ANNs were used to quickly generate a small set of candidate sequencing or scheduling rules from some larger set of heuristics and a more detailed evaluation of these candidates was carried out by simulation. The genetic algorithm was applied to the remaining set of rules to generate a single 'best' schedule.

4. Constraints And Objectives In Scheduling An FMS

Fox and Smith (1984) identified scheduling constraints as comprising of physical constraints (setup times, machine capacity and processing times), causal restrictions (operation and machine alternatives, and tool and material requirements), availability constraints (machine downtime and shifts) and preference constraints (operation, machine and sequencing preferences).

We note that in discussing the FMS scheduling problem and its component sub-problems, researchers propose working towards a variety of objectives. According to Rinnooy Kan (1976), objectives can be based on completion times, utilization and inventory costs, and on due dates, whilst according to Smith et al (1986), the most important criteria are meeting due dates, maximizing system and machine utilizations, minimizing in-process inventories, maximizing production rates, minimizing setup and tool change times, minimizing mean flow times and balancing machine utilizations. Grant and Clapp (1988) observed that the main consideration was maximizing throughput while ensuring that delivery due dates are met, inventory costs are maintained at acceptable levels, equipment, personnel and other limited resources are well-utilized, workloads balanced and adaptations made quickly in the event of an unexpected event. However an attempt to achieve several objectives simultaneously would lead to conflicts and contradictions.

Both here and in the earlier discussion of the nature and sub-problems of FMS scheduling, we observe a dichotomy of scheduling objectives, as illustrated in Table 3. One class of objectives is directly related to satisfying the needs of the FMS customers, whether these are true customers of the enterprise as a whole, or downstream processes dependant on supply from the FMS. These objectives are centered around minimizing lateness, meeting due dates, minimizing order lead times and achieving a high degree of flexibility.

[Insert Table 3 About Here]

The second class of objectives are essentially aimed at the internal efficiency of the FMS. Whilst this may well lead to some improvement from the customers' perspective, it need not: for example a higher utilization and setup performance can be achieved at the cost of flexibility. These secondary objectives may be better applied to the design of an FMS, as their achievement is frequently of little real value once the FMS capacity and configuration is realized.

The authors propose that only objectives directly relevant to customers demands should be employed as the primary objectives in dynamic scheduling of an FMS, and that the objectives related to internal efficiency of the FMS can play at most a secondary role. It may perhaps be better to consider primary objectives related to satisfying customer demand to be constraints on scheduling: customer demand must be met. Secondary objectives then serve as subsidiary targets. The essential point is that FMS scheduling is a process of prioritizing and balancing conflicting objectives, and that to be successful, no single objective can be applied, and no single sub-problem can be solved in isolation from the others. All the sub-problems must be addressed simultaneously with the common objective of meeting customer demand.

5. Resource constraints

Mukhopadyay et al (1991) described the scheduling problem in FMSs as comprising tool allocation, parts scheduling, pallets scheduling, machine scheduling and material handling equipment scheduling and formulated it as a hierarchical process and solved through eigen-vector analysis of priority ordering. And unless resources are assumed to be unlimited, schedules must be generated for each. If the availability of these resources are not synchronized, financial losses can be huge. Potential costs resulting from poor tool management can be significant (Chung, 1991) and the capital outlay for tooling could approach 25% of the initial cost of an FMS (Tomek, 1986). Also, handling cost can be as high as 2/3 of the total manufacturing cost (Ramana et al, 1997) and fixtures for machining operations amount on average to 10-20% of the total production cost (Fuh et al, 1993).

Rahimifard and Newman (1997) considered the simultaneous scheduling of workpieces, fixtures and cutting tools in an FMS. Rahimifard (1996) considered the allocation of batches of a single job across different machines in the cell, multi-machine loading (MML), which supposedly results in very high tooling costs because identical sets of cutting tools are loaded on different machines simultaneously and the limited number of parts included in a batch does not effectively utilize the tool lives. He explored an alternative job allocation policy, single-machine loading (SML), where all batches of a job are allocated to a single machine. MML provided the best method of achieving the completion dates, but resulted in higher manufacturing costs and that SML reduced the costs but did not guarantee the meeting of job completion dates. A novel job allocation policy, combined-machine loading (CML), was presented that incorporated the advantages of both by minimizing tool and fixturing requirements and achieving the completion dates of jobs by pre-allocating jobs to resources using SML and re-allocating potentially-late jobs by using the MML. Agnetis et al (1996) presented an approach that concurrently assigned and synchronized tools and parts in a two-machine flexible cell and the proposed approach was shown to provide near-optimal solutions in terms of make-span and mean flow-time. Alberti et al (1991) proposed an architecture of tool database, part database and rules for tool loading. The tool database contained relevant information related to each tool required by the process plan and included tool life, and the part database, the duration of each of the fixturing and defixturing operations. The rules for loading were based on longest or shortest residual tool life. Tsukada (1998) focussed on the problem caused by unexpected tooling requirements and recognized that the tool availability problem may be less restrictive if a required tool assigned to another machine could be borrowed. Three ways of handling tool availability - reject task, request for tool rescheduling and negotiation to relax local constraints - were considered. In handling rush jobs without tool borrowing, Tsukada (1998) considered three strategies which gave a tradeoff between accepting a new job and modifying the initial schedule as little as possible.

Sabuncuoglu and Hommertzheim (1989) considered AGV and machine scheduling with finite buffer capacity. Sabuncuoglu and Hommertzheim (1992) proposed an algorithm for scheduling machines and AGVs based on the idea that a job should not be scheduled on a machine (or AGV) if it will have to wait for an AGV (or machine) in the next activity. A hierarchical approach which considered both critical jobs and the unloaded travel times simultaneously, was employed. Ulusoy and Bilge (1993) formulated the combined machine and material handling problem as a nonlinear MIP model and decomposed it into two sub-problems that were solved by an iterative heuristic procedure. The procedure was based on three components, an algorithm that generates the machine schedules, another algorithm that finds a feasible solution to the vehicle scheduling problem, and an iterative structure that links the two and facilitates the search for a good solution. In this way, the AGV schedule was an integral part of the schedule rather than a reaction to the machine schedule. And Kodali (1997) developed a KBS involving a hierarchical approach where a first level categorized system parameters as over-valued, moderately-valued and under-valued (eg. under-utilised). AGVs were thus categorized based on utilization, idleness, distance from the requested work-center, and distance of work-centers from the idle AGV. The second level identified the relative importance of meeting one of the three criteria of work-center initiated, vehicle-initiated, and vehicle and work-center-initiated. The third level identified how best to reach the decision based on the first two levels.

A general case of the flexible flowline with limited in-process buffers was considered by Wittrock (1988) with a scheduling algorithm proposed to minimize makespan and in-process inventory. Banaszak and Krogh (1990) presented a deadlock avoidance algorithm (DAA) that used the current states of the resources and the known operation sequences for the active jobs to inhibit requests for resources only when they potentially led to circular wait conditions. Resource usage was maximized and potential deadlock states avoided. Leisten (1990) evaluated the effectiveness of different heuristics for scheduling in a buffer-constrained flowshop and Wysk et al (1991) presented a solution to resolving deadlocks by using a storage buffer. Also, Sawik (1993) designed a scheduling algorithm for a general case of flexible flowline with limited intermediate buffers, and Sharadapriyadarshini and Rajendran (1997) presented a bi-criterion heuristic for scheduling in a buffer-constrained flowshop.

Sabuncuoglu and Karabuk (1998) proposed an algorithm that considered the scheduling factors of machines, material handling, finite buffer capacity, routeing and sequence flexibilities and specifically utilized system and job-related information to generate machine and AGV schedules. They used heuristics and prevention and recovery strategies to handle deadlocks.

6. Assumptions

To model and solve the scheduling problem in a mathematically feasible way, many researchers have greatly simplified the problem. It turns out that analytical solutions are infeasible for problems of much complexity. For this reason, most scheduling problems are assumed to be deterministic and static, with only small number of resources and operations considered and constraints. But the FMS scheduling problem complexity is high because of the stochastic and dynamic environment, the multi-criteria optimization objective and the presence of secondary resources and transportation devices. Some researchers consider machining and assembly systems as independent because of the uncertainties involved with assembly. Also, most reported research consider none, one or at most some of the factors of route flexibility, tool slots, part transportation, machine availability, buffer spaces and pallets (Basnet and Mize, 1994).

7. Towards Integration

In order to address fully the problems of FMS scheduling even in relatively simple industrial contexts, it is necessary to be able to consider simultaneously all of the constraints discussed in sections 4 and 5 above. At the same time we see that most FMS scheduling is directed towards the generation of schedules which must be evaluated in the light of several conflicting criteria. At best, multi-criteria decision analysis tools permit schedules to be compared in terms of an aggregate utility subjectively defined to relate and weight these criteria. Such methods may work well where extended experience of good and bad outcomes can be used to derive utility functions. However acquiring such experience is difficult, slow and potentially very expensive, and this is accentuated in the case of FMS scheduling where the very need for flexibility expands the range of experience required to make judgements. Deriving utility functions to identify good, let alone optimal, schedules is unlikely to be practical within the lifetime of an FMS. Too many different scenarios occur, each too infrequently, to provide the necessary experience base.

An alternative approach is to use simulation of the application of alternate schedules to allow managers to select a preferred alternative. Such a selection process, although subjective in nature, can be informed by the provision of measures of the relevant criteria for each alternative. This offers two main benefits. Firstly, the acquisition of experience is accelerated, since for each real scheduling decision many alternate schedules are tested, albeit in simulation, and so understanding of the inter-relationships between scheduling criteria is gained more rapidly. Secondly, human schedulers are inherently good at subjectively balancing the criteria measures offered by the alternate schedules, and if managers are offered reliable predictions of the results of schedule selection, will be satisfied with the results of their selections. Further, this provides the opportunity for discussion and analysis of the selection decisions to add to a scheduling experience knowledge base.

Such an approach may lead to a hybrid scheduling methodology in which an initial range of proposed schedules is generated based either on conventional scheduling techniques or on knowledge based methods. The operation of each of these schedules is then simulated to evaluate performance using all criteria considered relevant to the FMS. A further knowledge based (or maybe multi-criteria decision analysis) then eliminates any unacceptable candidates and presents the alternates, perhaps categorised or prioritised, for selection. Feedback in the process can be provided at two levels: analysis of the selection decisions can provide refinement to the final schedule acceptance and prioritisation process as well as adding to the knowledge base used in generating candidate schedules in the first place. It is conceivable that such an evolving knowledge based methodology could eventually learn to present only one ideal schedule, although the authors would be sceptical about both the practicality and desirability of achieving this within the lifetime of an FMS.

8. Conclusion

This paper has identified several reported methods of generating schedules ranging from conventional to artificial intelligence and heuristic-based, assumptions ranging from static, deterministic environments to more complicated, unpredictable situations, and single to multiple criteria objectives. Different factors and assumptions have been simultaneously considered with the objective of reducing non-productive times, and based on other performance measures. From tables 2 and 3, and Figure 1, we see that very few researchers have considered problems involving great complexity. Few researchers have considered simultaneous scheduling of parts and resources using combinatorial optimization and heuristics. Even fewer have considered assembly using such methods.

[Insert Figure 1 About Here]

[Insert Table 4 About Here]

From table 4, we see that combinatorial optimization and heuristics have been used extensively in generating schedules. Combinatorial optimization is, however, being rapidly replaced by methods such as heuristics and AI that are capable of handling more unpredictable situations. We see that no publications have reported the use of certain methodologies in scheduling in certain situations (Table 4). Nevertheless, it is quite plausible to assume that since simulation and expert systems have individually been used to schedule stochastic conditions, heuristics would likely do the same, considering their similar capabilities. Also, if combinatorial optimization, with its limited capabilities, can handle assembly, multi-objective problems and simultaneous scheduling of resources individually, then more flexible tools like simulation and expert systems would likely produce satisfactory results if used to schedule similar problems.

Simulation and expert systems are individually regarded as flexible tools for modeling and analysis. Combined, they could be a very powerful tool capable of handling a larger variety of problems in a modeled manufacturing system if the strengths of each can offset the limitations of the other. The outcome, knowledge based simulation, is thus a proposed methodology that could aid the generation of a scheduling algorithm capable of handling the scheduling factors in table 4 (and possibly more), while ensuring that due dates (and other performance measures) are satisfied. It is hoped that such an algorithm would ensure that the FMS is flexible to the extent of handling any type of limiting conditions while producing results that satisfy FMS customers and justify its use.

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Performance Measures Showing Improvement	Effect on Performance Measure	Proportion of Responding Companies Reporting Effect
Lead time	30 - 60% savings	42%
Throughput	60 - 70% increase	65%
Inventory	Over 70% reductions	100%
Utilization	40 - 400% improvements	39%
Setup times	50 - 90% reductions	39%
Quality	Improved	64%
Responsiveness to demand	Increased	87%

Table 1 : Some of the achieved benefits of an FMS as adapted from Rush et al, 1992.

	Objectives	Ranking
1	Meeting due dates	57 (Most important to scheduling practitioners)
2	Maximizing system/machine utilization	44 (Researchers pay most attention to 2 and 5)
3	Minimizing in-process inventory	23
4	Minimizing setup times and tool changes	13
5	Maximizing production rate	13
6	Minimizing mean flow time	8
7	Balancing machine usage	3

Table 2: The importance of the scheduling objectives as adapted from Smith et al, 1986.

Secondary Objectives	Concerned with internal efficiency of FMS, and in particular:	Other	Minimising total throughput time. Minimising number of batches. Minimising total cell load variation. Maximising machine similarity within cells. Maximising association of part operations with machines. Minimising in-process inventories.
		Capacity Utilisation	Maximising FMS utilisation. Minimising duplicate machines. Minimising makespan.
		Machining Efficiency	Maximising average machine utilisation. Minimising total machining time and cost. Minimising disparity in utilisation of machines. Minimising tool changes. Minimising unproductive time. Flexibility to meet rapidly changing resource availability.
		Transport Efficiency	Optimising material handling movements. Minimising cost or distance of inter-cellular moves. Minimising total number of part transfers. Optimising AGV flow path. Minimising empty AGV journeys.
Primary Objectives	Directly concerned with satisfying customer demand		Minimising total production time. Minimising time between production batches. Minimising lateness. Minimising number of tardy jobs. Flexibility to meet rapidly changing resource demands.

Table 3: FMS Scheduling Objectives

Primary objectives	Secondary objectives			
	Concerned with internal efficiency of FMS, and in particular			
Directly concerned with satisfying customer demand	Transport efficacy	Machining efficiency	Capacity utilization	Other
Minimizing total production time	Optimizing material handling movements	Maximizing average machine utilization	Maximizing FMS utilization	Minimizing total throughput time
Minimizing time between production batches	Minimizing cost or distance of inter-cellular moves	Minimizing total machining time and cost	Minimizing duplicate machines	Minimizing number of batches
Minimizing lateness	Minimizing total number of part transfers	Minimizing disparity in utilization of machines	Minimizing makespan	Minimizing total cell load variation
Minimizing number of tardy jobs	Optimizing AGV flow path	Minimizing tool changes		Maximizing machine similarity within cells
Flexibility to meet rapidly changing resource demands	Minimizing empty AGV journals	Minimizing unproductive time		Maximizing association of part operations with machines
		Flexibility to meet rapidly changing resource availability		Minimizing in-process inventories

Table 3. FMS scheduling objectives.

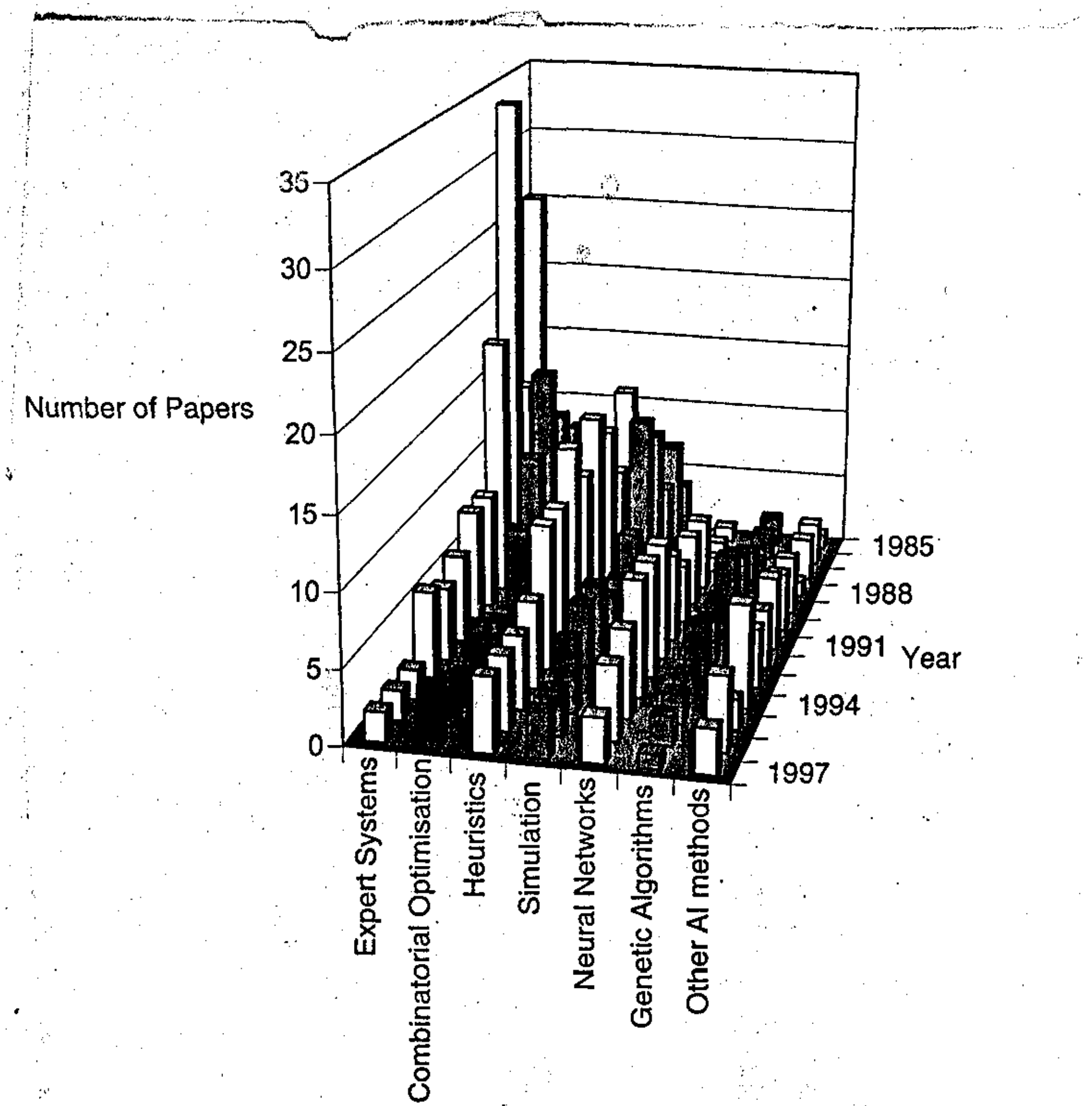

Figure 1. Trends in the application of methodologies to FMS scheduling.