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# Heuristic Scheduling Algorithms For Dedicated and Flexible Manufacturing Systems 

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## ABSTRACT

The scheduling problem of a general Flexible Manufacturing System (FMS) cannot be solved optimally due to its complicated structure, uncertainty and instabilities inherent in real life situations. Thus sub-optimal or approximate procedures are the only realistic alternative.

The objective of this thesis is to develop approximate methods which can be applied to FMS scheduling. Two heuristic algorithms are presented for solving the scheduling problem in a statically loaded FMS, the aim being to minimise the total cost resulting from the tardiness of jobs. Using the same heuristics, an iterative method of finding an optimal makespan and the average lead time is proposed. Modifications required to handle the case of a dynamically loaded FMS are then presented and a dynamic scheduling simulation package has been developed for the evaluation of performance of the heuristics. Simulation results show that the developed heuristics appear to out perform the other published techniques used in obtaining the schedules associated with minimum makespan, minimum average lead time and minimum cost of tardiness.

Finally, the simulation of the dynamic case shows that the algorithms could be implemented locally on each station for the on-line real-time scheduling calculation. The context within which these heuristic algorithms can be applied and some aspects of practical implementation are discussed.

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## CHAPTER 1: INTRODUCTION

### 1.1 Definitions

1.2 Classification
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1.4 Simulation
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1.5 Thesis Outline

## 1. INTRODUCTION

### 1.1 Definitions

'Scheduling is the allocation of resources over time to perform a collection of tasks' ( Baker, 1974 ). This is one of the many definitions available. All of them have two elements in common, though they use different words : resources and tasks. Resources (or facilities ) may be machines in a manufacturing industry, computers, doctors - nurses in a hospital, and generally processors. Tasks or more commonly jobs, require one or more operations on any combination of the facilities (Spachis, 1979 ).

Nowadays a number of problems can be formulated and solved as scheduling problems. The most common are : the control of air traffic in airports, the examination of patients by doctors in hospitals, the sequencing of programs in computers, the order of visiting cities by a salesman, preparing school timetables for lecturers and classes.

One of the more important applications of scheduling is in manufacturing planning. The scheduling is concerned with the problem of assigning specific jobs to specific work centres ( or stations ) on a weekly, daily, or hourly basis. The scheduling problem is complicated by the fact that there may be hundreds or thousands of individual jobs competing for time on the limited number of work centres. These complications are compounded by unforeseen interruptions and delays such as machine breakdowns, changes in job priority, rapidly changing market demand and worker absenteeism.

However, the real scheduling problems in the production context are not restricted to finding a schedule or sequence allowing the tasks to be performed, but also fulfilling some goals/objectives. In practice these may be :

1. Meet the required delivery dates for completion of all work on the jobs.
2. Minimise in-progress inventory. This is accomplished by minimising the aggregate manufacturing lead time.
3. Maximise utilisation of machines and manpower resources.
4. Increase production output.

Basically, scheduling can be described as consisting of the following two steps :

1. Machine loading
2. Job sequencing

To process the jobs through the factory, the jobs must be assigned to work centres. Since the total number of jobs exceeds the number of work centres, each work centre will have a queue of jobs waiting to be processed. Allocating the jobs to the work centres is referred to as machine loading, or shop loading, or operations scheduling. Ten jobs may be the loading for a particular work centre during the next week. The unanswered question is : In what sequence will the 10 jobs be processed ? Answering this question is the problem in job sequencing.

Job sequencing involves determining the order in which to process the jobs through a given work centre.

It is generally accepted that the problem of job sequencing can be solved by the establishment of priorities among the jobs in the queue. Then the jobs are processed in the order of their relative priorities. Panwalkar and Iskander (1977) have presented a paper to describe over 100 such priority dispatching rules for sequencing and scheduling. Among the priority rules that have been commonly used are the following :

1. SIP - select the job with the "shortest imminent processing time".
2. LIP - select the job with the "longest imminent processing time".
3. FOPR - fewest operations remaining.
4. MOPR - most operations remaining.
5. SRPT - shortest remaining processing time.
6. LRPT - longest remaining processing time.
7. FIFO - First-In-First-Out.
8. EDD - earliest due date.
9. SLACK - minimum slack time.

When a job is completed at one work centre, it enters the queue at the next work centre in its process routing. That is, it becomes part of the machine loading for the next work centre, and the priority rule determines its sequence of processing among those jobs. There are a variety of scheduling methods used in production ( see chapter 3 ). Different methods are appropriate, depending on the desired objective and whether the factory is engaged in flow-shop, job-shop, or flexible manufacturing operations.

### 1.2 Classification

There are several possibilities for distinguishing scheduling problems.
(i) Randomness

The problem is deterministic if all the data involved are deterministic ( processing times, sequences, technological constraints, availability of facilities ). The problem is stochastic if any of the data is stochastic.
(ii) Change of characteristics over time

The problem is static if none of the initial data changes over time, e.g. if all the jobs that are to be considered are available simultaneously at the beginning of the scheduling period. The problem is dynamic if the data is subject to change with time, e.g. when the jobs arrive intermittently during the scheduling period.

This broad classification can be represented in the following table :

|  | Deterministic | Stochastic |
| :--- | :---: | :---: |
| Static | 1 | III |
| Dynamic | II | IV |

The simplest form is the static and deterministic (I). At the other end the dynamic and stochastic (IV) ones are the most complex.

Further classification is possible based on the resources available. There may be only one unit of each resource or many in parallel (scheduling of parallel processors) and they may be in one single
stage or multi-stage ( general job-shop scheduling ).

The machining sequence ( technological and precedence constraints ) is another important feature for classification. The scheduling problems can be divided into : (a) flow-shop scheduling, (b) job-shop scheduling \& (c) Flexible Manufacturing System (FMS) scheduling.

In manufacturing industry, a job is a product or part to be completed. For that a piece of raw material is converted into a finished part through a single or multiple stages, on each of which an operation is run, such as turning, drilling, grinding, etc., on a suitable machine tool or by a skilled worker. Hence, a job is a task made up of multiple operations or work elements arranged in the technological order. Where the sequence of machines according to multiple - stage manufacturing is completely identical for all jobs to be produced, this shop is a flow-shop, and a scheduling for this is called flow-shop scheduling. This type of flow pattern is typical for mass production.

In case of variety production of most jobbing types and some batch types, the sequence of machines differs for each job, scheduling for such a job shop is called job-shop scheduling.

It has been estimated ( Cook 1975 ) that $75 \%$ of all machined parts are manufacturing in batches of less than fifty parts. Components cost is therefore 10 to 30 times greater than if mass production methods were used. Within the past ten years, a new mode of batch manufacturing has emerged in industries. Numerically controlled machines having large magazines containing cutting tools and automatic material handling devices (e.g. robots, automated guided
vehicle - A.G.V., etc., ) to become integrated systems capable of performing the operations required to produce parts with least human intervention. The system can simultaneously machine several parts of different types, and it may provide alternative routes for some operations. The movements of the workpieces between workstations, as well as the scheduling of operations at the station (i.e. job sequencing ), are controlled by one or more computers. The workstations are equipped with stored program controllers which direct local operations. Such production systems are commonly called Flexible Manufacturing System (FMS).

### 1.3 FMS

Flexible manufacturing systems are designed to fill the gap between high-production transfer lines and low production NC machines. The relative position of FMS concept is illustrated in figure1.1. Transfer lines are very efficient when producing parts in large volumes at high output rates. The limitation on this mode of production is that the parts must be identical. The highly mechanized lines are inflexible and cannot tolerate variations in part design and the rapidly changing of market demand. A changeover in part design requires the line to be shut down and retooled. If the design changes are extensive, the line may be rendered obsolete. On the other hand, stand alone NC machines are ideally suited for variations in workpart configuration. Numerically controlled machine tools are appropriate for job shop and small batch manufacturing because they can be conveniently reprogrammed to deai with product changeovers and part design changes. In terms of manufacturing efficiency and productivity, a gap exists between the high-production-rate transfer machines and the highly flexible NC machines. This gap includes parts produced in midrange volumes of 200 to 20,000 units per year (Groover, 1980 ).

The parts are of fairly complex geometry, and the production equipment should be flexible enough to handle a limited variety of part designs. Transfer lines are not suited to this application because they are inflexible. NC machines are not suited to this application because their production rates are too slow. The solution to this mid-volume production problem is the flexible manufacturing system. This new production technology is designed to attain the efficiency of well-balanced, machine-paced transfer lines, while


Figure 1.1 Application characteristics of the FMS concept.
utilisating the flexibility that job shops have to simultaneously machine multiple part types.

The following is a listing of advantages of FMS :

1. Production of families of workparts

An FMS is designed to handle a variety of workpart designs. The versatility of the FMS is not as great as for a stand-alone NC machine. It applies the group technology concept for the manufacture of several different part families on the same series of machines.
2. Random launching of workparts onto the system

Random launching means that any workpiece among the part families handled by the FMS can be introduced to the system without downtime for set up. The only limitation is that the workstations must be equipped in advance with the tooling required to process the part.
3. Reduced manufacturing lead time

Most workparts require processing in batches through several different work centres. There is set up time and waiting time at each of the work centres. With FMS, the non-operation time is drastically reduced between successive workstations on the line. Also, set up time is minimised in the FMS operation. Hence, the processing lead time will be significantly reduced.

## 4. Reduced in-progress inventory

The flow of parts of the FMS is limited. In fact, too many parts loaded on the system tends to cause congestion.
5. Increased machine utilisation

Most NC machines may operate at about $50 \%$ utilisation or less. Because of minimum set up times, efficient workpart handling, simultaneous workpart processing, and other features, the utilisation of an FMS may run as high as $80 \%$.
6. Reduced direct and indirect labour

In the typical operation of many NC machines, one machine operator is used per machine. In the operation of an FMS, the entire manning may consist of three or four direct labour personnel for 6 to 10 workstations ( one workstation is equivalent to one NC machine ). Hence, the ratio of direct labour to machine is reduced. Indirect labour is reduced compared to job shop operation through automated materials handling rather than manual parts handling between stations.

## 7. Better management control

Since lead time on the FMS is substantially reduced, parts do not have the opportunity to "get lost" in the shop. This results in better information and control of parts moving through the plant.

### 1.3.1 Classification of FMS

Recently, many new manufacturing facilities have been labelled FMS ( Dupont - Gatelmand, 1982). This has caused some confusion about what constitutes an FMS. Some systems are termed FMS just because they contain automated material handling services. Other systems use a computer to control the machines, but often require long set-ups or have no automated parts transfer. Some systems are
called flexible because they produce a variety of parts ( of very similar type, using fixed automation ). In most of these examples, the operation mode is either transfer line-like or based on producing batches of similar part types.

To help clarify the situation, eight types of flexibilities has been defined and described (Browne et al. 1984 ). They are now stated as follows :

## 1. Machine Flexibility :

The ease of making the changes required to produce a given set of part types . Measurement of these changes include, for example, the time to change tools in a tool magazine to produce a different subset of the given part type, and the time to replace worn-out or broken cutting tools.

## 2. Process Flexibility :

The ability to produce a given set of part types, each possibly using different materials, in several ways. Buzacott (1982) calls this "job flexibility", which 'relates to the mix of jobs which the system can process'. Gerwin (1982) call this 'mix flexibility'. This flexibility can be measured by the number of part types that can simultaneously be processed without using batches.

## 3. Product flexibility :

The ability to changeover to produce a new ( set of ) product (s) very economically and quickly. Mandelbaum (1978) calls this 'action flexibility, the capacity for taking new action to meet new circumstances'. Included in this concept is Gerwin's (1982) 'design -
change flexibility'. This flexibility heightens a company's potential responsiveness to competitive and / or market changes. Product flexibility can be measured by the time required to switch from one part mix to another, not necessarily of the same part types.

## 4. Routing flexibility :

The ability to handle breakdowns and to continue producing the given set of part types. This ability exists if either a part type can be processed via several routes, or, equivalently, each operation can be performed on more than one machine. Note that this flexibility can be:
(i) Potential : part routes are fixed, but parts are automatically rerouted when a breakdown occurs;
(ii) Actual : identical parts are actually processed through different routes, independent of breakdown situations.

The main, applicable circumstances occur when a system component, such as a machine tool, breaks down. This flexibility can be measured by the robustness of the FMS when breakdowns occur : the production rate does not decrease dramatically and parts continue to be processed.
5. Volume flexibility :

The ability to operate an FMS profitably at different production volumes. A higher level of automation increases this flexibility, partly as a result of both lower machine set-up costs and lower variable costs such as direct labour costs. This flexibility can be measured by how small the volumes can be for all part types with the system still being run profitably.

## 6. Expansion Flexibility :

The capability of building a system, and expanding it as needed and easily. This is not possible with most assembly and transfer lines. This flexibility can be measured according to how large the FMS can become.

## 7. Operation Flexibility :

The ability to interchange the ordering of several operations for each part type. Some process planner has usually determined a fixed ordering of all operations, each on a particular machine (type). However, keeping the routing options open and not pre-determining either the 'next' operation or the 'next' machine increases the flexibility to make these decisions in real-time. These decisions should depend on the current system state ( which machine tools are currently idle, busy, or bottleneck ). Hence, a supervisory computer with complicated control software is required to monitor the behaviour of the system.

## 8. Production Flexibility :

The universe of part types that the FMS can produce. This flexibility is measured by the level of existing technology.

An ideal FMS would possess all of the above flexibilities. However, the cost of the latest in hardware and the most sophisticated software to plan and control adequately would be quite high on some of these measures and low on others. For instance, processing a particular group of products may be made possible through the use of head indexers having multiple-spindle heads. However, they hinder both adding new part types to the mix and introducing new part
numbers, since retooling costs are high and changeover time can be a day. Also, some flexible systems ( such as the SCAMP system in Colchester, UK ) include special-purpose, non CNC machines, such as hobbing and broaching, which also require huge set-up times.

The above classification of flexibilities can help categorize different types of FMS. Browne et al. (1984) divided FMSs into four different types :

1. Type I FMS : Flexible Machining Cell

The simplest, hence most flexible type of FMS is a flexible machining cell ( FMC ). It consists of one general-purpose CNC machine tool, interfaced with automated material handling device which provides raw castings or semi-finished parts from an input buffer for machining, loads and unloads the machine tool, and transports the finished workpiece to an output buffer for eventual removal to its next destination. A robot, or pallet changer is sometimes used to load and unload. Since an FMC has all of the components of an FMS and it is actually an FMS component itself, hence it is the smallest FMS.

## 2. Type II FMS : Flexible Machining System

It can have real-time, on-line control of part production. It should allow several routes for parts, with small volume production of each, and consists of FMCs of different types of machine tools. Real-time control capabilities can automatically allow multiple routes for parts, which complicate scheduling software. The scheduling rule could be some appropriate, system-dependent, dynamic priority rule with feed back.

A Flexible Machining System is highly machine-flexible,
process-flexible, and product flexible. It is also highly routing-flexible, since it can easily and automatically cope with machine tool or other breakdowns if machines are grouped or operation assignments are duplicated.

## 3. Type III FMS : Flexible Transfer Line

For all part types, each operation is assigned to, and performed on, only one machine. This results in a fixed route for each part through the system. It is easier to manage because it operates similarly to a dedicated transfer line. The difference is that it is set up often and relatively quickly. A Flexible Transfer Line is less process-flexible and less capable of automatically handling breakdowns. However, the system can adapt by retooling and manually inputting the appropriate command to the computer, to re-route parts to the capable machine tool. This takes more time than the automatic re-routing available to a Flexible Machining System.

## 4. Type IV FMS : Flexible Transfer Multi-Line

It consists of multiple flexible transfer lines that are interconnected. This duplication does not increase process flexibility, but increase its routing flexibility in a breakdown situation.

All things being equal, a flexible machining system is operated 'flexibly', while a flexible transfer line is operated in a much more 'fixed' manner. However, all FMSs consist of similar components. The numbers and types of machine tool may differ. What really defines the flexibility of an installation is how it is run. The level of desired flexibility is an important strategic decision in the development and implementation of an FMS.

### 1.4 Simulation

Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies ( within the limits imposed by a criterion or set of criteria ) for the operation of the system. (Shannon, 1975)

A Model is a representation of an object, system, or idea in some form other than that of the entity itself.

One of the major applications of simulation is in the production industry. When newly designing an advanced manufacturing system with high investment cost such as FMS, much effort must be made not only for balancing the manufacturing activities, but also for avoiding the high investment risk of the manufacturing system to be realised. On the other hand, when operating installed manufacturing systems, some desired objectives such as shortening of production time, meet the due dates etc., must be attained under full utilisation of production facilities and resources. Therefore, in the design phase of manufacturing systems, it is necessary to select the best structure of the system, which can effectively accomplish the objectives imposed upon the system to be realised, by evaluating the long-term economy and flexibility of the system in advance of its installation. In the operation phase of the installed manufacturing system, it is required to maintain high system performance by predicting the system dynamic behaviour under any feasible production schedule and various control strategies which can meet the daily production requirements and by selecting the most effective production schedule
among the alternatives prior to its implementation. Furthermore, a suitable simulation program could be capable of having real-time, on-line control of a manufacturing system. The development of this kind of simulation package is one of the major objectives in this research work. All these necessities result in the use of the computer simulation techniques during the design and operation phases of manufacturing systems. Some other advantages of employing simulation techniques are briefly stated as follows :

1. A complete mathematical formulation of the problem does not exist or analytical methods of solving the mathematical model have not yet been developed. Many waiting line (queueing) models are in this category.
2. Analytical methods are available, but the mathematical procedures are too complex. Simulation provides a simpler method of solution.
3. Analytical solutions exist and are possible but are beyond the mathematical ability of available personnel. The cost of designing, testing, and running a simulation should then be evaluated against the cost of obtaining outside help.
4. It is desired to observe a simulated history of the process over a period of time in addition to estimating certain parameters.
5. Simulation may be the only possibility because of the difficulty in conducting experiments and observing phenomena in their actual environment - e.g., studies of space vehicles in interplanetary flight. 6. It is less likely that analytical methods could be used to predict the transient conditions, but it can be done by simulation.
6. Time compression may be required for systems or processes with long time frames. Simulation affords complete control over time, since a phenomenon may be speeded up or slowed down at will.

Analysis of urban decay problems is in this category.
8. Simulation may be used for the purpose of educational and training application. The development and use of a simulation model allows the experimenter to see and play with the system. This, in turn, should greatly assist him in understanding and gaining a feel for the problem, thus aiding the process of innovation.

### 1.4.1 Classification of simulation models

There are several ways to classify simulation models but unfortunately, none is completely satisfactory, although each serves a particular purpose. Some of these classification schemes are as follows :

1. Static vs. dynamic
2. Deterministic vs. stochastic
3. Continuous vs. discrete

Static models are those models which do not explicitly take the variable time into account, e.g. plant layout models which help us visualise space relationship. Dynamic models, on the other hand, follow the changes over time that result from the system activities, e.g. queueing, scheduling, inventory, and job shop models.

One other distinction that needs to be drawn between models depends upon the manner in which they can be described. Where neither the exogenous variables nor the endogenous variables are permitted to be random variables, and the operating characteristics are assumed to be exact relationships rather than probability density functions, the model is said to be deterministic. On the other hand, those models in
which at least one of the operating characteristics is given by a probability function are said to be stochastic models.

Many writers find it convenient to classify simulation models into two major categories : (a) continuous models or (b) discrete models. Continuous models are appropriate when the analyst considers the system he is studying as consisting of a continuous flow of information or items counted in the aggregate rather than an individual items, e.g. models of aircraft systems and chemical process. In discrete models, the analyst is interested in what happens to individual items in the system, e.g. model of a production plant.

Therefore, to assess an FMS discrete event simulation may be used with deterministic, stochastic, static and dynamic characteristics all present within the system model.

In addition, computer simulation may be broadly attempted at two distinct levels :
(1) Micro - level modelling.
(2) Macro - level modelling.

Micro - level simulation can be employed to model various resource working configurations ( e.g. operation of machines and robots ). All the movements within a cycle of operation are specified together with the governing parameters such as velocity and acceleration or tool failure and machine breakdowns. Computer graphical simulation can be employed to observe a three dimensional working picture of a resource in discrete number of positions, carrying out a required
sequence of tasks. In this manner various working conditions are investigated and an 'optimum' working routine is found.

Macro - level simulation on the other hand is concerned with the sequence of system processing activities and their interactions rather than the detailed behaviour of individual processes ( Pritsker 1982 ). It can be used both at the preliminary design stage as a tool to aid configuration sizing or in its dynamic form to provide a detailed prediction of system performance measures. In the former case simulation determines system capacity and optimum manning levels and assesses a proposed layout while in the latter case it aids production balance, inventory control, bottleneck relief and the establishment of schedules. In this thesis, only the Macro - level simulation will be considered.

### 1.4.2 Classification of time flow mechanisms

Since most simulation studies are concerned with a system's performance over a period of time, one of the most important considerations in designing the model and choosing the language in which to program it is the method used for time-keeping.

Timekeeping in a simulation has two aspects or functions: (a) advancing time or updating the time status of the system, and (b) providing synchronization of the various elements and occurrence of events. Since the actions of each element depend upon the state and actions of other elements, they must be coordinated or synchronized in time. Thus, the model must be designed to move through simulated time, causing events to occur in the proper order and with the proper
time intervals between successive events. Although components of a real system function simultaneously, components in a simulation model function sequentially, owing to the fact that a computer executes its instructions one at a time and thus can only consider the system components one at a time. Since events often occur simultaneously in different parts of the real world system, it is necessary to construct a timekeeping system that synchronizes the performance of the system components in the time domain.

Here two basic timekeeping mechanisms are considered : (a) the fixed time increment, and (b) the variable time increment methods. They are also sometimes referred to as fixed-time-step or interval-oriented and next-event-step or event-oriented, respectively. The fixed increment method updates the time in the system at predetermined, fixed-length time intervals ( the simulation walks through time with a fixed stride ). On the other hand, the next-event or variable time increment method updates at the occurrence of each significant event, independent of the time elapsing between events ( the simulation walks through time on events ). Discrete system simulation is usually carried out by using the next-event-step method, while continuous system simulation normally uses the fixed-time-step method.

It should be pointed out, however, that no firm rule can be made about the way time is represented in simulations for discrete and continuous systems. An interval-oriented program will detect discrete changes and can therefore simulate discrete systems, and an event-oriented program can be made to follow continuous changes by artificially introducing events that occur at regular time intervals.

The computations are simplified in fixed-time-step method because there is no event list nor associated processing. But there are a number of periods when no events occur, so that the time-advance computations are inefficient. In the case shown in figure 1.2, next-event-step is preferable because the added calculations for the event list do not exeed the time wasted in uneventful periods. If events occur on a fairly regular basis, the periods in the fixed-time-step method can be established in a way that minimises the chance of advancing to periods of inactivity. In this case, fixed time increment is likely to be perferred.

In "Mean Value Estimation from Digital Computer Simulation" Gafarian and Ancker (1966) have compared the relative efficiency of next-event-step simulation models and fixed-time-step models in estimating the expected ( or average ) output of the system. They examined the two time-advance methods for an equivalent simulated time ( which is not necessarily the same as equivalent computer running time ) and judged the efficiency of each in terms of the variance of its estimate of the mean effect. Gafarian and Ancker show that information about the behaviour of the system is always lost by using the fixed-time-step simulators - no matter how small the time increment. The loss of information shows up in figure 1.2 as the uncertainty about where the events occur within each unit of time. Therefore, for an equivalent simulated time, an analyst can always obtain the estimate with the smallest variance (i.e., the most reliable estimate ) by using next-event-step simulation models.

However, we cannot conclude from the Gafarian and Ancker analysis that next-event-step methods necessarily dominate fixed-time-step
change state for E2. advance lime from 55 to 56


Figure 1.2 Two different time flow mechanisms
methods because their study did not include computer running time as a factor in the evaluation.

Conway, Johnson and Maxwell (1959), and Nance (1971) have pointed out that the event-oriented method is not necessary faster than the interval-oriented method for discrete systems. As Conway et al. point out, if a system consists of $m$ components, then in a run of $T$ time units, using the fixed increment method, there will be $\mathrm{T} \cdot \mathrm{m}$ examinations of individual components to determine if updating is required. If the average length of an event is time units, there will be $\mathrm{T} \cdot \mathrm{m} / \mathrm{t}$ updating. This number of updatings is required no matter which method is used.

The next event method requires that we find the minimum of a set of $m$ values for each of the $T m / t$ updatings that would involve ( $m-1$ ) comparisons. Thus, we are comparing (Tm/t) (m-1) to Tm, and would prefer the fixed increment method if $t<(m-1)$.

Therefore we can offer no hard and fast rules as to when fixed increment vs. next event timekeeping is preferred. Under certain sets of circumstances each shows distinct strengths and advantages. The final decision depends upon the nature of the particular system being modelled. In general, we should consider a fixed time increment method when :

1. Events occur in a regular and fairly equally spaced manner.
2. A large number of events occur (i.e., m becomes larger ) during some simulated time T and the mean length of events (i.e. t gets smaller ) is short.
3. The exact nature of the significant events are not well known.

On the other hand, the next event timekeeping method :

1. Saves computer time when the system is static i.e., no significant events occur for long periods of time;
2. Requires no decision as to the size of time increment to use ( which affects both computation time and accuracy ) ;
3. Is advantageous when events occur unevenly in time and/or the mean length of events (i.e. $t$ gets larger) is long.

Some special simulation languages restrict the user to either fixed increment or next event time flow mechanisms, whereas others allow the use of either.

### 1.5 Thesis Outline

The aim of this study has been to develop a simulation package for the on-line, real-time scheduling of FMS. Heuristic algorithms have been suggested to optimise the system with various objective measures. Real-time implementation of the system has also been considered in this study.

The first chapter has been devoted to definitions, classification, different types of flexible manufacturing systems and simulation models related to scheduling.

Following this introduction, in the second chapter, the FMS development is reviewed in three different areas : FMS development in Europe, USA and Japan. The applications of FMS are also reviewed.

The third chapter deals with classification of different simulation languages, and also the suggestions for choosing a simulation language. Review on various manufacturing system simulations is presented such as flow shop, job shop and FMS simulations. The complexity of scheduling problems is investigated and the methods available for solving them are reviewed.

The need for heuristics in the scheduling of FMS is discussed in chapter four. Two heuristics ( H 1 and H 2 ) are developed to solve the static due date problem in both dedicated and flexible manufacturing environments. Evaluation of the heuristics on various manufacturing systems is also presented.

The fifth chapter is concerned with the development of approximate methods for minimising the makespan and average lead time. The developed heuristics associated with a due date assumption technique is suggested to solve these problems. An iterative procedure of due dates is described for the improvement of these objective measures. Evaluation of the heuristics on a number of FMS configurations is discussed. For the dynamic system, the heuristics have been applied to solve the dynamic FMS due date problem. Two different methods of due dates adjustment are developed to optimise the makespan and average lead time in dynamic FMS.

The development of the simulation package has been briefly discussed in the sixth chapter. Various models for FMS and control rules are presented. Results of several simulation exercises proved that system performance is greatly affected by applying different control rules. For the on-line control application, the FMS control system is outlined and followed by a discussion of the practical implementation.

The final chapter reviews the thesis, highlights the parts that are believed to be its original contribution and put further theoretical and applied research.

## CHAPTER 2: FMS DEVELOPMENT AND APPLICATIONS

### 2.1 Review On FMS Development

2.1.1 Development of FMS in Europe
2.1.2 Development of FMS in USA
2.1.3 Development of FMS in Japan
2.2 Review On FMS Applications

## 2 FMS DEVELOPMENT AND APPLICATIONS

### 2.1 Review On FMS Development

The first FMS installations began to appear in the USA in about 1967 and by 1981 approximately 25 installations were estimated to be in use in the USA. In the same year, a study sponsored by the USA National Research Council reported that Western Europe had 25 FMSs, about 25 in East Europe and about 40 in Japan. There are a few such systems in use in lesser-developed countries as well, giving a worldwide FMS population in 1981 of about 115 FMSs. In 1984, the number of FMS installations was increased to about 200, as reported in The FMS Magazine by Kochan (1984). So far, the rate of growth of the number of installed systems appears to be exponential, doubling about every three years or less. If that trend continues in the near future ( and there is no reason to expect that it will not do so , on average ), then we can anticipate that some 250 systems will be in use in world manufacturing industry by the end of 1985.

At the time of writing this thesis, a recent count of operational FMS installations had provided the information as shown in figure 2.1

From figure 2.1, Japan seems to be installing fewer FMS than Europe and about the same number as the USA. Those which are being installed in Japan are mainly in machine tool manufacturing industry where the conditions for the investment are somewhat false : the company can often use its own products in the FMS and is concerned not just with producing parts economically on a 'just-in-time' basis but also in demonstating its ability to build FMS projects to potential

FMS customers.

In Europe, the main countries now installing FMS are West Germany, Sweden, Italy and France. As a result of the UK Government's initiative in FMS, there is now a boom in the number of companies building FMS installation here. However, the Government scheme, announced in mid 1982 took a long time to get going - the first grants were not allocated until March 1983 - and since the conditions of it allow three years for installation to be completed, it will be some time before the full benefits of the scheme are evident. Systems at Beaver Machine Tools, Norwich , and Cessna Fluid Power, Glenrothes, are likely to be the first to go into full production.

There are different kind of industries which make use of FMS. Figure 2.2 shows the distribution among the different industries. The main user is the automotive industry which accounts for $38.5 \%$ of the systems under discussion.

Next comes general mechanical industry with 27.9 \% and machine tools with $18.3 \%$. Finally some $11.5 \%$ are in aerospace or defence industries. The remaining $3.8 \%$ are either in educational establishments or of unknown destination.

Among the systems operating in the automotive industries, some are producing parts for motorcycles, some for cars and trucks, and others for earthmoving equipment. The most common parts to be produced on FMS are parts for transmission system, such as gearbox housings and gears. Engine components such as housings , bearings, flywheels, crankshafts and oil sumps are also produced by FMS. In addition, in


Figure 2.1 Worldwide distribution of FMS installations


Figure 2.2 Industries using FNS

Sweden, Volvo uses FMS to machine inlet and exhaust manifolds for cars.

Most of the FMS installations in the machine tool industry are producing similar combinations of components. While the majority machine parts such as slideways, saddles, bases, columns and tables, a few are also producing gearbox parts and spindles.

In the aerospace and defence industries, FMS are responsible for a very wide range of production, from missiles to fuselage parts but no trends can yet be distinguished here.

Likewise, in the general mechanical industries, it is impossible to make any generalisations about FMS applications. Systems are being used for camera parts, high pressure turbine housings, serving machine bodies, mining equipment, pump housings, etc.

The distribution of the FMS installations in each country is shown in figure 2.3. Whereas, the automotive industry is the main user in both Europe and the USA, in Japan it is the smallest user with the machine tool industry building the largest number of systems.

In the UK it is the general mechanical industries which are accumulating the largest number of FMS installations, as shown in figure 2.4.

FMS is by no means restricted to metal cutting operations but few have so far been developed outside this area. Some assembly projects involving products such as electric motors, car headlamps,


Figure 2.3 Fris application industries- worldwide


Figure 2.4 UK application of FMS
pcb assembly, small hand tools and disc brake caliper units are thought to be either under development or already in operation, but few details are available yet. Assembly seems to be more sensitive about publicity than other areas.

### 2.1.1 Development of FMS in Europe

According to the recent publication of a report ( Frost \& Sullivan, 1984 ) on Flexible Manufacturing Technology ( FMT) markets by consultants Frost \& Sullivan, european investment in full FMS is estimated to be $\$ 60-70$ million in 1984. It predicts the investment will grow at an average rate of $40-50 \%$ per annum ( see figure 2.5 ). Until now, more than $60 \%$ of expenditure in FMS has been by large firms (more than 1000 employees) and less than $10 \%$ by small ones ( less than 500 employees ) but this pattern will have changed by 1990.

Frost \& Sullivan has analysed 120 FMS projects in its report, some of which are already running, some are in the installation and commissioning phase, and others are still orders. The geographical distribution of the 120 systems is shown in table 2.1, West Germany and the UK account for 60 \% , the others mainly being in Italy and France, with a few in Belgium, Holland and Sweden.

Frost \& Sullivan reports that nearly $75 \%$ of the FMS installed so far have included five machine tools or less, and nearly a third have comprised only two machines. Many of the installations with two or three machines have been ordered on the basis that expansion will be possible at a later date. However, the consultants forcast that small
/ medium size systems will continue to form the bulk of sales.

An analysis of the 120 FMS installations by industry sector is shown in table 2.2. The motor vehicle industry accounts for $43 \%$ of the total number but $49 \%$ of the total value, reflecting that it is the purchaser of the larger systems. The light automotive sector in particular has invested heavily.

Frost \& Sullivan reveals the identity of most of the 120 FMS installations it has found, giving the name of the user, the supplier and brief description of the type of parts produced. The list for the UK, for example, is shown in table 2.3.

In Europe, there are eight major suppliers of FMS in the EEC who between them account for just more than $50 \%$ of the total market. They are : Berardi, Comau, Mandelli and Olivetti in Italy; Burkhardt \& Weber, Scharmann and Fritz Werner in West Germany and Graffenstaden in France. It is clear that the major exporters of FMS are the Germans, mainly to the UK. Some of the FMS installations from West German suppliers are shown in table 2.4. The Italian suppliers will continue to be strong in vehicle applications, their specialisation; the list of some of the FMS installations in Italy is shown in table 2.5. The French, however, are confined at present to their own vehicle and aero industries. The companies which have installed FMS in France are Citroen, Renault, Caterpillar and Alsthom Unelec. In the UK, only KTM claims to have orders for several systems ( see table 2.3). However, many FMSs have been installed in the UK by other suppliers. This greater number of FMS installation in UK is largely due to the grants being offered by the Department of

Trade \& Industry. According to a report in The FMS Magazine (1985), which reports that most of the sales will be concentrated in the 1983 - 1987 period, and beyond that to 1990 the rate of growth will be slower. Figure 2.6 shows current and future investment in FMS in the UK.

By 1990, the automotive manufacturers and sub-contractors are expected to account for the greater proportion of total investment in FMS, followed by the general engineering sector ( $20 \%$ ), the aerospace sector, mainly Rolls - Royce, the machine tools manufacturers (13 \% ), electronic / electrical companies (10 \%) and finally the mining and construction / agricultural sectors.

In the UK, the systems are typically installed on a step by step basis by a wide size range of manufacturing operations. In overall investment terms they are smaller than those in the USA. At present, the following companies are Department of Industry approved consultancies for FMS :

1. The 600 Group,
2. KTM (Kearney and Trecker Marwin ),
3. FAST ( Factory Automation Systems Technology ), division of GEC Electrical Projects,
4. Mechtronics Partnership, TI Machine Tools and Taylor Hitec joint Company,
5. Ingersoll Engineers, and
6. Alfred Herbert.



Figure 2.6 Current and future investment in FMS in the UK

|  | No of Systems |
| :--- | :---: |
| Germany | 35 |
| France | $20-30$ |
| Italy | 25 |
| UK | 33 |
| Holland | 2 |
| Belgium | 2 |

## Table 2.1 Georraphical distribution of FMS in Europe

| Industry Sector | \% by number* of FMS | \% by value* of FMS |
| :---: | :---: | :---: |
| Ferrous metal | - | - |
| Non-ferrous metal | - | - |
| Agricultural machinery | - | - |
| Machine tools | 9 | 9 |
| Pumps/Valves/Compressors | 2 |  |
| Construction equipment | 4 | 5 |
| Mechanical handling | 2 | 1 |
| Other mechanical equipment | 8 | 8 |
| Industrial plant/Steelwork | - | - |
| Other mechanical engineering | 7 | 6 |
| Instrument engineering | - | - |
| Electrical engineering | 6 | 5 |
| Electro-domestic goods | 2 | 1 |
| Electronic products | 5 | 3 |
| Other electrical (including Switchgear) | 2 | , |
| Light automotive (cars. motor cycles) | 20 | 26 |
| Heavy automotıve (tractor, truck, bus) | 14 | 14 |
| Auto parts | 9 | 9 |
| Aerospace | 9 | 10 |

*Does not add to $100 \%$ due to rounding Vo share below $1 \%$ shown

Table 2.2 Analysis of FNS by industry sector in Europe

| Installation | Producing | Suppher |
| :---: | :---: | :---: |
| *Anderson Strathclyde | Minıng Machınery | Giddıngs Lewis-Fraser |
| *British Nuclear Fuels | Graphite Rods | KTM and Others |
| Beaver Machine Tools | Machine Tools | Beaver |
| British Aerospace | Aırframe Parts | Mitsur Seiki |
| British Leyland | Gearbox Parts |  |
| British United Shoe Machinıng | Shoe Machining | KTM |
| Caterpillar | Gearbox Parts | Scharmann |
| Caterpillar | Chassis Parts | Scharmann |
| Cessna Fluid Power | Gear Pump Bodies |  |
| +Cosworth | Cylnder Heads | Heller |
| Cummins | Valves | Cera |
| Deep Sea Seals | Propeller Seals | TI |
| Dowty | Mining Equipment |  |
| Ford | Gearbox Parts | Pittler |
| *Gardner | Diesel Crank Cases | KTM |
| $\dagger$ GEC Telecom | Cabinets | Press \& Shear |
| Imhof-Bedco | Cabinets |  |
| $\dagger$ Jaguar | Rotary Parts | TI |
| Klippon | Boxes | Various |
| +KTM | Machıne Tool Parts | KTM |
| *Lucas | Electrical Components | KTM |
| Mırrelees Blackstone |  |  |
| $\dagger$ Molins | Packing Machining | Fritz Werner |
| *Normalarr-Garrett | Ejector Release Unit | KTM, Hitachı-Serkı |
| Perkıns | Engine Parts |  |
| $\dagger$ Philips |  |  |
| Rolls-Royce | Turbine Discs |  |
| *Rolls-Royce | Blades | Elb |
| Rolls-Royce | Discs | NYK |
| *600 Group | Machine Tool Parts | 600 Group |
| * Cincinnatı | Machine Tool Parts | Cincinnatı |
| +Worthington Pumps | Pump Bodies | Fritz Werner |
| Yamasakı | Machine Tool Parts | Yamasakı |

[^0]| Supplier | Installation |
| :--- | :--- |
| Burkhardt and Weber | KHD, West Germany |
|  | Unspecified aerospace company |
| Deckel | Deckel, West Germany |
|  | Trumpf, West Germany |
| Diedesheım | Opel, West Germany |
| Pittler | Ford (2), West Germany |
| Scharmann | Caterpillar, Belgium |
|  | Brown Boven, Switzerland |
|  | Caterpillar (2), Scotland |
| Schiess | Caterpıllar, Scotland* |
| Steınel | Carl Zeıss, West Germany |
|  | Bosch, West Germany |
|  | Ford (2), France |

*Under construction or ordered

Table 2.4 FMS installations from West German suppliers

FMS Installations/Proposed Installations -Italy

| End Ciser | Product | Suppher |
| :--- | :--- | :--- |
| Iveco | Gearboxes/covers | Comau |
| Fiat Tratton | Clutch/transmıssion housings | Comau |
| Fiat Termolı | Automotıve flywheels | Comau |
| IBM |  | Mandellı |
| Rockwell-Iveco | Truck components | Mandell |
| Ferran Auto | Automotıve engine components | Mandell |
| Maseratı |  | Olivettı |
| Crema |  | Olivett1 |
| Alfa Romeo | Crankshafts, cylinder blocks, cylinder | Not yet |
|  | heads | finalised |

Table 2.5 FMS installations in Italy

### 2.1.2 Development of FMS in USA

The average cost of the FMSs currently being built in the USA is $\$ 12$ million. This figure is calculated from table 2.6 ( The FMS Magazine, 1985 ) which lists FMS projects installed or ordered during 1984/85. The list cannot hope to be comprehensive , mainly because of the extreme secrecy which most users wish to surround their installation with. Kearney \& Trecker is one supplier of FMS that has difficulty in revealing details of its customers and their installations. Having set up one of the early systems at John Deare which has been very successful, it more recently completed one at Hughes Aircraft (1983). Now, the company is believed to be in the process of installing or commissioning five new projects, the customers for which are : Union special (serving machine components ), Warner-Ishi ( turbo - charger housings ); Rigid Tool ( pipe-fitting hand tools ); Mercury Marine ( out-board motor crankcase and block ); and Onan ( generator frames ).

A relative newcomer to the list of FMS suppliers in the USA is Ingersoll Engineers. The company is now handling four FMS projects, two of which have been listed in Table 2.6. In addition, one will go to the Chrysler Corp. who will use it to produce 50 aluminium transmission cases an hour for the Dakota pick-up trucks to be built in the New Process Gear plant in Syracuse, NY. Another Ingersoll FMS has been delivered to a Pratt \& Whitney plant where it machines jet engine disks, hubs, spacers, and seals.

All the users of FMS shown in the list, apart perhaps from Onan, are either huge companies or machine tool builders with a double interest

| User | Main Contractor | Cost ( $\$$ milhons) | Date of startup | Worhpieces'l'arieti | Equipment |
| :---: | :---: | :---: | :---: | :---: | :---: |
| FMC Corporation. Aıken, S. Carolina | Cincinnatı Milacron | 8 | 1984 | 20 pants for Bradley fightung vehicle and multuple launch rocket system | 4 Milacron machine centres. DEA coordinate measuning machine (CMM) 3 Eaton-Kenuat Automated Guided Vehicles (AGVs) |
| Vought Aerospace. . <br> Dallas, Texas | Cincinnati Milacron | 10 | 1984 | 600 fuselage parts for B-1 aircraft | 8 Milacron machining centres. $2 \text { CMMs. } 4 \text { AGVs }$ |
| USArmy Watervhet Arsenal, Albany, NY | White Consolidated Industries (WCI) | 153 | $\begin{aligned} & \text { end } \\ & 1984 \end{aligned}$ | 6 steel alloy breech components | 8 White-Sundstrand machining centres 2 Bullard lathes, 2 White-Sundstrand CMMs, 2 AGV's, washing station |
| Cincinnatı Milacron, Plastics Div., Afton, Ohio | Cincinnatı Milacron | - | 1985 | 71 plastics machinery parts | 4 Cincinnatı machining centres. 3 Eaton Kenuas AGVs, DEA CMM automatic tool changing |
| Borg Warner York, Pennsylvania | Comau | 96 | 1985 | 80 parts for reciprocating compressor units | 4 Comau machining centres. vertical lathe. robot washing, conveyors, automated uarehouse |
| GM (Burck, Oldsmobile, Cadıllac), Grand Blanc, Michigan | Ingersoll Engineers | 9 | 1985 | welding jigs and fixtures | 7 Ingersoll/Bohle machining centres with robotic tool-changing AGVs |
| Onan Corporation, Minneapolis | Trumpf | 2.5 | 1985 | 1,000 sheet metal parts for generators, engines and electrical switchgear | Trumatic Laserpress with Fanuc tool-changing robot, automated warehouse |
| Boeing Commercial Aırplane, Auburn, Washington | Shin Nippon Kokı | - | 1985 | arrcraft structure parts fitting within 760 mm cube (150) | 5 SNK machining centres. SNK CMM, 2 AGVs, automated warehouse |
| Sundstrand Corporation, Ames, Iowa | Bendix Automation/ Kearney \& Trecker | 8-10 | 1985 | hydrostatic transmission components (100+) | 6 Toyoda machining centres, 2 Diedesheim turning centres, Bendix CMM, 3 Conco-Tellus AGVs. automated warehouse |
| Vickers, Omaha | LaSalle Machine Tool Div of ACME Cleveland Corp | 18 | 1985 | hydraulic piston pump cylinder blocks(27) | 5 LaSalle machining centres, 1 vertical broach, 3 Olofsson turming machines. 2 bonng machines, ASEA loading robots. inspection and washing stations bush assembly and heat treatment stations. and conveyors |
| Lucas Machine Div., <br> Litton Inds, Cleveland. Ohıo | Self | 6 | - | machune tool parts | 2 Lucas machining centres, Mauser CMM, 2 AGVs, automated tool changing |
| Sundstrand Aviation, Rockford, Illinois | Toyoda | - | - | - | 2 Toyoda machining centres. LK Tool CMM. deburning and washing stations. AGVs, automated tool change |
| Ingersoll Enguneers. Rockford, Illinous | Self | 20 | 1986 | machine tool parts | 9 Ingersoll/Bohle machining centres. 5 AGVs (two fitted with a tool-change robot), 3 CMMs, automated warehouse |
| GM, Detroit Diesel | Lamb Technicon | - | 1986 | parts for four-cycle Senes 60 engines |  |
| General Dynamics. Fort Worth, Texas | Westınghouse Industry Electromics | - | 1987 | 80-100 aluminium components of F-16 alrcraft | 6 De Vhieg machining centres fitted with Fanuc tool-change robots. 2 LK Tool CMMs, 2 Jervis Webb AGVs |
| McDonnell Douglas, St Charles, Missoun | Giddings \& Lewis (G\&L) | 18 | 1987 | missile bodies (72) | 2 G\&L turning centres. 5 G\&L boring mills. DEA CMM, 4 Conco-Tellus AGVs, 3 ASEA deburnng robots, automated warehouse |
| Westinghouse ElectroMechanical Div., Cheswick, Pennsylvana | WCl | - | 1987 | nuclear reactor coolant pump seals and beanngs (63) | 2 Bullard lathes. 1 White-Sundstrand machining centre, WCI CMM, GCA gantry robot. 2 automated warehouses |
| White-Sundstrand, Belvidere, Illinors | Self | 20 | 1988 | machine tool parts | 11 machining centres, 2 lathes, 2 AGVs, washing and inspection equipment |

in using FMS. It believes that the larger machine tool companies will become more system-orientated, either through self-development of software capabilities or through the acquisition of specialist software houses. The other elements, such as AGVs, robots and materials handling systems will be largely bought-in through sub-contractors. However, there are undoubtedly many smaller general engineering companies in the USA treading carefully on the FMS paths, taking on the challenge with step-by-step approach in order to spread the investment and technology leap over a period of time. Figure 2.7 shows a graph of forecast investment ( The FMS Magazine, 1985) in FMS in the USA. In the latter half of the decade, demand by the aerospace industry will have peaked but major investment in FMS will be required by the agricultural and construction equipment manufacturers and by the automotive industry. The machine tool sector will also automate considerably in this period due to the need to install state-of-the-art technology. The general engineering and electrical sectors will provide the greatest markets for manufacturing cell technology.

### 2.1.3 Development of FMS in Japan

In Japan, the factory automation has been actively pursued with the various concepts and approaches. Especially in a low volume production with high variety environment, many attempts have been made in the course of continuing the effort to realise the flexible and effective production. The implication in Group Technology, the active introduction of NC machine tools with intensive utilisation of them and the earlier challenge to the computer integration of machine shops by applying the DNC system are some examples of these efforts


Figure 2.7 Forecast investment in FMS in the USA
in parts manufacturing.

The development of the FMS is, in a sense, one of the solutions derived from these experiences. Up to date, a wide variety of the FMSs has been developed in this context. Therefore, it is not surprising that the FMS is considerably diversified with the various concepts and also with the different levels in automation. In May 1982 a party of 28 engineers, managers, researchers and academics from seven European nations set out for a study tour of FMS in Japan (Knight, 1982 ). The objective was to enable assessment of Japanese FMS. Brief descriptions and other details of the nine FMS installations visited are given below :

1. Toshiba Tangaloy :

Product: carbide cutting tools and associated cutting bodies
FMS: a DNC system comprising N.C. lathe, 4 machinery centres,
N.C. composite grinding machine

Work types : 3600
Comments : No inter-machine workhandling but pallet pool enables unmanned night shift to operate : manufacture is to high precision requirements, in process gauging on grinding.
2. Fujitsu Fanuc :

Product : industrial robots, CNC wire cut EDM's and mini CNC machine tools.

FMS: 30 machine tools with robot
loading, automatic warehouse, automatic transportation by robot.

Work types : 450
Comments : 4 or 5 machines with in process gauging, Fanuc adaptive control using spindle motor current on some machines, unmanned night shift. $\mathrm{CO}_{2}$ laser for hardening.
3. Yamatake-Honeywell :

Product: flow control valves, flowmeters
FMS: seven special design N.C. machine tools, fixed path conveyor between workstations

Work types : 400
Comments: in line washing station, automatic warehouse.
4. Toshiba Machine

Product: Machine tools, industrial machinery, textile machinery FMS: Small flexible manufacturing cell comprising 2 machining centres with APC ( auto pallet changers ).

Work types: Not known
Comments : own N.C. controller used Tosnuc 500 linked to FMS T5003 control computer for DNC.
5. Shinmeiwa :

Product : machine tools, aircraft, special vehicles
FMS: Small flexible manufacturing cell with 2 machining centres and fixed path conveyor between workstations; larger more modern FMS with 4 machining centres with APC, rail guided work transfer vehicle; other
small flexible cells.
Work types : Not known
Comments : Unmanned operation at night, 66 loading stations on small FMS.
6. Okuma Machinery :

Product: Machine tools
FMS: Seven machining centres with APC and robotruc materials handling between workstations.

Work types : 95
Comments : Okuma CAMPUS 5000 system control computer, auto transport of tooling to and from tool station to outside machine tool magazine.
7. Yamazaki Machinery

Product: Machine tools
FMS: Large system of 18 machine tools called FMF ( flexible manufacturing factory ).

Work types : 74 types ( 1,200 variations )
Comments : Most advanced FMS in the world, automatic tool transportation system.
8. Toyoda Machine

Product: Machine tools
FMS: None in plant visited
Work types : Not applicable
Comments : Toyoda have supplied over 20 FMS to other companies.
9. Brother Industries

Product: Typewriters, sewing machines
FMS: DNC machining line with 22 machine tools.
Work types: 4
Comments : System is a flexible transfer line developed by Brother Industries

The Japanese have a rather loose definition of FMS, many things go by title for instance, FMC ( flexible manufacturing cell ), FMS ( flexible manufacturing system ) or FMF ( flexible manufacturing factory ) together with more flexible transfer lines are all included. What was abundantly clear however is that FMS is CNC machines in DNC configuration with a materials handling capability to move workpieces from element to another with overall central computer control. In fact, the Japanese situation is rather strange. The machine tool builders appear to be constructing large, expensive, and impressive systems in their own plants but so far few, if any, have installed systems at customers' plants. Yamazaki, for example, has installed some huge projects in its own plants both in Japan, and now in America, but in Europe the only sale of anything approaching an FMS has been a two-machine cell to Babcock Bristol in Croydon, UK.

The one Japanese company which has installed FMS in plants, other than its own, is Okuma which has also sold outside Japan to the USA. Another interesting company to watch is Yasuda whose Yasda machining centres are being sold into Europe where companies like BT Handling of Sweden are linking them up into FMS. Three or four of this kind of system have been set up in Sweden. Other companies such as Mori Seiki, Hitachi Seiki, Ikegai, Mitsubishi and Makino are also involved in the development of FMS in Japan.

One reason why Japanese companies have hardly sold FMS outside Japan is that few have set up adequate sales and marketing organizations capable of handling the complexity of an FMS project.

### 2.2 Review On FMS Applications

There has been a widespread of FMS installations in different countries. Here some of them are studied in order to understand the practical construction of FMS being applied to various production environments.

## The UK

1. Anderson Strathclyde of Motherwell

It is one of the largest companies manufacturing mining machinery and mining-related equipment in Scotland. Its turnover is about £99.8 million and it has overseas companies in the USA, Australia and South Africa which operate independently.

In 1983, Anderson Strathclyde spent about $£ 6.2$ million to develop an FMS with the help of Giddings \& Lewis - Fraser ( $G \& L-F$ ). The main objectives of installing the FMS are based on three points : reduction in inventory, lower manufacturing costs and the reduction of speculative purchasing. Giddings \& Lewis-Fraser, Arbroath based machine tool manufacturer is the UK subsidiary of Giddings \& Lewis Machine tool Co., Wisconsin, USA. In developing the FMS, it builds and supplies the machine tools from the Arbroath factory. Tooling comes from the Davis Division in the USA, and software from Giddings \& Lewis Electronics in the USA.

The system which has been finally decided on incorporates six machining centres serviced by a single automated guided vehicle. It has been designed to handle cast steel parts which fit in the envelope $2 \mathrm{~m} \times 1 \mathrm{~m} \times 1 \mathrm{~m}$ and weigh up to 2.5 tons. These components from part
of the gearboxes and booms for Anderson Strathclyde's coal cutting machinery range of products. Initially the system is set up to machine seven different parts, but in the future, it will be increased to 14 .

The six machines include a special horizontal boring machine and five model G60 RTX machining centres, two of which are used for roughing operations, the other three for finishing. All the machines have a built-in rotary table with 'flow-thru' pallet ( see figure 2.8 ) transfer so that automatic loading from the AGV is possible. All the machines have automatic tool changing with a capacity for 100 tools each. Control is provided by G \& L-Fs own NumeriPath CNC 800 M which has been fitted with a DNC interface to enable it to communicate with a PDP 11/44 executive computer. The control system also includes two G \& L-F PC400 programmable controllers, one for the load/unload station and one for the AGV.

The machines are laid out in a straight line as shown in figure 2.9. The AGV travels up and down the line, following a cable which has been buried in the floor, delivering palletised parts to the various machines and returning them to the load station situated in a small adjacent room. It has a load carrying capacity of $15,000 \mathrm{lb}$.

## 2. SCAMP

In 1976, the Department of Industry issued a general invitation to UK machine tool builders to participate in its ASP ( Automated Small Batch Production ) program. The 600 Group was eventually the only company to take up this challenge.


Figure 2.8 'Flow-thru pallet transfer system


Figure 2.9 Layout of FWS at Anderson Strathclyde

SCAMP (Six Hundred Computer Aided Manufacturing Project ) is set up at the premises of the New SCAMP Systems Ltd. which shares the site of the 600 Group's Colchester Lathe Co. . It has been designed and engineered by the 600 Group with small batch production as its main purpose. SCAMP is the result of five years of design, development, discussion and delay.

The System's budgeted cost is about $£ 3$ million. The nine machine tools in SCAMP, together with eight robots account for the major part of the investment, about $£ 1.25$ million. The computer hardware and software cost an estimated $£ 0.5$ million, the conveyor $£ 0.25$ million, and the remainder went on general development work.

The system is designed to bring the work-in-progress to the absolute minimum. It could produce commonly-used components such as sinafts, discs and gears, complete and untouched by hand, in a total time of less than three days. In conventional batch production, parts are made typically in batches of 10 to 50 with a throughput time of 10-20 weeks. In SCAMP batch quantities tend to be larger - in the range 25 - 100, but the three-day completion time offers the prospect of large savings in working capital.

Essentially, the system consists of eight robot-serviced machining cells, all of which comprise one machine tool and one robot, except for one cell of two machines. Blanks and semi-finished parts are transported by conveyor from cell to cell on pallets. figure 2.10 shows the layout of SCAMP.

The first four machines in the line perform first operations. The


Figure 2.10 Layout of SCAMP at Colchester
first two are the prototypes for Colchester's new CNC 650 range of lathes and are equipped with Sandvik block tooling. The others are specials, based on the CNC 650 but designed to offer 5-axis machining. Parts which require milling and drilling go on the 5-axis machines but have to be correctly orientated first to within $0.5^{\circ}$ of a desired position. This is performed automatically on a vision system developed by British Robotic Systems Ltd.

Stations 5 and 6 are serviced by a single robot. One machine is a Sykes Genertron gear shaper which is specially fitted with an electronic interface between the work head and the cutter head for the DNC link. The other is a Sykes CNC gear chamfering machine with the Allen-Bra, 'ley 7300 CNC.

The TI Matrix CNC cylindrical grinder in Station 7 is a new machine designed to be particular suitable for a DNC link. Station 8 is a Sykes H 160 hobbing machine. This is a non-NC machine which has been specially adapted for spline milling and robot loading. Finally, Station 9 is a Clarkson horizontal broaching machine incorporating special fixtures to minimise changeover times.

Each machine is automatically loaded and unloaded by a 600 Fanuc M1 robot which removes the part from its pallet on the conveyor, loads it into the machine and then returns it to another pallet. SCAMP's control system has been designed by Systime. The computer control architecture is shown in figure 2.11. Overall control is provided by a Systime 5000-E computer which is duplicated so that if the first should develop a fault the second can take over control instantly.

The 600 Group has claimed that the system is designed to be operated by three people. The first job which has to be done when an order is received, is to enter the parts on to the computer schedule. The machining data such as material, sequence of operations, part programs and so on, for all the components being machined in the system will be stored in the supervisory computer. The operator, then, has simply to enter the number of parts he wishes to make and the computer will calculate the machining times on the various machines required. The computer indicates to the operator what blanks to load into the system, their configuration on the pallets and quantity by means of a graphic display on the terminal at one of the six load stations in the system. The loaded pallets stay at the loading station until a space becomes available at one of the first operation queueing stations. The computer then sends instructions for the loading station to release another pallet. Each pallet has a pallet identification strip which carries coding tags based on a binary code. Strategically placed sensors enable the computer to accurately locate and identify individual pallets and the components carried by those pallets. By use of these sensors, the pallet is correctly routed to the appropriate workstations for the components it carries.

Linking the conveyor and pallet system to the machine tools are the eight Fanuc M1 robots. These were initially programmed manually using a teach box, and the program for each component in the family are now stored in the local cell computers and called up by the central supervisory computer as required.

Tool changing is at present entirely manual. Tools for the lathes are stored in cabinets beside the machines and are changed at the end of a
batch in accordance with instructions from the central computer displayed on the screen of each machine's control system. Tool life is monitored for each cutting tool by counting the number of parts it has cut. On the basis of experience a figure for the life of each tool is stored in the computer, and the operator is given advance warning of its being reached. When a batch of work is completed and tools are being changed for the next task, a record is displayed to the operator for any tools which are carried over from one batch to the next, showing the number of parts already cut by each tool and the total number expected of it. On the basis of this information the operator can decide whether it is better to leave the tool in place or to replace it .

At present, the 600 Group has ben approved as an FMS consultancy by the Department of Industry for its FMS grant scheme.
3. Kearney and Trecker Marwin

KTM, the Brighton-based machine tool manufacturer, has set up a group within the company which is specifically orientated towards FMS. In fact, it is one of the first companies to be awarded a grant by the Department of Industry to help finance the installation of FMS.

KTM's main business is in building machining centres which themselves can, and have been, incorporated into FMS. In the past few years, KTM has produced spare parts or low volume engines with a high degree of variation for the petrol engine manufacturers. Other customers are those coming from the petrochemical , pump and valve industries.

In 1981, KTM was heavily involved in the first FMS to be set up in the UK at Normalair - Garrett, whose system incorporated two KTM machining centres specially adapted to FMS . At the same time, KTM made quite a sensation at the European machine tool show in Hanover when it exhibited its revolutionary multi-headchanging machine for the first time.

In 1983, KTM developed an FMS for its own production requirements. It is a two machine system designed to produce more than 100 machine tool parts for the company's product range. The goals of this investment are reducing work-in-progress and throughput times.

Figure 2.12 shows the layout of the flexible machining system. There are two identical KTM 760 machining centres in the system which have been modified in various ways to suit FMS operation. These are supplied with palletised parts by a rail-guided vehicle, which takes the pallets to and fro between a static pallet pool and the machines. Computer simulation has been used to assess the number of pallets which are necessary to handle the throughput of work.

KTM eventually operated the system with some unmanned periods and some manned periods. During manned periods, operators are concerned with loading and unloading pallets into the system and changing tooling. This they do according to instructions prepared by a master scheduling package. The existing COPICS system knows the parts that have to be produced over the next 24 hours. With this data, the scheduling package will produce a production program for the next eight hours according to the tool management situation. In this way, KTM claims that it will optimise tool use and minimise tool changing.


Figure 2.11 Computer control architecture for an FMS


During the operation, worker follows the instructions from a VDU as to which parts to load, with which fixtures, in what order, and confirm back to the system when he has performed the required actions. From this moment onwards, the master computer will keep records of where each pallet is and the part, or parts, it has on it; so that when a pallet is scheduled to go on a machine the relevant cutting program or programs will be down-loaded. A safety device is also incorporated to check that part and cutting program match. This involves a probing cycle to check an identification feature which is designed into all the fixtures.

This probing cycle takes place prior to each machining cycle. KTM used a PDP 11 minicomputer to co-ordinate the operation of the machine tools and transport system, while an IBM computer is employed to handle all the management responsibilities and is linked directly to the company's materials requirements planning system.

## 4. Imhof - Bedco

One of the first companies to receive support under the DOI's ASP ( automated small batch production ) schemes, Imhof-Bedco, completed the DNC linking of its automated paint shop in 1982. The shop's PDP 11/23 minicomputer is able to down load programs automatically to the three RAMP paint spraying robots according to a production scheduling program. The software and internal links were carried out under contract by the National Engineering Laboratory.

Imhof-Bedco, the subcontract subsidiary of the Electronic Enclosures Division of Phicom, processed about 1000 batches in 1981. A typical batch size is 100 but some could be as large as 3000 . Using DNC in
this kind of jobbing shop environment, the company should be able to respond more quickly to orders and hence become more competitive. The company has recently installed a second Wiedematic 2040 CNC turret punch press together with another PDP 11/23 minicomputer for its fabrication shop.

## West Germany

1. Zahnradfabrik

Zahnradfabrik (ZF) of Friedrichshafen is one of the largest suppliers of gears and gear boxes in the world. As early as 1965, the company began running gear hobbing machines unmanned during night shifts. There are now more than 100 such machines keeping production going 24 hours a day with only limited operator attendence during the day and none at night. This is made possible by the development of a workpiece storage magazine and rotary loader.

The involvement in developing storage magazine and rotary loading devices led to the establishment of a new division, ZF Handling Technology. Its products now also include a hydraulically - operated robot, and it is represented in the UK by Hahn \& Kolb of Rugby. ZF Handling Technology is the company which has been largely responsible for the planning, design and construction of the new FMS installation.

In 1976, ZF Handling Technology began to develop an FMS with substantial backing from the West German Government's BMFT ( Ministry for Research Technology ) under the title 'Improving work conditions by linking flexible manufacturing systems based on a modular automation system '. The objective of this development is
not only to automate machine tools but also to automate the handling, and to manufacture in small batches with very short throughput times. Hence, it is possible to produce finished gears from rough blanks at lower costs.

The first step towards planning the FMS was to undertake a study of the different parts in production to identify a family of components suitable for production as a group. The result of this investigation was that four types of gear, which had relatively similar shape, dimensions and machining requirements, were selected for production on the FMS. Having identified the parts to be made, the next stage was to plan the system, calculate what types of machine tool and how many of each would be required. The aim was to produce approximately 16,000 components per month in batches of between 50 and 500. The maximum tool changeover time was to be of the order of 25 minutes, a reduction of $30 \%$ on conventional production methods.

The layout of the resulting FMS is shown in figure 2.13. Machines are arranged in two straight line, either side of a static magazine store. Each machine is serviced by its own ZF TIII L robot. An overhead gantry crane ( see figure 2.14 ) transfers the magazines between store and machine tools, or between machine and machine. In front of each machine is a magazine base unit with three positions, any one of which can take a magazine. The magazines have a capacity for 30 or 60 components, depending on their diameter, and the system has the capacity to handle 180 such magazines in the central area. Magazines can be stacked in two layers in the static store. All of the different types of gear made in the system have a central bore which is used as


Figure 2.13 Floor plan of ZF system at Friedrichshafen


Figure 2.14 Cross-section of ZF production system
a location feature in the magazine. It is estimated that at any one time there could be 4000 or 5000 parts in the system, accounting for about 100 different batches. On average, each blank visits eight machines, and each operation takes an average of three minutes. It takes about a week for any part to pass through the entire system.

There is a load/unload station in the FMS. At this position, an operator takes rough blanks and puts them on a short conveyor from where they are transferred by robot to a magazine. At the end of the machining cycle, the same robot unloads finished parts from the magazine onto the conveyor from where the operator removes them by hand. A robot is used to load the magazines, not an operator, because of the careful handling required by these delicate parts and the accuracy with which they must be positioned.

The whole system is co-ordinated by a mainframe computer which is housed in a control room adjacent to the machining system, and it is here where the status of the machines and transport system can be monitored. A colour VDU with complex colour coding system shows what is happening at any one time in the system ; whether machines are cutting, being set up or whether they are down. It will also indicate where all the magazines are in the system and whether they are full, half-full or empty. The same VDU can also indicate what is happening in one specific station, the serial number of the part being machined, the size of the batch, the job number and the program number.

Scheduling is performed by the computer on a daily basis. A weekly schedule of work is roughly calculated by one of the system operators
and this will then be loaded into the computer which will calculate the exact schedule on a daily basis. If a machine should go down, the work will be rescheduled to maintain production and by-pass the 'down' machine.

The FMS is now running two shifts and the reduction in manpower to produce equivalent quantities of gears is about $30 \%$. This tremendous success has encouraged $Z F$ to build another FMS in the near future.

## 2. Carl Zeiss

A highly original FMS has been installed by precision instrument and measuring equipment company Carl Zeiss of Oberkochen in West Germany. The system was first planned in 1978, and it was fully occupied producing work in 1983.

The system incorporates four Steinel Type BZ 20 horizontal machining centres linked by a shuttle car to each other and to a Zeiss VMC 850 three axis co-ordinate measuring machine and a load/unload station. Layout of the FMS is shown in figure 2.15. A 40-station tool magazine for each machine was found to be adequate from a process planning analysis of the 122 different workpiece, because each machine is carrying out batch work on only one part number at a time. However, the company is working towards a reduction in the overall number of tools required in the system by establishing a set of 'standard tools' which can cop with most of the work. Furthermore, this could open up the possibility of having alternative machines for the same operation, hence raising the flexibility of the whole system.

## France

1. Renault

The 'JUST-IN-TIME' production system operates at Renault Vehicles Industriels ( RVI, Renault trucks ) in Boutheon, France, producing various components for a new family of gearboxes. The factory employs 570 people exclusively engaged in the machining and assembly of gearboxes, but only 15 work on the FMS.

The complete system has been installed by Renault Machines Outils, using other Renault companies as necessary. For example, Seiv Automation supplied robot carriers. The variety of different components handled by the system is four; three of which are made from grey cast iron, and one from aluminium alloy. It incorporates seven CNC machine tools, with eight robot carriers to transfer parts between stations. A real-time computer controls the entire FMS, optimising the workload of each machine and enabling instantaneous adjustments of the work program to take into account unscheduled machine downtime.

The seven CNC machines in Renault's FMS includes four Graffenstaden Machining centres, two head changers and a reaming and facing machine, the last three are built by Renault. The machining centres, developed by the CIT Alcatel Group company, Graffenstaden, are four-axis machines which carry out drilling, reaming, fine boring, tapping, counter boring and milling operations from the rough state through to finishing. Each machine has an automatic tool changer with 60 - tool capacity. The machining centres are linked in pairs to contribute to the overall flexibility of the system. Two have the capability to perform all the roughing operations while the other two
perform all the finishing operations. The head changer machines use multiple spindle heads to perform drilling, counterboring, boring and tapping operation. Each one includes a conveyor for storing and feeding the heads in the proper sequence with a total storage capacity of 45 multiple spindle heads. For each component there is a corresponding series of multiple heads held in readiness on a conveyor system and moved into position according to the task to be performed.

Each of the unmanned stations has a double pallet station at entry and at exit. There are also seven buffer stations scattered throughout the shop, each having capacity for one part, to ensure continuity of part supply to machines. Parts are transported around the Renault FMS by eight self-propelled wire-guided carts built by Seiv Automation. There are four load/unload stations where the parts are manually clamped and unclamped onto palletised fixtures. The carts then transport these palletised parts to the appropriate machines, guided by frequency loops embedded in the floor.

The whole FMS system is controlled on a real time basis by a Solar minicomputer housed in a controlled environment. This is the control at the heart of the system's flexibility and adaptability. The objective of the control system is to maximise the utilisation rate of the facilities under production constraints, such as the constant ratio between the various parts processed and production deadlines. The different constraints were imposed by an objective of minimum inventory level between the machining shop and the assembly shop. Renault's 'just-in-time' concept aims to machine parts one day and assemble them the next.

The FMS plant now running has already proved itself capable of some product flexibility. Since receiving the order in the middle of 1979 and commissioning in early 1982, several modifications to the design of the gearbox components were easily accommodated. In addition, when Renault does decide to introduce a new gearbox model, the production will also be absorbed without difficulty into the FMS.

In addition to Renault's large FMS at its Boutheon plant, a two-machine system built by Renault for aircraft manufacturer Messier-Hispano-Bugatti went into production in May 1983. The system produces six different complex prismatic components in random sequence. Ultimately the cell will be producing nine different parts in 30 set - ups. The two Graffenstaden four -axis machining centres are linked to the load station and to the storage system by a stacker crane. Each machining centre carries 100 tools. A feature of the system is that it is controlled not by a computer but by a programmable controller, SMC 500, and Renault believe that this relatively simple configuration will attract the attention of many smaller companies which would be discouraged by the complexity of large FMSs such as the one in Boutheon.

## Finland

1. Wartsila Vaasa

Since 1983, the Wartsila Vaasa factory in Finland has had an FMS for machining diesel engine parts which operates non-stop with unmanned periods eight hours long. The system incorporates three identical machining centres, an automatic warehouse, load/unload station, sub-assembly section, and a minicomputer for controlling material flow. Layout of the FMS is shown in figure 2.16.


Figure 2.15 Layout diagram of the Zeiss FNS. In front of the shuttle car track are the load/unload station and 30 buffer stations for fixtured work awaiting transfer to a machine or to load/unload


Figure 2.16 Layout of the FMS at the Wartsila Vaasa factory

The system can, in fact, produce more than 150 different prismatic components without a break for setting the machines, but so far Wartsila has only used it to machine four different kinds of cylinder heads for diesel engines. At the heart of the system is an automatic warehouse with stacker crane, supplied by Bugg och Transport Ekonomi ( BT Handling ) of Sweden. This stores raw blanks, part finished cylinder heads, and pieces awaiting assembly, as well as fixtures and other sub-assemblies. The whole system is controlled by a PDP 11/23 minicomputer. With a DEC LA 38 terminal and two RL02 disc units with a memory capacity of 10 M byte. The computing system and software was supplied to Wartsila by SATT Electronics of Sweden.

This is the first FMS to be installed at the Wartsila Vaasa factory and it has exceeded almost all expectations. Since implementation in Summer 1983, stock and work-in-progress has been reduced by approximately $80 \%$. The lead time from casting to assembled cylinder head is now two days. Manpower productivity, because of unattended operations, is also higher. In addition there are advantages in quality and continuity of production. Breakdown of any single machine and unit of the FMS will not interrupt production. The FMS gives the added benefit of high flexibility in accordance with changes in company environment. In an extreme case, the FMS can be switched to complete different products without loss in productivity.

## The USA

1. Cincinnati Milacron

Cincinnati Milacron is one machine tool company that has managed to
develop a formula for FMS that customers seem to want. The US company in Cincinnati, Ohio, is currently installing its third FMS project in a 12 month period.

In 1984, a new plant was installed at Vought Aerospace's factory in Dallas, Texas, this is the first of Cincinnati's customers for FMS. The system comprises eight 20 HC horizontal machining centres, each with 90-tool magazine and Cincinnati Acramatic CNC System, two 10-pallet work-changer units, four automated guided vehicles, an inspection station, a washing station and the supervisory computer. A special chip-collection system separates ferrous and non-ferrous materials for reclamation. The layout of FMS is clearly shown in figure 2.17. After this installation of FMS, the company has saved $\$ 25$ million . Conventional methods would need about 200,000 hours to do the equivalent volume of work as the FMS would do in 70,000 hours. The savings result partly from reduced manual involvement. Once workpieces are loaded manually on pallets, automatic operation through three shifts is possible.

Cincinnati's second customer for a major FMS installation is the FMC Corporation in Aiken, South Carolina, which produces about 20 different parts for the US Army's Bradley Fighting Vehicle and Multiple Launch Rocket System. The third customer of a Cincinnati FMS is in fact Cincinnati's own plastics machinery division in Afton, Ohio. Layout of the FMS is shown in figure 2.18. The system generally follows the Cincinnati formula. It has four horizontal machining centres equipped with 90 -tool magazine and Acramatic CNC system, three Eaton Kenway AGVs, a 10 -pallet work-changer and a DEA coordinate measuring machine. There is also a washing station.


Figure 2.17 Layout of FMS in production at Vought Aerospace, Dallas, Texas


Figure 2.18 Layout of FMS in construction at Cincinnati's plastics division in Afton, Ohio

A DEC PDP 11/44 acts as the host computer with a PDP 11/24 for the coordinate measuring machine.

One addition to the standard approach is a more advanced tool management system. As well as transporting parts to and from the machine tools, the AGVs also provide automatic tool supply. Spare tools are prepared in a 24 -tool magazine at a tool setting area. An AGV will take the spare tool magazine to machines needing replacement tooling. Worn tools in the permanent magazine will be replaced with new tools from the mobile magazine by a transfer arm at the back of the machining centre. This operation can be performed without interrupting machining because the permanent tool magazine is split into two sections.

The main objective of the Afton System is to achieve maximum control over production quantilties and manufacture in batches of one, if necessary. It is hoped to reduce workpiece queue times from a couple of days, in some cases 20, down to a few hours.

The majority of the FMS proposals Cincinnati is currently handling concern phased installations - those in which a number of cells will be built over a period of three or so years and then eventually linked to form an integrated system. However, whether the controls and computer vendors can cope with this approach require further investigation.

## Czechoslovakia

There are more than 20 machining systems, at different levels of
automation, operating in Czechoslovakia now. Generally these systems are manually attended NC or CNC machines, which means that such systems cannot be run for unmanned periods. Due to a lack of skilled personnel and an enormous demand for increased productivity in industry, in combination with flexibility, a big government program was started in 1973. Under that program three FMSs with completely unmanned technological processes have been developed. These systems are in operation now. They are used by machine tool companies for small to medium batch production. It is thought that modifications of these three systems will be used widely in Czechoslovak industry.

All the machining units used in these FMSs have been built for unmanned production. The research and development work under the governmental project has been under taken by VUOSO Praha, Research Institute of Machine Tools and Machining, in collaboration with the main machine tool producers in Czechoslovakia.

The general lay-out of one of the FMSs is shown in figure 2.19. The FMS is used for machining complicated parts made from bars up to 80 mm diameter. There are six machining units in the system, connected by a parts handling system. Finished parts are placed in pallets and stored in a rack. In the system the finished parts are put into transport pallets, which are delivered by stacker crane to a rack store.

The application of the FMS has brought a dramatic improvement in floor-to-floor time and productivity. As many as 12 operations previously done on a variety of machines, are now performed on one
machine in one set-up without any manual intervention.

## Japan

1. Hitachi Seiki

In 1984, Hitachi Seiki started full production of a Yen 1.5 billion ( $£ 4.75$ million ) FMS, at its Abiko headquarters, which is intended to increase productivity by a factor of three and cut work-in-progress to a third of its previous value. These aims are being achieved by operating the installation 24 hours a day, during which eight are minimum manned, the other 16 being unmanned. However, increasing production and reducing work-in-progress are not the only reasons for the investment. Technological development and production streamlining are also important factors.

The technological development engaged in for this new plant has mainly been concerned with the control software, as the plant has to be able to handle a large variety of workpieces. With the new software packages, Hitachi Seiki is able to produce 79 large prismatic workpiece types, 131 smaller prismatic workpiece types and 468 different turned workpieces. In order to machine those three different categories of parts, the Hitachi Seiki installation essentially comprises three FMS lines : FMS 112 for large prismatic parts; FMS 113 for small prismatic parts; and FMS 114 for turned parts. The layout of the factory is shown in figure 2.20.

FMS 112 comprises four large machining centres supplied with parts by a rail-guided pallet carrier. There are 30 pallets used in the system. In addition, an optical fibre data highway transfers NC data


Figure 2.19 FMS for cylindrical parts-bars up to 80 mm diameter


Fisure 2.20 Layout of Hitachi Seiki's new factory
and machining schedule to the carrier and machining centres. The parts produced on this line are workpieces such as beds and columns.

In FMS 113, two horizontal and two vertical machining centres, arranged in a line, are used to produce small and medium-size plate and cubic workpieces. In front of the machining centres is the track type carrier which transfers parts from machine to machine. This is supplied with parts from a rack storage and stacker crane system with the capacity to store 162 pallets. Also included in FMS 113 is an automatic tool supply device and tool storage for 528 tools. A robot, acting under command from the computer, transfers fixturised tools to the buffer storage system. Tools are carried to the machining centres on a cart and automatically inserted in the tool magazine, replacing worn tools.

FMS 114 comprises three turning centres and one horizontal machining centre. Pallets are transferred to and from the machines by a rail-guided vehicle. At each machine parts are loaded and unloaded from the pallet by robot, the robot being controlled by the CNC unit on the machine tool. Tool transfer in this system is fully automatic for the turning centres. It is based on a block tooling method with an overhead gantry robot to transfer blocks of tools from a 240 tool storage drum to the tool magazines on the individual machines.

There are a total of 17 controllers for machine tools and other equipment to carry out all the control tasks such as work scheduling control, production control, fixture and tool control, transfer control, etc..

Hitachi Seiki hopes that the introduction of this new advanced machining system will enable it to enter a new market. Its previous customers were usually large scale companies often manufacturing farm machinery or automotive products. Now, Hitachi Seiki is trying to attract the small and medium-size companies.

Apart from Czechoslovakia, there are also many FMSs in Eastern Europe. In 1970, East Germany installed one of the world's first flexible machining systems and is now aiming to get into FMS in a big way, with 12 systems projected for completion by the end of 1985. To handle very large FMS contracts, the WMW, the country's machine tool export/import organization, has set up a special company called RAWEMA in Karl-Marx-Stadt in 1984. The company is working on the development of fully automated machining cells in which all support functions such as tool flow and failure diagnostics are to be fully automatic.

In Asia, other than Japan, Taiwan is another country to put investment on FMS development. Recently The Republic of China (ROC) set up the Industrial Technology Research Institute (ITRI). It is sponsored partly by government and partly by industry, with the aim of developing advanced products that industry can then commercialise. Thus, ITRI has developed a couple of robots, some CNC and the FMS. Most of these systems originated in ITRI's Mechanical Industry Research Laboratory (MIRL). The first FMS installation was a simple system due to the late development of FMS in Taiwan, with its trolley on rails, and computer control of the machines does not operate with a broken tool.

## CHAPTER 3 : SIMULATION AND SCHEDULING

### 3.1 Classification Of Simulation Languages

3.2 Choosing a Simulation Language
3.3 Review On Manufacturing System Simulation
3.3.1 Flow shop and job shop simulation
3.3.2 FMS simulation
3.4 Computational Complexity in Scheduling
3.5 Assumptions
3.6 Review On Scheduling Problems
3.6.1 Single machine scheduling
3.6.2 Flow shop scheduling
3.6.3 Job shop scheduling
3.6.4 FMS scheduling

## 3 SIMULATION AND SCHEDULING

Analytical methods can be developed to study system dynamics and calculate outputs. Because of the complex nature of manufacturing processes, suitable analytical models cannot be easily constructed to deal with general characteristics of such systems. In most cases a lot of assumptions are usually made, mainly; infinite capacity at every waiting queue, zero defective rate, perfect reliability of system resources, exponential processing times, normal or poisson arrival of parts, fixed transfer times and equilibrium behaviour (Buzacott and Shanthikumar 1980, Secco-Suardo 1978, and Solberg 1977 ). The consequence of such assumptions is to obtain resource utilisation rates, estimates of queueing times and production rates which correspond to steady-state working characteristics. Therefore, the use of these methods is more suitable in prediction of performance in systems with a limited transient nature such as continuous flow systems or fully automatic cells with long mean time between failure (MTBF) characteristics.

In general the effective use of analytical methods is restricted by the following :
(1) Modelling constraints in solving real and complex problems which involve a number of parameters that give rise to transient behaviour. (2) Computational constraints in the available CP memory needed to store all the possible system states and configurations, as well as long runtime requirements which are necessary for executing such sizeable codes.

Therefore, only simple and reliable FMS can be modelled and assessed
by the existing analytical methods (Dupont-Gatelmand, 1982). In the author's experience while scheduling, network optimisation and applied queueing theory approaches offer some solultions to specific manufacturing problems, by and large they lack modelling flexibility as a result of their excessive underlying assumptions.

In contrast to analytical methods, the scope for use of simulation is only limited by computational constraints and expertise in model building. In fact, to a large extent simulation is applied where there is either no analytical method applicable or existing methods require a large computational facility (storage and runtime ).

In recent years, the application of simulation on various aspect has increased rapidly, for example, computer time sharing design, job shop scheduling. In particular, system simulation has exhibited its power as a tool to evaluate the system performance of a capital intensive Flexible Manufacturing System.

In simulation work, a system could be defined as an aggregation of objects joined in some regular interaction or interdependence (Gordon, 1969), the term entity is used to denotes an object in a system, the term attributes denotes the characteristics of the entity, and any process which caused the change in the system is referred to as an activity. Some examples of entities, attributes and activities in the context of different systems are given in Table 3.1.

### 3.1 Classification of Simulation Languages

The concepts of event, activity and process are especially important when building a model of a system. An event signifies a change in state of an entity. An activity is a collection of operations that transform the state of entity. A process is a sequence of events ordered in time. To illustrate the relationships among these concepts we consider a job arriving at a machine shop with two tasks to be performed. Figure 3.1 shows the arrival and the eventual service that each task receives.

These three concepts give rise to three alternative ways of building discrete event models (Kiviat , 1967). These are called event scheduling approach, activity scanning approach and process interaction approach. The development of the three concepts is related to the development of discrete event computer simulation programming languages.

In comparing different simulation languages, Kiviat (1969) has proposed using these three approaches as a basis for classification. The classification of simulation languages is briefly described as follow :
(i) Event scheduling languages

Each event must be represented as an instantaneous occurrence in simulated time, scheduled to occur when it is known by the dynamics of the model that the proper conditions exist for its occurrence. Whenever an event is scheduled, a record identifying the event and the time at which it is to occur is filed in a special list. When the
instruction to select the next event is encountered, the computer simulation searches this list to find and perform the event with the earliest scheduled time. Then simulated time is advanced to this scheduled time, thus skipping the "dead" time.
(ii) Activity scanning languages

They represent time-dependent acts as instantaneous occurrences in simulated time. In using these languages, we do not schedule the occurrences within a program, but specify under which conditions they can happen. No "activity schedule" statements appear in these languages, but they contain executive programs that can scan sets of conditions before each simulation time advance to determine whether any activities can take place. In this type of language, the program is composed of a test section and an action section. Whenever simulation time is advanced, all activity programs are scanned for possible performance. All test conditions must be met for the state-changing and time-setting instructions in the action section to be carried out. Should one of the test conditions not be met, the action instructions are passed over. By cyclic scanning of activity programs, we ensure that all possibilities have their opportunity to take place and that all interactions are accounted for.
(iii) Process interaction languages

These languages attempt to combine the efficiencies of the event scheduling languages and the concise notation of the activity scanning languages. They have a list of scheduled events and also a list of conditional events. After executing an event scheduled at a specific time it scans the list of conditional events, executing those that are then possible. Recycling continues until no more scheduled or
conditional events can be executed. Time is then advanced to the date of the next earliest scheduled event, and this entire procedure is repeated. The appeal of the combined event scheduling - activity scanning capability is immediately evident.

The original classification of languages by Kiviat (1969) has been updated by Fishman (1973), he reviews several languages of historical interest which are now little used or obsolete. Kiviat and Fishman both present excellent reviews of discrete simulation languages and their development. In addition, Fishman compares the event scheduling approach as used in GASP II and SIMSCRIPT with the activity scanning approach and the process interaction approach employed in other languages. Table 3.2 categorises some of the commonly used simulation languages according to the modelling approach employed. The most prominent event scheduling languages are SIMSCRIPT and GASP IV. Among the process interaction languages, GPSS and SIMULA are the most prominent. The best known examples of activity scanning approach are CSL, ECSL and SIMON.

The widespread use of simulation as analysis tool has led to the development of a large number of programming languages. These languages are devised on the basis of specific concepts with relevant statements to represent the state of a system at a given time, and its transition from state to state.

Figure 3.2 categorises some of the most widely used languages as well as some recently developed modes. The grouping is achieved in terms of the effort required to represent a system and its manipulation. Those in group 1 can be considered as basic high-level

| System | Entities | Attributes | Activities |
| :---: | :--- | :--- | :--- |
| Bank | Customers | Balance <br> Credit status | Depositing |
| Supermarket | Customers | Shopping list | Checking-out |
| Traffic | Cars | Speed | Driving |

Table 3.1 Examples of Entities, Attributes, Activities in a system

| Event scheduling <br> languages | Activity scanning <br> languages | Process interaction <br> languages |
| :---: | :--- | :--- |
| GASP 11 | CSL | GPSS/360 |
| GASP IV | ECSL | SIMULA |
| SIMSCRIPT | SIMON | QGERT |
| SIMSCRIPT 1.5 | MILITRAN | SIMAN |
| SIMSCRIPT 11 | SLAM | SIMSCRIPT 11.5@ |
| SIMSCRIPT 11.5 |  | SLAM |
| GEMS |  |  |
| SIMAN |  |  |
| SLAM |  |  |

Table 3.2 Simulation Programming Languages: Modelling Approaches
@ Recently, SIMSCRIPT 11.5 has been extended by the addition of concepts called resources and activities which allow the program to be used in a process interaction manner.


Figure 3.1 Event, Activity and Process


Figure 3.2 FMS Simulation : a qualitative comparison of programming languages
programming languages used for general mathematical modelling but with a large effort required to simulate dynamic systems. Group 2 contains codes which are easily written for simulation purposes but lack special features encountered in manufacturing. Group 3 includes simulation languages which are either 'general purpose' with diverse modelling capability or 'special purpose' to suit manufacturing needs. Some of the most widely tested simulation languages fall into this category. For example, SLAM has been used to determine system capacity, balance production, control inventory and establish schedules etc. by organisations worldwide such as NASA, IBM, Anoconda Minerals, Boeing, CDC, FORD, GM, US Air Force and a host of others. SEEWHY, an interactive visual simulation system manufactured and marketed by Istel limited is a stand alone facility that runs on a portable computer. SEEWHY also provides colour graphics display. It allows model creation and manipulation at will. It can create manufacturing situations, equipment alterations and a host of other parameters. Moving colour graphics are used during the execution of the model. This system has been used widely in UK by companies such as Austin Rover, Locus, Cummins Engines and KTM among others.

The 'general purpose' class languages in Group 3 impose a minimal number of modelling restrictions and provide a greater degree of flexibility. However, they require larger efforts in programming (Shannon 1975). This class includes languages such as GPSS, GEMS, SIMON or DRAFT, ECSL and SLAM. 'Special purpose' languages have reduced flexibility and adhere to certain output requirements. However,they provide direct means of expressing the required concepts, automatic generation of the necessary data and collection
and display of the statistics. This class includes languages such as SIMAN, SEEWHY, HOCUS and a host of others.

In the present work, it is not intended to analyse the performance and usefulness of each simulation language. Therefore, some of the existing languages with the source of information are presented in table 3.3; thus the reader interested in this area can be referred to the literature.

| Simulation languages | Source |  |
| :---: | :---: | :---: |
| GASP | Kiviat and Colker | (1964) |
|  | Naylor et al. | (1966) |
|  | Pritsker and Kiviat | (1969) |
|  | Pritsker | (1974) |
| SIMSCRIPT | Karr | (1962) |
|  | Geisler and Markowitz | (1963) |
|  | Markowitz | (1963) |
|  | Markowitz et al. | (1963) |
|  | Karr et al. | (1965) |
|  | Naylor et al. | (1966) |
|  | Kiviat et al. | (1968) |
|  | Gordon | (1969) |
|  | Kiviat | (1969) |
|  | Wyman | (1970) |
|  | Consolidated Analysis Centres | (1971) |
|  | Fishman | (1973) |
| GEMS | Phillips and Handwerker | (1979) |
| SIMAN |  |  |
|  | Pegden and Ham | (1982) |
| SLAM |  |  |
|  | Pritsker | (1982) |
| CSL |  |  |
|  | Buxton and Laski | (1964) |
|  | IBM | (1966) |
|  | Buxton | (1966) |

Table 3.3 Simulation languages with source of information

| ECSL | Clementson | $(1966)$ |
| :---: | :--- | ---: |
| SIMON | Hills | $(1967)$ |
| MILITRAN | Systems Research Group, Inc. | $(1964)$ |
|  | Naylor et al. | $(1966)$ |
|  | IBM | $(1967,1969)$ |
|  | Gordan | $(1969)$ |
|  | Emshoff and Sisson | $(1970)$ |
|  | Pall | $(1971)$ |
|  | Fishman | $(1973)$ |
|  | Schriber | $(1979)$ |
|  | Dahl and Nygaard | $(1966,1968)$ |
|  | Dahl et al. | $(1968)$ |
|  | UNIVAC | $(1971)$ |
|  | Fishman | $(1973)$ |
|  | Lamprecht | $(1983)$ |
|  | Pritsker and Happ | $(1966)$ |
|  | Pritsker and Whitehouse | $(1966)$ |
|  | Whitehouse and Pritsker | $(1969)$ |
|  | Pritsker | $(1979)$ |
|  |  |  |
|  | Istel Ltd. |  |
|  | British Leyland System Ltd. |  |

Table 3.3 ( continued)

### 3.2 Choosing A Simulation Language

Emshoff and Sisson (1970) have suggested two factors which must be considered in choosing a simulation language. They are as follows : (a) one must decide which languages will be available on the computing facilities to be used.
(b) an analyst must choose from among available languages which are suitable for the particular problem. Factors that have to be considered here are the operational characteristics of the language and its problem oriented characteristics.

The operational interest that should be considered are programs and documentations necessary to implement and use the language, such considerations including :
(1) The availability of intelligibly written user's manuals,
(2) The compatibility of the language compiler with available computer systems,
(3) Whether or not the language is supported by a major interest group ( manufacturer, university or software company ) so that it will be updated or improved,
(4) Whether the language is easy to learn,
(5) Whether the language translater provide documentation and extensive error diagnostics,
(6) The cost to install, maintain and update the language, and
(7) The compiling and running time efficiency of the language.

As to problem orientation, one must examine the relationship between the characteristics of the language and those of the problems most likely to be encountered. This would include consideration as follows:
(1) time advance methods,
(2) discrete or continuous system,
(3) deterministic or stochastic model,
(4) event, activity or process orientation,
(5) random number and random variate generation capabilities,
(6) forms of output available and statistical analyses that can be performed on recorded data, and
(7) capability for inserting user-written sub-routines.

### 3.3 Review On Manufacturing System Simulation

### 3.3.1 Flow shop and job shop simulation

Simulation has been used to solve many practical problems in general manufacturing systems. Simulation experiments for scheduling problems have been reported for the first time by Rowe and Jackson (1956), Jackson (1957), Baker and Dzielinski (1960) and since then a lot of research has been devoted in simulation of flow shops and job shops especially in the study of queueing disciplines (Gere 1966, Conway et al 1967, Hollier 1968, Panwalkar and Iskander 1977 ). Freeman (1964 ) used simulation to study the effect of unequal allocation of buffer capacity for a three-stage transfer line. The concept of reliability was incorporated by Buzacott (1967) in formulating a discrete-time model. The apportioning of buffer capacity to attain maximum line efficiency was studied by Masso and Smith (1974). Case studies on the application of in-progress buffers in a bottling plant and an automotive hood line were reported respectively by Kay (1972) and Law, et al (1975). Sheskin (1976) used a decomposition algorithm to study the allocation of a fixed buffer capacity. Ignall and Silver (1977) described a heuristic procedure for estimating the output of a two-stage system having several machines in each stage. Hollier and Satir (1982) developed a simulation model to control inter-stage stocks in cotton-spinning mills having different numbers of parallel machines at each stage. Browne and Davies (1983) developed a digital simulation model to provide an insight into the effects of modifying the batch sizes used in the machine shop. Ovuworie (1982) used the GASP-IV simulation package to test an unreliable series production line. A simulation
model was developed by Pegels and Narayan (1976) to evaluate effects on overtime, work centre bottlenecks, in-progress inventory build up, delivery delays and other output variables caused by individual part delays of different load mixes, modifications in work centre capacities, installation of more automated machinery, and modification in scheduling rules.

In manufacturing simulation, a number of parameters related to the characteristics of the scheduling problems are of importance; they are stated as follows :
(i) Scheduling rules, sometimes referred to as dispatching, priority or loading rules.

There are various rules encountered in the literature and in practical applications. Some are extremely simple and some quite sophisticated. Reviews of these rules can be found in Conway et al (1967) and in Panwalkar and Iskander (1977). Broadly speaking, dispatching rules can be classified as local or global. Local rules use information available locally at a particular work centre, where the decision will be implemented, regardless of useful information on the rest of the shop. Global rules use both local information and from other sources, requiring therefore a more complicated information system. The dispatching rules can be classified also as static, where the priority of a job does not vary over time, and as dynamic where the priority is a function of time. In the last two decades, many studies have been devoted to evaluating and comparing the dispatching rules in various job-shop environments. The SIP ( Shortest Imminent Processing time ) rule came out as a very efficient rule and very simple to implement ( Conway et al. 1967, Jones 1973 ).

It produces low throughput ( or lead) time and small makespan but has the drawback that long operations tend to be left unprocessed for very long periods of time. To overcome this problem a 'truncation' has been superimposed on the SIP rule, so that when the waiting time of a job in a queue exceeds a predetermined period of time, the job is given the highest priority to all other ordinary jobs waiting in the same queue ( Conway et al. 1967, Eilon and Cotterill 1968, Malouin 1973, Eilon et al. 1975 )
(ii) Arrival patterns

There are many simulation models describing arrivals in job shops, where arrivals occur singularly or in batches. Single arrivals have been employed in a number of simulation works, where the interarrival periods were assumed to be from a negative exponential or other distribution ( Conway 1965, Jackson 1963, Conway and Maxwell 1962 ). This model has no practical interest, because single arrivals in real life scheduling problems are very rare. On the other hand, jobs arriving in batches are much more realistic, especially when the interarrival times are fixed, corresponding to the industrial practice of receiving orders over a fixed period of time and releasing them to the shop daily or every week. Therefore, deterministic batch sizes and interarrival times have been used in the FMS scheduling (in Section 5.4 ).
(iii) Job shop size

Baker and Dzielinski (1960) have shown that the shop size has no significant effect on the relative performance of the scheduling rules.

This conclusion has been confirmed by Conway et al. (1967) where it has been suggested that experiments with a job-shop of six machines are adequate to show the complexities that are likely to arise in larger job shops. Therefore, in the evaluation of the developed heuristics on the performance of FMS ( see chapter 4 and chapter 5 ), six machines are assumed in each experiment.
(iv) Due-dates

These parameters are very important because they usually involve cost, e.g. cost due to tardy job. A number of methods for determining due-dates have been investigated by Eilon and Hodgson (1967), Conway et al. (1967), Holloway and Nelson (1975). The main conclusion is that some methods can produce better results for specific scheduling rules and that changes in the parameters involved in defining the due dates can control effectively the values of the criteria of performance.
(v) Routing of jobs

In the common flow shop and job shop simulation, all the routings are fixed. However, in an FMS, it is possible that a particular operation can be performed by more than one machine.

### 3.3.2 FMS simulation

The previous simulation studies have been only reviewed on simple flow shop and job shop systems. Over the past few years there has been increasing evidence of worldwide research and application in

FMS simulation. Using it as a design evaluation tool, such as plant layout optimisation, establishment of schedules, control inventory, balance production and determine loading capacities. Countries working in the FMS area such as West Germany, France, Japan, USA and UK have been active in this field.

The first direct application of queueing theory to FMS is due to Solberg (1977). Using the theory for closed networks as developed by Jackson (1963) and Gordon and Newell (1967), he constructed an analytical model for system behaviour that shows good agreement with those performance measures obtained from simulating actual FMS. However, the model must take several unrealistic assumptions.

Another work that uses this same network of queues theory as part of an optimal work allocation scheme is performed by Secco-Suardo (1978) . A formulation is given for finding the optimal routing for each job. The optimisation problem is solved by a linear programming method under constraints. However, only one part-mix is allowed within the network.

An approach that uses elementary queueing theory within a network flow optimisation scheme is discussed by Kimemia and Gershwin (1980). However, machine failure cannot be considered. There are many researchers either using analytical or simulation models for the design and control of FMS, a survey has been made by Dupont-Gatelmand (1982). In general, simulation is more applicable to characterise the behaviour of FMS due to the inefficiency of analytical models to study complex and real systems such as FMS because of their restricted assumptions.

The widely published report on the CMS of the Caterpillar Tractor Company ( Solberg et al. 1975 ) describes a system consisting of nine machine tools fully integrated with a material handling system and an inspection station ( figure 3.3 ). The entire system is controlled by a PDP 11/20 computer on a real-time basis. The nine machine tools consist of four machining centres, three drilling machines and two vertical lathes. These machines are arranged on opposite sides of a centre rail on which two cross-travelling shuttle mechanisms, provide in-progress material handling. The carts also deliver parts to the inspection station. The computer simulation model was constructed as closely as possible to the actual system while still maintaining the versatility which was desired in order for it to be used as a tool for experimentation. The simulation events mainly consist of loading or unloading of the parts onto or out from the machines. Transportation time, positioning time on machine or cart, and the actual loading time were included in the program. The output of the simulator consist of a set of graphs describing the production levels at all times as well as plots of the throughput time for individual component. Other statistics like the analysis of machine utilisation are produced.

Hughes (1976) has developed a model for the Kearney and Trecker FMS at Allis-Chalmers. The system comprises a group of machine tools and other workstations that are connected by a material transport system, with the overall system under computer control. The plant layout of this system is shown in figure 3.4. The simulation model was designed to evaluate the best from the several types of material transportation systems under different working conditions. Evaluation of part processing details such as the desirability of


Figure 3.3 CMS of Caterpillar Tractor Company


```
\square transport cart
A: machining centre
B: milling machine
D: duplex head index machine unit
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Pigure 3.4 Kearney and Trecker FMS system
alternative processing stations, the effects of bottlenecks in the system and the number of palletized fixtures were included in the simulation program. Others like system control algorithms and planning support can be evaluated from the simulation model.

Cook et al. (1978) and Cook (1979) have involved the work on design and analysis of computerized manufacturing systems (CMS). The goal of this work has been to develop a computer model of a CMS which will be useful to potential users of CMS, manufacturers of CMS, and researchers working for a better understanding of CMS. While the model will handle many types of part manufacture, it provides particular understanding regarding small parts of rotation; an area which has received much less attention than others (i.e. large prismatic parts ) but which encompasses a large portion of batch-type manufacture.

Carrie $(1978,1980)$ has developed a plant layout package which utilises the mathematics of graph theory. The program is a general purpose computer package to aid component production system design and plant layout analysis. It is particularly useful for the analysis of small-batch high-variety manufacturing circumstances and can be used to generate solutions based on either functional or group technology layout principles.

Carrie et al. (1984) have employed ECSL to develop a model for the Anderson Strathclyde FMS at Motherwell. Among the objectives were the improvement of performance by accelerating the company's implementation of new technologies in both manufacturing technology and information processing techniques. Certain weakness in the
initial design and control system software were found. It has shown that simulation of an FMS is not a once-and-for-all activity, but must be carried out repeatly as information mature and the issues investigated shift from assessing system capacity to operating decisions.

Iwata et al. (1984) have developed a general purpose discrete-event type simulator written in FORTRAN -77 based on GASP. This simulator can be used as a useful tool when newly designing an effective and economic FMS as well as effectively operating the installed system through the evaluation of the performance of hardware and/or software systems prior to their implementation. The system is modelled as a combination of the following modules so as to be able to simulate different configurations; various types of workstations ( machining, assembly, inspection, loading/unloading ), cart and/or conveyor type transportation system, material handling system ( shuttles, robots ), storage system ( warehouse, buffers ), other auxiliaries ( cutting tools, jigs, fixtures, pallets ), and operators as well as production information processing system including the software. In addition, graphic animation capability is incorporated in the simulator which allows the user to visually monitor the dynamic behaviour of the system and also displays the intermediate and final simulation results on a graphic CRT terminal in the form of a table and chart.

Crossley (1983) describes the design and implementation of a computer-based simulation system. The system was specifically designed for ease of use by a manufacturing engineer concerned with optimisation of the choice and layout of machines, operators, and
handling equipment in a flexible manufacturing cell. In particular, the system is designed to handle sheets, stacks, nests and discrete sheet metal parts. The software is written in the BASIC -PLUS language and is mounted on a SYSTIME 6400 system ( a PDP 11/44 computer) in the Department of Aeronautical and Mechanical Engineering at the University of Salford. A modular approach to the system design was adopted. There are four main components in the software system. Firstly, there is a model builder which is used to describe the structure of the cell of machines : that is, the relationships between processes (or operations ), queues, and routes. Secondly, there is a routing model builder which describes the geometry and associated attributes of the components to be manufactured. This model includes the details of the operations plan and the corresponding load, operation, and unload times. Thirdly, there is a work-to list builder which is used to construct the initial queue or work to be processed by the cell. Fourthly, there is the simulation model which is used to determine the actual performance of the cell in terms of such parameters as operation and queue statistics.

Claybourn and Hewit (1982) have developed a simulation package which allows the assessment of the effects of important parameters such as machining times, machine priorities, etc. on the performance of a robot served manufacturing cell. This package is mainly developed from a commercially available simulation language ECSL which also has facilities for graphically displaying the dynamic operation of a proposed cell system. However, the main drawback from this package is the inefficient scheduling method. Fixed priority rules for machine service order has been employed for scheduling the cell. Changes in the jobs to be processed, and other occasional
handling duties as described in the paper, render such rules inapplicable, since they depend for their success upon a consistency of processing times to ensure high actual cell utilisation.

ElMaraghy and Ho (1982) have produced a general purpose discrete-event simulator, FMSSIM, for flexible manufacturing systems. The package is programmed in FORTRAN. It is capable of simulating different configurations, material handling systems, and topologies including bidirectional tracks. The simulator checks blockage of routes due to interference of carts and simulates random failures and repairs of the various components in the system. It provides the user with a wide range of priority rules to select from and enables him to define his own if required. The simulator produces reports on various vital system performance statistics. It also displays the movement of parts through the system on a CRT. This simulator is a modular, user-oriented package which enables the designer to evaluate a wide range of systems with varied design parameters and select an efficient FMS.

Kochan (1984) reported that the P-E Consulting Group has developed a simulation package, Hocus, for FMS application. The beauty of Hocus is that it is simple. It takes the user through an easy procedure to manually formulate a model of his system. The model is represented as an easily understood flow diagram enabling everyone concerned, however technical or not, to enter the discussion, to confirm the model, to contribute their experience and create a model in which everyone believes. It is just as important that the model should be correct as that the people who are concerned with the results should believe in them. The P-E consulting group has used the package on

FMS using machining centres and pallet pool systems, those with inspection machines and AGVs, turning systems with robot handling and tool changing, also fabrication shop equipment. In addition, Hocus has simulated the effects of tool wear and tool failure,pcb assembly systems, and robotic and mixed manual/automation assembly systems for domestic appliances, and vending machines. A large variety of main frame computers including ICL, Prime, IBM and DEC models can run the Hocus programs. There is also a microprocessor based version which can be applied to some smaller systems. Hocus also provides the graphic displays with full colour facilities. However, it is difficult to consider complicated scheduling algorithms. In fact, this is a common disadvantage in using commercial canned simulation package.

In the UK, British Aerospace and GEC have formed a joint venture to develop and market FMS software. The agreement announced in March 1985, involves BAe's Military Aircraft Division and the Factory Automation Systems Technology ( FAST) Division of GEC Electrical Projects. These two companies are expected to obtain a good product by combining BAe's experience in production engineering with FAST's experience in marketing and systems engineering.

The above references prove that simulation techniques, which have been neglected in the past in helping decision making produces in the day to day life of production management problems, are now being increasingly used. The role of computer modelling and other related operations research techniques are to assist production engineers to achieve the optimum design of the systems they design and operate.

### 3.4 Computational Complexity In Scheduling

In the past two decades there has been a substantial growth in the field of sequencing and scheduling research. This research can be divided mainly into two categories ( Panwalkar and Iskander, 1977) : theoretical research dealing with optimising procedures limited to the static problems and experimental research dealing with scheduling ( dispatching ) rules in both static and dynamic cases. Management science and operational research in scheduling have focused on understanding the variety of scheduling environments that exist, and constructing scheduling algorithms specific to them. Four types of "shops" are distinguished in the literature :

1. single machine - single operation,
2. parallel machines - single operation,
3. flow shop series of machines - multiple operations, 4. job shop network of machines - multiple operations.

Nowadays, FMS is the most common sense in the automation industry( chapter 2 ). However, the development of an efficient scheduling technique for FMS is still behind the development of hardware ( Hartley 1984 ). This problem is extraordinarily complicated, and requires major advances in the state of the art in systems engineering, operations research, and decision and control sciences. There are four major reasons for the complexity of the problem :

1. Large number of different events that can take place in an FMS. For example, just considering permutations, the number of different orders in which 10 different workpieces may be sent into an FMS is 10 ! or 3628800. Hence, complete enumeration is not applicable because it requires an excessive amount of computation time.
2. The inherent, and unavoidable, stochastic behaviour of the basic building blocks in any manufacturing systems, e.g., random failures of machines and transportation devices, and random processing times. The presence of random effects can vastly increase the complexity of a problem.
3. The flexibility of the operation routing for some parts even makes the problem more complex.
4. The random input of parts.

### 3.5 Assumptions

There is a common set of assumptions encountered in the literature on scheduling problems (Gere 1966, Mellor 1966, Conway et al. 1967, Day and Hottenstein 1970, Baker 1974 ).

1. Machines do not break down and do not need servicing.
2. Preemption is not allowed ( operations that start being processed are completed without interruption).
3. Machines can process one operation only at a time ( no overlapping possible ).
4. Job operations may not overlap ( each job can be processed by one machine only at a time).
5. Set-up and transfer times are either negligible or incorporated in the processing times.
6. No machine interchange ( flexibility ) is possible, exept when FMS is considered.
7. Processing times are fixed ( the estimated time is equal to the actual ).
8. There are no cutting tools availability constraints( i.e. tools are always available for each operation ).
9. An important assumption that will be adopted is that the machines are used as single processors ( one machine only in each workstation ). There is another category of problems where $n$ jobs have to be processed on $m$ machines in parallel ( usually identical ), with or without precedence constraints, due dates etc., with the objective of minimising makespan or the number of processors required.
10. Another assumption that is adopted is that no precedence constraints exist for operations from different jobs. This assumption in fact excludes assembly operations.

### 3.6 Review On Scheduling Problems

A large number of references on job scheduling have been published, irrespective of approach used. A good scheduling approach will bring overall beneficial results by achieving the following :
a. greater output,
b. shorter throughput or lead time,
c. less in-progress inventory,
d. better facility planning and utilisation of machinery and manpower, e. better delivery performance.

In this section, a review on the various scheduling techniques in different manufacturing environments such as a single machine shop, flow shop, job shop and FMS are presented. However, scheduling in single machine shop has no practical interest and is very rare in real life. Therefore, some of the scheduling techniques applied in this manufacturing environment are only briefly stated.

### 3.6.1 Single machine scheduling

The problems of sequencing several jobs on a single machine so as to optimise a desired objective are briefly stated as follows :

- minimise the sum of weighted completion times

Smith (1956), Horn (1972), Sidney (1975)
The objective is to find a feasible sequence which minimises the sum of weighted completion times $\sum w_{i} c_{i}$. The first results of this problem were derived by Smith (1956). He shows that when there are no deadlines the problem can be solved by sequencing the jobs in
non-decreasing order of $\mathrm{p}_{\mathrm{i}} / \mathbf{w}_{\mathrm{i}}$. This algorithm is referred to as Smith's WSPT ( Weighted Shortest Processing Time ) rule, where $p_{i}=$ processing time of job $i$,
$\mathbf{w}_{\mathrm{i}}=$ positive weight of job i , and $c_{i}=$ completion time of job i .

- Minimise the sum of weighted completion times, with due dates Potts and Van Wassenhove (1983)

Method:
A branch and bound algorithm which incorporates lower bounds that are obtained using a technique called the multiplier adjustment method.

- Minimise the maximum tardiness, all jobs become available at time zero.

Jackson (1956)
Algorithm :
Sequence the jobs in an order of non-decreasing due dates.

- Minimise the sum of weighted tardiness, all jobs become available at time zero.

Method : Branch and bound (Elmaghraby 1968 and Shwimer 1972 ).
Method : Dynamic programming (Held and Karp 1962 ).

- Minimise the sum of weighted tardiness, with unit processing times and different arrival times

Method : Dynamic programming ( Lawler 1964 ).

- Minimise the number of late jobs

Method : Heuristic procedure ( Moore 1968 ).

- Minimise the total tardiness

Method : Branch and bound (Lawler 1977 ).
Method: Heuristic algorithm (Sarin 1982).

- Minimise the maximum tardiness, with different job arrival times .

Method : Branch and bound ( Bratley et al. 1971, Dessouky and Margenthaler 1972, Baker and Su 1974, McMahon and Florian 1975).

### 3.6.2 Flow-shop scheduling

Johnson's (1954) two-machine algorithm selects the shortest operation time among jobs with the same routing. If that operation is on the first operation machine it places that job first in the sequence; if the operation is on the second operation machine, it places that job last in the sequence. Continuing this process for each job, the final list of jobs is the sequence which will minimise the makespan. Johnson has shown that this rule applies also to special cases of three-stage operation.

Dynamic programming has been used for flow-shop problems of two-machines and sequence dependent set-up times (Corwin and Esogbue 1974 ).

Integer linear programming has been employed in the formulation of scheduling programs minimising makespan. Bowman (1959) estimated that formulating a simple problem involving three jobs and
four machines would require an integer programming problem containing 300 to 600 variables and many more constraints. At about the same time, the formulation by Wagner (1959) of the problem would be of the same order of magnitude. Manne (1960) has produced another formulation for the general problem. Greenberg (1968) has developed a more efficient formulation for minimising makespan as well as average lead time. This formulation for a problem of 10 jobs and 4 machines requires an integer programming problem of 220 variables and 390 constraints for minimising the average lead time, or 400 constraints for minimising the makespan. Page (1961) has mentioned that when there are several machines and a queue of jobs builds up in front of one of the later machines, it is sometimes possible to rearrange the order of processing these jobs through the succeeding machines (i.e. job passing is allowed) and so to obtain a smaller cost. However, integer linear programming is usually used to solve the scheduling problem without job passing. In fact, none of the authors claims that his formulation is computionally practical.

For the $n$-jobs m-machines flow-shop problem, Lomnicki (1965), Ignall and Schrage (1965) and McMahon and Burton (1967) have applied branch-bound technique to minimise makespan. Ashour and Quraishi (1969) made a study comparing the various available methods and concluded that Lomnicki's method was probably the best, taking into account total computational costs.

The problem of minimising the sum of completion times (or average lead time ) in a two-machine flow-shop was formulated and solved by Kohler and Steiglitz (1975), using branch and bound technique with a lower bound developed by Ignall and Schrage (1965) and Lomnicki
(1965). Baker (1975) has made a comparative study of flow shop algorithms. Using a set of test problems, he investigated various branch-and-bound and elimination strategies in a comparative study and then combined them to produce an efficient solution algorithm. However, the developed algorithm can only be applied to minimise the makespan with no job passing.

The above mentioned flow shop scheduling techniques are either restricted to very small systems or required uneconomical computational effort. Conway et al (1967) have concluded that only very small problems can be solved optimally within reasonable time. Such small problems are often based on the single machine problem and a variety of criteria to be optimised as presented in the previous section of this chapter, or are restricted to the flow shop sequencing problem. Even with this flow shop problem the combinational difficulties are immense, and recourse usually has to be made to the use of heuristics. Recent work by Dannenbring (1977) shows that excellent solutions can be obtained by these methods, and he states that " In general, heuristic methods are relatively economical in their utilisation of computational resources when compared with optimising techniques". As a result, there is an increasing trend towards accepting approximate or near optimum solutions and developing efficient and effective heuristic algorithms for generating such solutions. These heuristics provide near optimum solution to scheduling problems at a fraction of the computation required for exact solution techniques.

A large number of heuristics for flow-shop problems has been suggested over the years, covering different approaches ( Page 1961,

Giglio and Wagner 1964, Palmer 1965, Campbell, Dudek and Smith 1970, Gupta 1972, Gupta and Maykut 1973, Krone and Steiglitz 1974, Dannenbring 1977, Gelders and Sambandam 1978, King and Spachis 1980, Stinson and Smith 1982, Narasimhan and Panwalker 1984.) . The most important and representative ones are reviewed below.

Page (1961) has developed heuristics based on sorting techniques by individual exchanging, group exchanging, pairing and merging. In the exchanging procedure, starting with a given sequence ( permutation), each successive pair of adjacent jobs is tested to see whether it should remain as it is or exchanged in case a smaller makespan is achieved. If an exchange reducing the makespan is obtained, the procedure is repeated. The same principle is used for exchanging the position of strings ( chains ) of jobs instead of a single job. The pairing and merging of strings is based on replacing each successive pair of strings into a new ordered string, the order being the one with the best makespan. Repeating this procedure, an optimal chain containing all jobs is constructed. This is usually an inefficient method of sorting, but its simplicity is a recommendation for the scheduling application.

Giglio and Wagner (1964) have attempted to develop approximate methods for solving the classic three-machine flow shop scheduling problem. The basic mathematical problem is to select an optimal permutation of $n$ jobs, where the objective function employed is the makespan. The methods tested are integer linear programming, ordinary linear programming with answers rounded to integers, a heuristic algorithm based on Johnson's (1954) method, and random sampling.

Palmer (1965) has suggested a quick method of finding a near optimal makespan by giving priority to jobs by determining a numerical slope index for each job and constructing a schedule in a non-decreasing order of the slope index. All the jobs must be passed in the same order on each machine. It is based on the idea that jobs placed early in the sequence should have processing times that tend to increase from machine to machine as the jobs progress through the technological ordering, while jobs assigned to late positions should have decreasing processing requirements. A slope order index for job i on $m$ machines, $S I_{i}$ is defined as:

$$
S I_{i}=\sum_{j=1}^{m}(2 j-m-1) t_{i j} / 2
$$

Where $t_{i j}$ is the processing time for job $i$ on machine $j$.

Campbell et al. (1970) have described a simple algorithm to produce approximate solutions to flow-shop problems. They treat the problem as $m-1$ sub-problems (where $m$ is the number of machines ) and then construct $m-1$ schedules using Johnson's (1954) two machine optimum method, selecting the best amongst these schedules. The above methods consider makespan as the performance criterion.

Gupta (1972) has developed three heuristic algorithms for seeking a quick and near optimal solution to the general flow shop scheduling problem. The heuristic algorithms are not only restricted to be used
to find an optimal sequence for makespan, but can be employed to minimise the average lead time. The results obtained from the proposed heuristics have been compared favourably with the results found by the Campbell-Dudek-Smith algorithm (1970). Another heuristic-programming solution for a static flow shop problem with average lead time as the objective function is presented by Krone and Steiglitz (1974).

Gupta and Maykut (1973) have suggested a heuristic decomposition approach to solve the flow shop scheduling problem. It is based on the heuristic job-pairing technique and the decomposition strategy, generating at least a near optimal schedule for minimum makespan. The job-pairing algorithm built a schedule by selecting jobs in such a way that the machine slack experienced by the last machine tends to be minimum. The decomposition approach consists of partitioning the original problem into a number of equally sized, smaller, more managable sub-problems. Each of these subproblems is optimised, and then the best combination of these subsequences is taken as the solution.

A heuristic programming procedure for sequencing the static flow shop has been developed by Stinson and Smith (1982). The objective is to minimise the makespan. Basically, the procedure is performed in two overall steps. In the first step, each of the jobs is tested as a potential immediate follower to each of the other jobs. In effect, this step of the procedure asks the question, 'how well does a particular job fit in terms of job blocking or machine idleness if it were to follow some other job ?'

An overall figure of merit, or cost $c_{i j}$, is determined for each $j o b j$ as a follower to another job i. Six different heuristics are presented for determining sets of $\mathrm{c}_{\mathrm{ij}}$ values. Using these values of $\mathrm{c}_{\mathrm{ij}}$, the second step then heuristically develops a job sequence by solving the travelling salesman problem.

All the above heuristic algorithms are aimed for obtaining either minimum makespan or minimum average lead time. Gelders and Sambandam (1978) have attempted to develop four heuristic methods for optimising a complex cost function, i.e. the sum of weighted tardiness and weighted lead time costs in a flow shop. They also claimed that the developed heuristics can be used for any other cost function.

### 3.6.3 Job-shop scheduling

The most simple method applied to job shop scheduling problems is employing decision rules. Most decision rules are evaluated by computer simulation studies under certain assumptions of job arrivals and running the simulation model until 'steady state' conditions occur. An early study by Conway et al. (1960) was extended by Conway and Maxwell (1962). Due date considerations were discussed by Conway (1965). Eilon and Hodgson (1967) evaluated five loading rules for different rates of job arrivals. A modified form of the Shortest-First-Operation-First (SFOF) rule was analysed by Eilon and Cotterill (1968) and a truncated version discussed by Malouin (1973). The behaviour of a set of ten dispatching rules was studied by Eden (1975), and their performance measured by four different criteria. Dynamic decision rules were
suggested by Worrall and Mert (1980) to meet the due dates in a large petrochemical plant. Miyazaki (1981) has suggested a method of due-date assignment which can adapt to various job shops. The assignment method is combined with the sequencing procedure to construct the total scheduling system for reducing job tardiness. For more detailed information, a review on the application of decision rules was presented by Blackstone et al. (1982).

Brooks and White (1965) were amongst the first to apply branch and bound algorithms to job shop problems. They also compared their solutions to the 'shortest imminent processing time first' and 'longest remaining time first' decision rules and they showed that this method produced smaller makespan than the decision rules. Since then, many researchers have contributed towards improving its efficiency by either increasing the tightness of bounds or reducing the computational effort. (e.g. Charlton and Death 1970, Florian et al. 1971, Ashour and Hiremath 1973, Florian et al. 1975, Bestwick and Lockyer 1979 ).

A decomposition approach for the job shop scheduling problem was suggested by Ashour (1967). The original problem is partitioned into a series of smaller, more manageable sub-problems. The objective is to minimise the makespan. Within each subproblem, it is solved independently to obtain the subsequence which gives the minimum schedule time. Finally, the schedule times of the sequences within each subproblem are combined to obtain the optimal makespan.

Nicholson and Pullen (1971) have proposed a practical scheme of control for job shop scheduling. The control system presumes that
only the inlet times of the jobs into the production system can actually be decided and managed by a production planner, and not the subsequent internal operation start times, as previous studies have often assumed. A method for optimising the schedule was developed on the basis of this form of control and has been used to minimise the tardiness.

Aggarwal and Wyman (1973) have suggested a composite cost-oriented priority scheduling rule, and it has been used to compare with three other well-known rules, that are basically time oriented, i.e. SIP ( shortest imminent process ), SST ( shortest set up time ), and S/OPN ( slack per remaining operation ). The criteria used for comparison include : total cost per job, number of late jobs, machine utilisation, in-progress inventory and the number of late jobs in-progress. Simulation results shown that the SIP and the cost-oriented rules are preferred in most of the criteria.

Gere (1966) has considered the heuristics in job shop scheduling problem with minimisation of the sum of tardiness. The approach is simulative in that the operation of the shop is simulated in a Fortran program, but in addition to the straight forward use of priority rules for determining sequences of jobs on the machines, a number of heuristics are incorporated. Unlike most of the scheduling researchers such that they considered static ( all jobs on hand at time zero ) problems only, Gere has investigated both the static and dynamic ( new jobs admitted from time to time ) problems. The approach can be also applied to solve the minimum makespan problem in the static case.

Muhlemann et al. (1982) have found that shop performance is greatly affected by both the employed scheduling heuristic and the frequentcy of scheduling. They have analysed the performance of a number of heuristics in the form of dispatching rules under different scheduling conditions which are determined by the scheduling period and the level of uncertainty in the process times and machine breakdowns. Various different measures of performance which could be of importance to management were considered. These included mean ratio of lead time to process time, mean queueing time, mean lateness, percentage of jobs late and net CPU times required to generate schedules in the simulation process. They have concluded that more frequent scheduling can produce significant improvements on shop performance.

### 3.6.4 FMS Scheduling

Extensive researches have been made on the production scheduling problem which is one of major problems encountered in the optimal production control of manufacturing systems ( see chapter 3.6.1 3.6.3 ). However, many of these researches lack considerations for the characteristics of an FMS such as system structure, complexity, and flexibility, with the result that it is impossible to apply these results directly to the production scheduling of FMS in practice. Several researches deal with the complex combinational problem associated with the production scheduling of FMS and provide analytical or heuristic techniques.

The FMS scheduling problem is known to be Non-linear Programming(NP)-complete ( i.e. computationally very demanding ).

Due to the size of typical FMS (5-20 machines, 10-50 parts ), and the added complication of machine failures and alternative routings, an exact solution would involve an unacceptable amount of computation. Recent articles in the literature have recommended that research in the scheduling area be directed toward developing practical approaches which can be easily understood and applied. Therefore, approximate techniques must be found that accurately model the complex behaviour of FMS. Viewing each machine as a node in a network through which parts must flow, Network Queueing Theory offers a possible method for predicting the performance of FMS. However, queueing models have made a few unrealistic assumptions ( e.g. infinite buffer size, machines are all reliable, exponential processing time, steady state performance, etc. ) which discourage the FMS designer to use them. At present, the most feasible solution for solving FMS scheduling problems is obtained by simulation with the application of some simple dispatching rules or heuristic procedures.

Iwata et al. (1978) have concerned themselves with a scheduling problem which allows flexibility in the sense that alternative machine tools can be taken into account for each process of machining sequences of parts. The problem is to determine a minimum makespan production scheduling by simultaneously optimising selection of machine tools, loading sequences of parts and machining conditions §in job-shop type machining systems where parts are produced in batch. The production scheduling problem is analysed by the use of a network graph and solved by employing the branch-and-bound technique. The main drawback from this method is the limitation of solving large-scale scheduling problems, such that the computational
effort is increased dramatically with the system size and also increases with the number of parts to be scheduled. Furthermore, this technique can only be applied to solve static scheduling problems.

Iwata et al. (1980) developed two dispatching rules, EFT ( Earliest Finishing Time ) and EFTA ( Earliest Finishing Time with Alternative operations considered ), to solve a large-scale scheduling problem for a job shop type machining system taking into consideration a set of alternative machine tools for each machining process of parts. The problem has been treated with the use of a network graph and solved by employing dispatching rules. It was found that EFTA rule was useful to solve large-scale scheduling problems. The makespan of the schedule was decreased and the efficiency of machine tools has been increased by taking into account the alternative machine tools for the processes of the parts. Although this method only provides sub-optimum schedules, it is fast to obtain the feasible schedules when compared with the conventional Branch-and-Bound method.

Iwata et al. (1982) have developed an effective scheduling method for the complex production scheduling of FMS which consists of machine tools, buffer storage, and material and cutting tool transportation systems. The parts are produced randomly, and alternative machine tools for each processing stage of parts are permitted. Each machine tool has a buffer of specified capacity and some particular cutting tools for common use are automatically delivered by a cutting tool transportation system. The problem is to determine the schedules of machining and transporting parts, and of transporting cutting tools simultaneously so as to minimise the makespan of production. A
heuristic procedure is presented to obtain better schedules by using the decision rules. A decision rule, named ESTA ( Earliest Starting Time with Alternatives considered), is proposed to achieve a high utilisation of the machine tools and the transportation systems.

Secco Suardo (1979) presented a few algorithms to optimise the workload distribution in an FMS, based upon a closed-network queueing model. Using this approach, a workstation would be normally modelled as a single-server queue and the material handling system as a multi-server queue. The number of pallets in the actual system is assumed to be constant and plays the role of the fixed number of clients in the modelling network. The basic mathematics of the model is stated as a non-linear programming (NP) problem with linear constraint and convex objective, but it has been shown that in most practical situations the solution of the problem is satisfactorily approximated by the solution of a linear programming (LP) problem. The model highlights the optimal production rate when the utilisation of the bottleneck machine approaches saturation. However, the assumptions which have been made in this queueing model are not realistic, such as blockage of network is not allowed. Furthermore, complicated scheduling rules cannot be applied to this model, in fact this is a common disadvantage of using mathematical model.

Stecke and Solberg (1981) have reported an experimental investigation of operating strategies for a computer-controlled FMS. The system was built by the Sundstrand Machine Tool Division of White Corporation for Caterpillar Tractor Company in Peoria, Illinois. It consists of nine machines, an inspection station, and a centralized
queueing area - all interconnected by an automatic material handling mechanism. The operating strategies considered involve policies for loading ( allocating operations and tooling to machines ) and real-time flow control. The results are different from those of classical job shop scheduling studies, showing the dependence of system performance on the loading and control strategies chosen to operate this FMS. For example, the Shortest Processing Time (SPT) rule, which has shown superior performance with respect to system utilisation in many simulation studies (Conway and Maxwell 1962, Conway 1965, Schrage 1968, Jones 1973 ), produced below-average results in this one.

Hildebrant (1980) developed a method for scheduling parts in an FMS with consideration of machine failure. The method relies on a recent technique from Networks of Queues Theory to characterise the behaviour of FMS. It is called Mean-Value Analysis (MVA). The method considers closed networks, where a fixed number of jobs circulate among the nodes ( machines ), and yields throughput, utilisation and average queue size. It takes its name from the fact that it deals mainly with the mean value of distributions associated with the underlying probability space of the problem. The analysis is based on a relation between the mean waiting time at a machine and the mean queue lengths for a system. One advantage MVA has over other queueing techniques is its computational simplicity and easy implementation for multi-part-mix networks. However, some drawbacks to MVA that are common to most queueing techniques such as the queueing discipline is FCFS ( First Come First Serve ), the service times must be exponentially distributed, and the system is assumed to have reached equilibrium.

## CHAPTER 4 : ESTABLISHMENT OF HEURISTICS ON DUE-DATE PROBLEMS

### 4.1 The Need For Heuristics

### 4.2 FMS Heuristics

4.2.1 Theory of Alternate Operation heuristic (H1)
4.2.2 Theory of Alternate Operation and Look Back
heuristic $(\mathrm{H} 2)$
4.3 Evaluation of The Developed Heuristics
4.3.1 Static job shop due-date problem
4.3.2 N jobs and single machine due-date problem
4.3.3 Static flow shop due-date problem
4.3.4 Application for the static FMS

## 4 ESTABLISHMENT OF HEURISTICS ON DUE-DATE PROBLEMS

### 4.1 The Need For Heuristics

Scheduling problems in the real world are very complex and even with simplification they are often difficult to solve exactly. Operations scheduling for processing $N$ jobs on $M$ machines is a combinational problem, where there are ( N ! ${ }^{\mathrm{M}}$ alternatives, among which an optimal solution, according to a certain measure of performance, definitely exists and can theoretically be found in a finite number of computational iterations. However, a large number of computations are required, increasing rapidly as the problem size increases, for instance, $(5!)^{8} \sim 4.3 \times 10^{16}$ evaluations for even a small scheduling problem such as 5 jobs on 8 machines, if a direct search by enumeration is used. Accordingly, it is not practical even when using a large computer. Besides, in most of the real life problems, an exactly 'optimal' solution is not essential. In fact, a sub-optimal solution is usually acceptable. The idea of using sub-optimal methods is not new . Heuristics have been in use for some time and their successes and failures have been subject to a lot of discussion (Conway et al. 1967, Baker 1974).

Campbell et al. (1970) have pointed out that the researcher must be concerned not only with obtaining an optimal solution but also with the practical and economical application of the solution technique. It is this second aspect of the problem which has led to the consideration of approximate methods or heuristic techniques. At present, companies with sequencing problems involving large number of jobs and machines must use approximate methods or simple
heuristic dispatching rules (e.g. FIFO-First In First Out, SIP-Shortest Imminent Processing time) whilst awaiting further development of exact techniques or faster and more economical computers. Another reason to investigate heuristic techniques is that the procedural steps can be kept simple enough so that the problem solver does not lose sight of the overall view of the problem, thus enabling man to make the best use of his intuition and judgement.

In practice, the orders in the shop floor may be classified into two types (Worrall and Mert 1980) such as (a) emergency - have to be done now, and (b) non-emergency - can be delayed until later. In this type of 'job shop', the predetermined schedule becomes immediately out of date as soon as an emergency order is received and is more likely to happen in an FMS. Consequently, non-emergency orders are continually moved back in the schedule and forecasted completion dates are not met. Furthermore, if the orders entering the system exceed the normal available capacity, the backlog will continue to increase causing more disruption of schedules. Therefore, the researcher will deal with the above problems by applying either simple dynamic dispatching rules (e.g. SLACK- minimum slack time rule ) or heuristic algorithms for the day-to-day scheduling to ensure completion dates are met or other desired performance measures are obtained. However, in the case of applying simple dynamic dispatching rules for sequencing at machine centres, the resulting schedule may be far from optimal, because the schedule generated is based on local information at each machine centre. Therefore, attention in this work is focussed to simple methods and efficient heuristic algorithms that will allow generation of solutions close to optimal and an assessment of their performance.

In the case of an FMS, because the entire system is under rigid computer control, the processing times for individual operations are deterministic. Thus, it may appear that a fixed schedule for the operations could be developed off-line (Stecke and Solberg 1981). If this were so, quite sophisticated methods might be used to obtain a fixed, optimal schedule. These kind of systems can be described as "guidance" systems. They construct schedules which are meant to guide the actual scheduling decision making performed on the shop floor. In practice, however, the system is subject to many random disturburances (such as tool or cart or machine failures), which preclude any advantages of operating from a fixed schedule. In addition, such a scheduling problem is mathematically intractable and once a schedule is fixed, it imposes constraints on the production planning function. However, these constraints are artificial, as they exist only because of a local optimisation decision which has been developed off-line. Such constraints reduce the efficiency and flexibility of the manufacturing system and should be removed in order to ensure a better overall optimisation (Halevi and Weill 1984). Consequently, the present work restricts the investigation of on-line dynamic scheduling technique which can be implemented without prescribing printed schedules on the factory floor.

It is accepted that in this research project the discoveries about the FMS scheduling problems require a change of direction of research in scheduling. Earlier, a lot of effort was directed at finding optimal or exact solutions for the general flow shop or job shop problems. This is not considered to be a very fruitful direction any longer. Instead, the aim of this work is to develop efficient heuristic algorithms ( Chan and Pak 1986) for scheduling FMS in a near real time manner.

### 4.2 FMS Heuristics

In recent years many operational researchers have suggested different methods of solving part routing problems in FMS. Buzacott(1982) has suggested that the manufacturing paths can either be found in advance, or a set of dispatching rules can be established which may be used to schedule the jobs in real time. Reviews of relevant research on real time control policies have been given by Olsder and Suri(1980) and Kimemia and Gershwin(1983). Coffman(1976) has applied the combinatorial techniques to solve the job shop scheduling problem, but the computational effort for solving the job shop problems increased rapidly with the number of jobs and machines. Hitz(1979) described a periodic scheduling algorithm which is a heuristic combinatorial technique for obtaining schedules that maximise the production rate of an FMS. However, the routes for all the parts must be established before the computation of the periodic schedule is possible. Solberg(1981), Secco Suardo(1979), Buzacott and Shanthikumar(1980) and Stecke and Solberg(1982) have applied analytical techniques which are based on queueing theory to examine the effects of routing policies on the lead times and in progress inventory of an FMS. A survey of analytical methods for solving the scheduling problems in some larger production systems appears in Buzacott and Yao (1982).

In common industrial practice, jobs are scheduled in such a way that the workloads at the workstations are equal (Olker 1978 and Solberg 1977). This idea is not novel however, having been implemented by Muhlemann and Lockett (1975) where they chose to adopt a schedule which took a route that minimised the makespan at a given stage.

Nicholson and Pullen (1971) have suggested routing a job to the workstation with the least current load whenever there is a choice of machines. The SEST(Short Effective Service Time) rule from Eden(1975) was also developed from the similar idea of workload balancing. All the above suggestions produced reasonable results, therefore the idea can be applied to solve the problem of alternative routing in an FMS such that jobs will be scheduled to the station where the workload is minimum, i.e. shortest waiting time. For this reason, the solution techniques of the heuristics are not intended to determine the optimal part-routing in advance, but rather focus the work on scheduling locally at each workstation. It is therefore unnecessary to enumerate all of the possible routes for each part type in advance and is more adaptable to the real-time on-line control manner.

In this context, the original work of Gere(1966) is extended and two heuristic algorithms for FMS application are developed. The algorithms are built into a simulation program( see chapter 6) which is written in Fortran and runs on a Cyber 855 computer system. For the due date problem, the heuristics are used to obtain a schedule such that the respective due dates are met, or failing this, the cost of tardiness is minimised. This cost includes: (1) direct dealing with the customer - paper work, telephone calls, executive time, (2) any penalty clause in the contract, if there is one, and (3) loss of goods resulting in an increased probability of losing the customer for some or all of his future jobs, or perhaps in a damaged reputation which will turn other customers away. For the makespan and average lead time problems (see chapter 5), the algorithms find an optimal due date, $d_{j}{ }^{*}$, for each job. Using these values of $d_{j}{ }^{*}$, the algorithms are
applied locally on each station to decide which job should be scheduled next. This approach renders the algorithms suitable for use with on-line scheduling of tasks in an FMS.

The following assumptions are made in the development of the heuristic scheduling algorithms :
(1) no machine may process more than one operation at a time,
(2) no job may be processed by more than one machine at a time,
(3) a finite process time is assumed which includes the set up time,
(4) the time intervals for processing are independent of the order in which the operations are performed,
(5) the machines are used as single processors ( one machine only in each machine centre ),
(6) cutting tools are always available for each operation,
(7) the job routing is given and alternative routings are permitted. When there is an alternative route for a job to take for its next operation, the station which offers the shortest waiting time will be selected, i.e. balanced workload,
(8) transportation times between stations are either fixed or negligible,
(9) due dates are known and fixed when the objective measure of performance is the cost of tardiness,
(10) there is a local storage buffer at each station ( figure 4.1 ), and
(11) precedence constraints exist for the operations of every job, but there are no precedence constraints for operations from different jobs. This assumption in fact excludes assembly and splitting operations.


STATION 3

Figure 4.1 Model of a flexible manufacturing system

Where $B_{1}, B_{2}, B_{3}$ are local input buffers.

A summary of necessary notation is presented below to formulate the heuristics. The notation is as follows :-
$\mathrm{K}_{\mathrm{j}} \quad=$ total number of operations for job j
$\mathrm{k} \quad=$ operation number (on job j ), $\mathrm{k}=1,2, \ldots \ldots \ldots, \mathrm{~K}_{\mathrm{j}}$
$\mathrm{J} \quad=$ total number of jobs
j $\quad=$ job number, $j=1,2, \ldots \ldots \ldots, J$
$n_{j} \quad=$ number of next operation to be scheduled (on job $j$ )
$\mathrm{t} \quad=$ present time
$\mathrm{d}_{\mathrm{j}} \quad=$ due date of job j
$\mathrm{d}_{\mathrm{j}}{ }^{*}=$ optimal due date of job j
$p_{j, k}=$ mean processing time for the $k^{\text {th }}$ operation of the $j^{\text {th }}$ job
$S_{j} \quad=$ slack time for job $j$
j* $\quad=$ job selected to be scheduled
$\Psi_{m} \quad=$ the set of jobs waiting to be processed on the given machine m at time t
$P_{j}{ }^{*}=$ priority rating for job $j^{*}$
$(C F)_{j}=$ cost per unit lateness of job $j$
$C_{j} \quad=$ cost of lateness if $j o b j$ is scheduled
$C_{1, j}=$ cost of lateness obtained from the scheduled job $j$ which was already late
$C_{2, j}=$ cost of lateness obtained from those jobs which have been queued inside the buffer $m$ if job $j$ has been scheduled (i.e. jobs in the set $\gamma_{j}$ )
$C_{3, j}=$ cost of lateness for those jobs which will be queued inside the buffer $m$ in future time if job $j$ has been scheduled
$t_{j, m}=$ the time job $j$ arrives at buffer $m$
$T_{J s, m}=$ the completion time for the scheduled job Js on machine m
$A_{m} \quad=$ the set of jobs which have been scheduled to machine $m$ for their next operation, they are being processed on some other machines or being transported at time $t$
${ }^{1} \Omega_{\mathrm{Js}, \mathrm{m}}=$ a subset of $A_{m}$ with the condition such that jobs satisfy $\mathrm{t}_{\mathrm{j}, \mathrm{m}}<\mathrm{T}_{\mathrm{Js}, \mathrm{m}}$
${ }^{2} \Omega \mathrm{Js}, \mathrm{m}=\mathrm{a}$ set of critical jobs due to reach the machine m at some future time, yet before the scheduled operation on Js is completed
$\gamma_{j} \quad=a$ set of critical jobs queued inside the buffer if job $j$ has been scheduled
$r_{j k}=$ number of alternative routes for $j o b j$ in the $k^{\text {th }}$ operation
$q_{j k l}=$ machine number for processing job $j$ in the $k^{\text {th }}$ operation, $I=1,2, \ldots \ldots \ldots \ldots, r_{j k}$
$\left(t_{p}\right)_{j, m}=$ processing time for the job $j$ on machine $m$.

### 4.2.1 Theory of Alternate Operation heuristic ( H 1 )

The establishment of Alternate Operation heuristic ( H 1 ) can be stated as follows, and the simplified flow diagram is shown in figure 4.2.
(1) Select a dynamic job dispatching rule which takes into account the due date, the present time and the remaining processing time. e.g. job slack rule,

$$
P_{j}^{*}=\min _{j \in \psi_{m}} \begin{cases}d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t=s_{j} & \text { if } S_{j} \geq 0 \\ (C F)_{j} \cdot\left(S_{j}\right) & \text { if } S_{j}<0\end{cases}
$$

where $p_{j, k}=\left[\sum_{l=1}^{r_{j k}}\left(t_{p}\right)_{j, q_{j k l}}\right] / r_{j k}$
(2) Schedule the operation according to the selected rule.
(3) Check to see if this will make another job "critical" ( that is, see if the slack of any other job has just become negative ). If so, revoke the last operation, and schedule the next operation on the critical job.

Suppose the original selected job is $j^{*}$, and the set of critical jobs is $J_{1}{ }^{*}$, compute and record the cost of lateness $C_{j}{ }^{*}$ due to job $j^{*}$ being scheduled on the machine m(table 4.1).
i.e. to obtain

$$
\begin{gathered}
d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t-p_{j}^{*}, n_{j}^{*} \quad, \quad \text { for } j \in \Psi_{m} \& j \neq j^{*} \\
d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t \quad, \quad \text { for } j=j^{*}
\end{gathered}
$$

Hence obtain the set of critical jobs $J_{1}{ }^{*}$ which satisfy $S_{j}<0$, such that for those jobs with $S_{j}<0, j \in J_{1}{ }^{*}$. If $J_{1}{ }^{*}=\{\phi\}$, STOP and retain the original schedule $j^{*}$. Otherwise, compute $C_{j}^{*}$ and go to step (4).
where

$$
\begin{aligned}
& C_{j}^{*}=C_{1, j^{*}}+C_{2, j^{*}} \\
& \left.C_{1, j^{*}}=\max \cdot\left\{0,-\left(S_{j}^{*}\right)^{\cdot(C F}\right)_{j^{*}}\right\} \\
& C_{2, j^{*}}=\sum_{j \in J_{1}^{*}}(C F)_{j} \cdot\left|S_{j}\right|
\end{aligned}
$$

(4) Check to see if the set of critical jobs $J_{1}{ }^{*}$ makes another set of critical jobs $J_{2}$. If so, compute the cost of lateness $C_{i 1}$, where $i 1 \in J_{1}{ }^{*}$ and go to $\operatorname{step}(5)$. Otherwise, STOP and consider the set $\left\{J_{1}{ }^{*}\right\}$, select the job which has minimum slack time.
$C_{i 1}=C_{1, i 1}+C_{2, i 1}$
where $C_{1, i 1}=\max .\left\{0,-\left(S_{i 1}\right)^{\cdot}(C F)_{i 1}\right\}$

$$
C_{2, i 1}=\sum_{j \in \gamma_{i 1}}(C F)_{j} \cdot\left|S_{j}\right|
$$

and

$$
\begin{aligned}
& d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t-p_{i 1, n_{i 1}} \quad, \quad \text { for } j \in \gamma_{i 1} \& j \neq i 1
\end{aligned}
$$

$$
d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t \quad, \quad \text { for } j=i 1
$$

(5) If all the jobs found in the set $\mathrm{J}_{2}$ have been considered before, go to step(8). Otherwise, obtain a set of unscheduled critical jobs $\mathrm{J}_{2}{ }^{*}$.
(6) Check to see if this set of critical jobs $\mathrm{J}_{2}{ }^{*}$ makes another set of critical jobs $J_{3}$. If so, compute the cost of lateness $\mathrm{C}_{\mathrm{i} 2}$, where $i 2 \in \mathrm{~J}_{2}{ }^{*}$ and go to $\operatorname{step}(7)$. Otherwise, STOP and consider the set $\left\{\mathrm{J}_{2}{ }^{*}\right\}$ and select the job which has minimum slack time.
(7) Repeat $\operatorname{step}(5)$, but replace $J_{a}$ by $J_{(a+1)}, J_{a}^{*}$ by $J_{(a+1)}{ }^{*}$ and $i_{a}$ by ${ }^{i}(a+1)$.
(8) Schedule the job Js which gives the minimum value of the cost of lateness.
i.e. $C_{J s}=\min .\left\{C_{j}\right\}$
where $j \in\left\{j^{*} \cup J_{1}{ }^{*} \cup J_{2}{ }^{*} \cup \cdots \cdot \cdot \cup J_{i}{ }^{*}\right\}$
and $\mathrm{Js}=$ the final selected job.

Note : If more than one minimum exists, select the job which makes the least number of critical jobs. However, if a tie happens again,


Schedule the operation according to the
STEP 2
selected rule, i.e. job $\mathrm{j}^{*}$ is selected


Figure 4.2 Simplified flow diagram for heuristic Hl


STEP 8

```
Compute \(\mathrm{C}_{\mathrm{Js}}\)
Where \(C_{J s}=\min .\left\{C_{j}\right\}\)
and \(j \in\left\{J^{*} \cup J_{1}^{*} \cup J_{2}^{*} \cup \ldots \ldots . . \cup J_{1}^{*}\right\}\)
and \(J_{s}=\) the final selected job
```

Figure 4.2 ( continued)
select the one which has been waiting for a longer time.

### 4.2.2 Theory of Alternate Operation + Look Back heuristic ( H 2 )

This heuristic is actually a continuation of the Alternate Operation heuristic. The simplified flow diagram is shown in figure 4.3.

Step(1) - Step (8) are exactly the same as in the previous heuristic H 1 .
(9) Check to see if there are critical jobs due to reach this machine in some future time, before the selected operation is completed. In an FMS, those critical jobs which have alternative routes in their next operation will not be considered. If there are such critical jobs, check for the effects of these on other jobs. Depending on the resulting analysis of lateness, either select a new schedule or keep the previously selected operation.
ie. to obtain $t_{j, m}$, where $j \in A_{m}$
If $\left(t_{j, m} \geq T_{J S, m}\right)$ for all $j$, then $S T O P$ and retain the original schedule, i.e. job Js is actually scheduled on machine m .

However, for those jobs satisfying ( $\mathrm{t}_{\mathrm{j}, \mathrm{m}}<\mathrm{T}_{\mathrm{Js}, \mathrm{m}}$ ), put $\mathrm{j} \in{ }^{1} \Omega_{\mathrm{Js}, \mathrm{m}}$. Hence a set of jobs ${ }^{1} \Omega_{\mathrm{Js}, \mathrm{m}}$ is obtained such that ${ }^{1} \Omega_{\mathrm{Js}, \mathrm{m}} \subset A_{\mathrm{m}}$.
(10) Obtain the values of $\left\{d_{j}-t_{j, m}-\left(T_{J s, m}-t_{j, m}\right)-\sum_{k=n_{j}} p_{j, k}\right\}$ where $\left(T_{J s, m}-t_{j, m}\right)=$ minimum waiting time for the future arrival job $j$ in buffer $m$ if the job $J s$ is now being processed.
and $j \in{ }^{1} \Omega$ Js,m

After simplification, the values of $\left\{d_{j}-T_{J s, m}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}\right\}$ are but $T_{J s, m}=t+p_{J s, n_{J s}}$
$\therefore$ obtain $\left\{\mathrm{d}_{\mathrm{j}}-\mathrm{t}-\mathrm{p}_{\mathrm{Js}, \mathrm{n}_{\mathrm{Js}}}-\sum_{\mathrm{k}=\mathrm{n}_{\mathrm{j}}}^{\mathrm{K}_{\mathrm{j}}} \mathrm{p}_{\mathrm{j}, \mathrm{k}}\right\}$
If $\left\{d_{j}-t-p_{J s, n_{J s}}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}\right\} \geq 0$, for all $j \in{ }^{1} \Omega_{J s, m}$, then STOP and retain the original schedule, i.e. Js is actually scheduled on machine m.

However, for those jobs satisfying $\left\{d_{j}-t-p_{J s, n_{J s}}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}\right\}<0$,
then put $j \in{ }^{2} \Omega \mathrm{Js}, \mathrm{m}$. Hence a set of future critical jobs ${ }^{2} \Omega \mathrm{Js}, \mathrm{m}$ is obtained, where ${ }^{2} \Omega \mathrm{Js}, \mathrm{m} \subset{ }^{1} \Omega_{\mathrm{Js}, \mathrm{m}}$.
(11) Compute the cost of lateness due to selection of the original job Js on machine $m$ by taking into account the cost of future lateness of some other jobs.
i.e. $C_{J s}=C_{1, J s}+C_{2, J s}+C_{3, J s}$
where $C_{1, \text { Js }}$ and $C_{2, \mathrm{Js}}$ can be obtained as before,
but $C_{3, J s}=\sum_{j \in{ }^{2} \Omega_{J s, m}}\left|d_{j}-t-p_{J s, n_{J s}}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}\right| \cdot(C F)_{j}$

$$
\therefore C_{J s}=C_{1, J s}+C_{2, J s}+\sum_{j \in{ }^{2} \Omega_{J s, m}}\left|d_{j}-t-p_{J s, n_{J s}}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}\right| \cdot(C F)_{j}
$$

Let $\beta_{1}{ }^{*}=\gamma_{J s} \cup{ }^{2} \Omega_{J s, m} \quad$ ( see table 4.2)
(12) compute the cost of lateness due to selection of each job in the set $\beta_{1}$ * on machine $m$ by taking into account the cost of future lateness of some other jobs. This can be done in two parts :-
(a) For those jobs $i \in \gamma_{J s}$

$$
C_{i}=C_{1, i}+C_{2, i}+c_{3, i}
$$

where $C_{1, i}$ and $C_{2, i}$ can be determined as before.
computation of $\mathrm{C}_{3, \mathrm{i}}$
Repeat step(9) and step(10), but replace Js by job i, hence obtain ${ }^{1} \Omega_{i, m}$ and ${ }^{2} \Omega_{i, m}$. However, if $\left(t_{j, m} \geq T_{i, m}\right)$ for all $j$, where $j \in A_{m}$, then ${ }^{1} \Omega_{\mathrm{i}, \mathrm{m}}=\{\phi\},{ }^{2} \Omega_{\mathrm{i}, \mathrm{m}}=\{\phi\}$ and $\mathrm{C}_{3, \mathrm{i}}=0$.

$$
C_{3, i}=\sum_{j \in 2_{\Omega_{i, m}}}\left|d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t-p_{i, n_{1}}\right| \cdot(C F)_{j}
$$

(b) For those jobs $i \in{ }^{2} \Omega_{\mathrm{Js}, \mathrm{m}}$ (i.e. consider those critical jobs which will arrive in some future time )
again $\quad C_{i}=C_{1, i}+C_{2, i}+C_{3, i}$
but now $C_{1, i}=\max .\left\{0,-\left[d_{i}-t-\sum_{k=n_{i}} p_{i, k}-\left(t_{i, m}-t\right)\right] \cdot(C F)_{i}\right\}$
the term $\left(t_{i, m}-t\right)$ is the machine idling time due to awaiting of job $i$.
After simplification,

$$
c_{1, i}=\max .\left\{0,-\left[d_{i}-\sum_{k=n_{i}} p_{i, k}-t_{i, m}\right] \cdot(C F)_{i}\right\}
$$

and $C_{2, i}=\sum_{J \in \Psi_{m}} \max .\left\{0,-\left[d_{j}-t-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-\left(t_{i, m}-t\right)-p_{\left.i, n_{1}\right]} \cdot(C F)_{j}\right\}\right.$

After simplification,

$$
C_{2, i}=\sum_{j \in \psi_{m}} \max .\left\{0,-\left[d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t_{i, m}-p_{\left.i, n_{i}\right]} \cdot(C F)_{j}\right\}\right.
$$

Assume $\quad D_{j}=d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t_{i, m}-p_{i, n_{i}}$
Hence a set of critical jobs $\gamma_{i}$ may be obtained which satisfy the following conditions :-

1) $j \in \psi_{m}$ and
2) $D_{j}<0$

Now, compute $C_{3, i}$ for those jobs satisfying the following conditions:-

1) $j \in A_{m}$
2) $j \neq i$
3) $t_{j, m}<T_{i, m}$

$$
c_{3, i}=\sum_{\substack{j \in A_{m} \\ j \neq i \\ t_{j, m}<T_{i, m}}} \max .\left\{0,-\left[d_{j}-t-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-\left(T_{i, m}-t_{j, m}\right)\right] \cdot(C F)_{j}\right\}
$$

where the term $\left(T_{i, m}-t_{j, m}\right)=$ waiting time of the future job $i$ in buffer m if another future job i has been scheduled on machine $m$.

Assume $\quad E_{j}=d_{j}-t-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-\left(T_{i, m}-t_{j, m}\right)$
Hence a set of critical jobs ${ }^{2} \Omega_{\mathrm{i}, \mathrm{m}}$ may be obtained which satisfy the following conditions :-

1) $j \in A_{m}$
2) $j \neq i$
3) $t_{j, m}<T_{i, m}$
4) $E_{j}<0$

Note : In case (b) where $\mathrm{i} \in{ }^{2} \Omega \mathrm{Js}, \mathrm{m}$, if the term $\mathrm{C}_{1, \mathrm{i}} \neq 0$, job i will be an element in the critical jobs set ${ }^{2} \Omega_{\mathrm{i}, \mathrm{m}}$ as well.
(13) Check to see if this creates another critical job set $\beta_{2}{ }^{*}$ which had not been considered before. If so, schedule the next operation on the critical job and obtain the resulting job lateness. Otherwise, schedule the job which offers the minimum cost of lateness.


Table 4.1 An example to show the relationship between $\mathrm{j}, \gamma_{\mathrm{j}}$ and $\mathrm{C}_{\mathrm{j}}$ for $\psi_{m}=\{1,2,3,4,5\}$

| Scheduled job j | Critical jobs set |  | Cost of lateness $C_{j}$ |
| :---: | :---: | :---: | :---: |
|  | inside buffer $\gamma_{j}$ | future arrival ${ }^{2} \Omega_{\mathrm{j}, \mathrm{~m}}$ |  |
| Js $\rightarrow 5$ | 2 | 6,7 | $\mathrm{C}_{5}$ |
| $\beta_{1}{ }^{*}\left\{\begin{array}{l}2 \\ 6 \\ 7\end{array}\right.$ | 1,5 2 4 | $\left.\begin{array}{l}6 \\ 7 \\ 6\end{array}\right\}$ | $\begin{array}{lll} & & \\ \beta_{2} & & C_{2} \\ & C_{6} \\ & C_{7}\end{array}$ |
| $\beta_{2}^{*}\left\{\begin{array}{l}1 \\ 4\end{array}\right.$ | 2,3 5 | $\left.\begin{array}{l}7 \\ 6\end{array}\right\}$ | $\begin{array}{ll}\beta_{3} & C_{1} \\ & C_{4}\end{array}$ |
| $\beta_{3}{ }^{*}\{3$ | 2 | 1 | $\mathrm{C}_{3}$ |

Table 4.2 An example to show the relationship between $\mathrm{j}, \gamma_{\mathrm{j}},{ }^{2} \Omega_{\mathrm{j}, \mathrm{m}}$ and $C_{j}$ for $\psi_{m}=\{1,2,3,4,5\}$ and $A_{m}=\{6,7\}$. Assuming the original scheduled job Js is job 5


Figure 4.3 Simplified flow diagram for heuristic H2


Figure 4.3 (continued)

### 4.3 Evaluation Of The Developed Heuristics

### 4.3.1 Static job shop due-date problem

The heuristic algorithms can be illustrated by a small example which is taken from Nicholson and Pullen( 1971 ). This is a 5 -job, 3 -machine job-shop problem. The machines never breakdown and they can only process one operation at a time. Once an operation has been started it cannot be interrupted. The times which the operations take on the various machines are given together with the earliest start times and due dates ( table 4.3 ). There are no set-ups or transit times, and the cost per unit lateness is unity and the same for each job.

Application of the heuristic H 2 is demonstrated as follows :-

## At $t=0$

Step(1) \& step(2) : job 1, 3 and 5 are queued at the station A, job 2 and 4 are queued at station $B$, i.e. $\psi_{A}=\{1,3,5\}$ and $\psi_{B}=\{2,4\}$. Compute the corresponding $S_{j}$ and then determine the values of $j^{*}$ which will be loaded on machines A and B.

| machine | job | $S_{j}=d_{j}-\sum_{k=n_{j}}^{K_{j}} p_{j, k}-t$ | $j^{*}$ |
| :---: | :---: | :---: | :---: |
|  | $j$ |  |  |
| $A$ | 1 | $16-12-0$ | $=4$ |
|  | 3 | $10-8-0$ | $=2$ |
| $19-11-0$ | $=8$ | 3 |  |
| $B$ | 2 | $12-9-0$ | $=3$ |
|  |  | $11-4-0$ | $=7$ |

Step(3) : check to see if this make another job "critical ".


Job 3 and 2 are actually loaded on machine $A$ and $B$ respectively figure 4.4 ).

## At $t=2$

Step(1) and $\operatorname{step}(2): \psi_{A}=\{1,5\}$ and $\psi_{C}=\{3\}$

| machinejob <br> $j$ | $S_{j}=d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t$ | $j^{*}$ |
| :---: | :---: | :---: |
| A | $16-12-2=2$ <br> $19-11-2=6$ | 1 |

Only job 3 is queued in station $C$, it is not necessary to compute the value of $S_{3}$, and job 3 is temporarily selected.

Step(3) :

| machine $j^{*}$ | job <br> $j$ | $s_{j}=d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t-p_{j}^{*}, n_{j}^{*}$ |
| :---: | :---: | :---: |
| $A$ | $J_{1}{ }^{*}$ |  |

Job 1 is temporarily selected to load on the machine $A$.
Step(9) : check to see if there are critical jobs due to reach machine $A$ and machine $C$ in some future time, before the selected operations (i.e. job 1 on machine $A$, and job 3 on machine $C$ ) are completed.

Obtain $A_{A}=\{\phi\}$ and $A_{C}=\{2\}$

Hence job 1 is actually loaded on machine A. However, the lateness effect on job 2 has to be checked if job 3 has been processed on machine $C$.

Obtain $t_{2, c}=3$ and $T_{3, c}=5$
since $t_{2, c}<T_{3, c}$,
$\therefore{ }^{1} \Omega_{3, c}=\{2\}$

$$
\begin{aligned}
\operatorname{Step}(10):\left\{d_{2}-t-p_{3,2}-\sum_{k=2}^{3} p_{2, k}\right\} & =\{12-2-3-(5+1)\} \\
& =1 \\
& >0
\end{aligned}
$$

Hence the original selection is retained, i.e. job 3 is actually scheduled to machine C .

## At $t=3$

Job 2 goes to station C, and job 4 is temporarily selected to load on machine $B$.

Step(9) : $A_{B}=\{1,3\}$
obtain $t_{1, B}=6$ and $t_{3, B}=5$, but $T_{4, B}=4$
since $\left(t_{j, B}>T_{4, B}\right)$ for all $j, j \in A_{B}$

Job 4 is actually loaded on machine B.
At $t=4$
Job 4 goes to station $A$.

## At $t=5$

Job 3 goes to station $B$, and it is temporarily selected to load on machine $B$.

Step(9): $A_{B}=\{1\}$
Obtain $t_{1, B}=6$, and $T_{3, B}=8$
since $t_{1, B}<T_{3, B}$,
$\therefore{ }^{1} \Omega_{3, B}=\{1\}$
$\operatorname{Step}(10):\left\{d_{1}-t-p_{3,3}-\sum_{k=2}^{3} p_{1, k}\right\}=\{16-5-3-(2+6)\}$
Hence the original selection is retained, i.e. job 3 is actually scheduled to machine B.

On the other hand, job 2 is loaded on machine $C$ with $A_{C}=\{\phi\}$.
At $t=6$
Job 1 goes to station B, and job 4 and 5 stay at station $A$.
Step(1) and step(2): $\quad \Psi_{A}=\{4,5\}$

| machine job | $S_{j}=d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t$ | $j^{*}$ |
| :--- | :--- | :--- |
| $A$ | $11-(2+1)-6$ <br> $19-(2+8+1)-6=2$ |  |

In the event of a tie, job 5 is selected because it has been waiting for a longer time than job 4.

Step(3) :


Job 5 is temporarily selected to load on machine A.
Step(9) : $A_{A}=\{2\}$
obtain $t_{2, A}=10$ and $T_{5, A}=8$
since $t_{2, A}>T_{5, A}$, the original selection is retained.
i.e. job 5 is actually loaded on machine $A$.

At $t=8$
Step(1) and step(2) : job 5 goes to station $B, \psi_{A}=\{4\}$ and $\psi_{B}=\{1,5\}$

| machine | $S_{j}=d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t$ | $j^{*}$ |
| :---: | :---: | :---: |
| A | 4 | 4 |
| $B$ | 1 | $16-(2+6)-8=0$ <br> $19-(8+1)-8=2$ |

Job 4 and job 1 are temporarily selected.

Step(3) :

| machine $j^{*}$job <br> $j$ | $S_{j}=d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t-p_{j}^{*}, n_{j}^{*}$ | $J_{1}{ }^{*}$ |  |
| :---: | :---: | :---: | :---: |
| $B$ | 1 | 5 | $19-(8+1)-8-2=0$ |

Hence job 4 and job 1 are temporarily selected to load on machine $A$ and $B$ respectively.

Step(9) : $A_{A}=\{2\}$ and $A_{B}=\{\phi\}$
job 1 is actually scheduled to machine $B$.
obtain $t_{2, A}=10$ and $T_{4, A}=10$
since $t_{2, A}=T_{4, A}$,
$\therefore$ job 4 is actually loaded on machine $A$.

At $t=10$

Both job 4 and job 1 go to station $C$, and job 2 is delivered to station A. Obviously, job 2 and job 5 will be scheduled to machine A and machine $B$ respectively. The only thing which has been left to determine is which job will be scheduled to machine $C$.

Step(1) and step(2) :

| machine | job j | $s_{j}=d_{j}-\sum_{k=n_{j}}^{K_{j}} p_{j, k}-t$ | $j^{*}$ |
| :---: | :---: | :---: | :---: |
| C | 1 | $16-6-10=0$ | 1 |
|  | 4 | $11-1-10=0$ |  |

In this case, job 1 and job 4 are equal in priority since they have arrived at station $C$ at the same time. Therefore both of the jobs have to go through the computation in step(3).

Step(3) :

| machine | $j^{*}$$j o b$ <br> $j$ | $S_{j}=d_{j}-\sum_{k=n_{j}}^{k_{j}} p_{j, k}-t-p_{j}^{*}, n_{j}^{*}$ | $J_{1}{ }^{*}$ |  |
| :---: | :---: | :---: | :---: | :---: |
| $C$ | 4 | 1 | $16-6-10-1=-1$ | 1 |
| 1 | 4 | $11-1-10-6=-6$ | 4 |  |

Step(4) :

| Scheduled job | Critical jobs set | Cost of lateness |
| :---: | :---: | :---: |
| $j$ | $\gamma_{j}$ | $C_{j}$ |
| 4 | 1 | $0+1=1$ |
| 1 | 4 | $0+6=6$ |

Step(5) and step(8) : since job 4 offers the minimum cost of latenes, it is selected to load on machine $C$.

The remaining work is quite straight forward, giving the result that job 1 and job 5 will be loaded on machine $C$ at $t=11$ and $t=18$ respectively. The completed Gantt chart is shown in figure 4.4.

As a result, only job 1 is late by 1 time unit, and the completion times for these five jobs are ( $17,11,8,11,19$ ) which agree with the results obtained from Nicholson and Pullen( 1971 ).

In this example, the solution is obtained by applying the Alternate Operation + Look Back heuristic( H2 ). However, the same results would be produced by using the Alternate Operation heuristic ( H 1 ) alone and this is left for the reader to justisfy.

The heuristic algorithms are also used to solve a problem which was proposed by Brooks and White(1965). The objective performance measure is to minimise the total cost of tardiness with a constraint two of the jobs have been assigned a higher priority to load on the machines. The developed simulation program is then modified to adopt this kind of scheduling problem. A loading priority factor is assigned to each of the constrained jobs. Therefore, where there is a queue at each station, the job with the highest loading priority factor will be immediately scheduled to the machine even when other jobs have been delayed for many hours. This method can be introduced into the program and matches perfectly well with the heuristic algorithms to produce the same results which were calculated by Brooks et al.


Fisure 4.4 Gantt chart for the due date problem (Nicnolson and Pullen 1971)

### 4.3.2 N jobs and single machine due-date problem

Simple system with due date problems were also used to validate the heuristics, such as N jobs - one machine sequencing problems in Elmaghraby (1968), Moore (1968) and Shwimer (1972). Data is given in Appendix A. The results are summarised in table 4.4.

In comparisons 1 and 3, cost per unit tardiness for each job is given. However, in comparison 2, the algorithm developed by Moore is aimed at minimising the number of late jobs rather than the total cost of tardiness. Therefore, the cost per unit tardiness for each job was not given. In order to have a general comparison between the heuristics and Moore's algorithm, cost per unit tardiness of each job is assumed equal to unity. Alternate operation heuristic H 1 is used alone to compute the optimal sequence as shown in table 4.4, and it is not necessary to test heuristic H 2 on these simple problems because there is only one machine in the system. The results of these comparisons encourage a further evaluation of the heuristics on other complicated scheduling problems, for example, flow shop and FMS.

### 4.3.3 Static flow shop due date problem

It has been mentioned that the heuristics were validated against Nicholson's job shop example as well as some simple single machine problems. Here some static flow shops due date problems are solved by employing the developed heuristic algorithms.

Muhlemann and Lockett (1975) have suggested that because of the difficulty in evaluating a particular heuristic, some of the common

| Job <br> number | Sequence of <br> operations | Duration of <br> operations | Earliest <br> start time | Due date |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  | 2 | 6 |
| 0 | 0 | 16 |  |  |  |  |
| 1 | A B C A | 3 | 5 | 1 | 0 | 12 |
| 2 | B C A | 2 | 3 | 3 | 0 | 10 |
| 3 | A C B | 1 | 2 | 1 | 0 | 11 |
| 4 | B A C C | 2 | 8 | 1 | 0 | 19 |
| 5 | A B C |  |  |  |  |  |

Table 4.3 Data for a job shop due date problem


Table 4.4 Comparative evaluation of the developed heuristic algorithms on single-machine scheduling problems
loading (or dispatching) rules are used as a basis for comparison with the developed heuristic. Generally speaking, loading rules are probably the most widely developed heuristics in the area of scheduling, and some of these are discussed in detail in Gere (1966), Panwalkar and Iskander (1977), Eilon and Cotterill (1968) and Eilon et al. (1975).

In this section, the resulting cost of tardiness is compared with solutions which are obtained by some general dispatching rules. The minimum slack time rule (SLACK) and the shortest imminent processing time rule (SIP) are employed for comparison with the developed heuristics. It is generally believed that the first rule is the simplest rule for the due date problems, and the second rule will provide a good estimate of the makespan.

Six different examples are considered here. There are 6 jobs and 4 machines in all cases (where the last machine is an inspection station with very short processing time). Data are presented in table 4.5 which are basically obtained from Giglio and Wagner (1964). However, Giglio et al. have only considered the optimisation of makespan problem in their research, hence due dates were not given in their paper. Therefore, two assumptions which have been made for this study:-
(1) due date of a job is proportional to its mean total processing time in the system (Conway 1965, Conway et al. 1967, Eilon and Hodgson 1967 and Eilon and Chowdhury 1976).


Table 4.5 Data for the static flow shop due-date problems

## $\mathrm{K}_{\mathrm{j}}$

In this analysis, $\mathrm{d}_{\mathrm{j}}=1.5 \times \sum_{\mathrm{k}=1} \mathrm{p}_{\mathrm{j}, \mathrm{k}}$
Where $\sum_{k=1}^{k_{j}} p_{j, k}=$ mean total processing time of $j o b j$.
(2) the cost per unit tardiness for each job is equal to unity.

Since the optimal solutions for these examples are unknown, the performance of the heuristics and dispatching rules have been evaluated by means of a relative ranking index as shown in table 4.7. For clarity, all the results have been presented at the back of this chapter in tabular form. With this method, when a heuristic or dispatching rule gives the best solution value, it is ranked with index 1. For the second best value, it is ranked with 2 . In the case of two or more techniques giving the same value, they are all ranked with the same index, equal to the average (e.g. 1.5). With this method, the sum of ranks is the same for all test problems. The resulting schedules (i.e. job sequencing on each machine) for these static flow shop due-date examples are presented in table 4.6. A comparative evaluation and a ranking analysis of the heuristics are presented in table 4.7 and table 4.8 respectively.

Inspection of table 4.8 shows heuristic H 2 ranks highest (i.e. best) in the measure of the cost of tardiness. In addition, it provides 5 times the minimum cost of tardiness in 6 tests. Although the SLACK rule is generally accepted to be the simplest rule to deal with due date problems, here it gives very poor results. It is generally accepted that the SIP rule will not produce a good result for the cost of
tardiness, this has been vertified by the lowest ranking (i.e. worst) which it has received. In the analysis of makespan, the SIP rule ranks highest as was expected. Heuristic H 2 also ranks highest in the measure of average lead time. Heuristic H 1 gives the second best solution for makespan, average lead time and the cost of tardiness.

Besides always providing the optimal schedules associated with the minimum cost of tardiness, the short computational time is another attractive feature for applying these heuristics. When the simulation program runs on a Cyber 855 computer system, the average execution time for these 6 examples is 1.05 cp second for heuristic $\mathrm{H} 1,1.09 \mathrm{cp}$ second for heuristic $\mathrm{H} 2,0.85 \mathrm{cp}$ second for SLACK rule and 0.73 cp second for SIP rule.

### 4.3.4 Application for the static FMS

In the previous section, heuristic H 2 always provided the optimum cost of tardiness for the static flow shop problem. In this research, our main goal is to solve some scheduling problems in FMS. Therefore, it is necessary to see its application to some static FMS.

Baker and Dzielinski (1960) have conducted a study in which they reported that the shop size has no significant effect on the relative performance of the scheduling rules. This conclusion has been confirmed by Conway et al. (1967) where it has been suggested that experiments with a job-shop of six machines are adequate to show the complexities that are likely to arise in larger job-shops. Due to the limited number of publications on FMS due date scheduling examples, evaluation of the heuristic algorithms on the due date
problems in FMS will be based on some hypothetical problems. The number of machines used in this study is six, and this should be large enough to show the complexities that are likely to occur in larger FMS.

Two different cases which involved 16 examples are considered here. In CASE 1, due date of each job is assumed as it has appeared in the
previous flow shop due date problems, i.e. $d_{j}=1.5 \times \sum_{k=1} p_{j, k} \cdot \ln$ CASE 2, due dates are set more tightly, i.e. $d_{j}=1.3 \times \sum_{k=1}^{K_{j}} p_{j, k}$. In both
cases, the number of operations was varied from 4 to 5 , the number of jobs was 7 and the number of machines was 6 . Re-visiting of machine is permissible for some of the jobs. Only one set of data is presented in table 4.9, but other data can be found in Appendix B(DATA B1-B4) and Appendix C(DATA C1-C4).

$$
\underline{\text { CASE } 1}\left(\mathrm{~d}_{\mathrm{j}}=1.5 \times \sum_{\mathrm{k}=1}^{\mathrm{K}_{\mathrm{j}}} \mathrm{p}_{\mathrm{j}, \mathrm{k}}\right)
$$

The job sequence on each machine and the operations schedule (i.e. job routing ) for each job are clearly presented in table 4.10. Operations scheduling is the allocation of jobs to be processed on the corresponding machines. From this table, a Gantt chart of each example can be reproduced for each scheduling technique if it is required. A comparative evaluation and a ranking analysis of the heuristics are shown in table 4.11 and table 4.12 respectively. The
resulting cost of tardiness is again compared with solutions which are obtained by the SLACK and SIP rules.

From table 4.12, it can be seen that heuristic H 2 ranks highest (i.e. best) again in the analysis of the cost of tardiness. In addition, it provides 7 times the minimum cost of tardiness in 8 tests. In the analysis of makespan, the SIP rule ranks highest again as happened in the analysis of flow shop due date problems. Heuristic H 1 again offers the second best prediction of the tardy cost. However, the SLACK rule gives the worst results for all the three performance measures. According to the schedules which have been presented in table 4.10, most of the operations schedules obtained from heuristic H1 are similar to that determined by the SLACK rule (i.e. 6 similar operations schedules in 8 examples). However, there are only 2 exact job sequences ( example no. 2 and 5) appearing in this study. This is mainly due to the mechanism of the alternate operation in heuristic H 1 which takes into account other critical jobs, hence it arranges a better machining sequence and eventually it produces a better estimation of the tardy cost. A further improvement of obtaining the tardy cost is achieved by applying heuristic H2 due to its effective consideration of the arrival of future critical jobs. When comparing heuristic H 2 to heuristic $\mathrm{H} 1,6$ similar operations schedules were found in these 8 examples, but only 4 of them have the same job sequences. As a result, heuristic H 2 gives an excellent prediction of the cost of tardiness.

CASE 2 $\left(d_{j}=1.3 \times \sum_{k=1}^{K_{j}} p_{j, k}\right)$

The job sequence on each machine and the operations schedule for each job are again presented in table 4.13. A comparative evaluation and a ranking analysis of the heuristics are shown in table 4.14 and table 4.15 respectively.

From table 4.15, heuristic H 2 again out performs the other techniques in obtaining the minimum cost of tardiness. In addition, it ranks highest (i.e. best) in determining the average lead time. The SLACK rule again produces the worst results of all the three performance measures. In CASE 1, the operations schedules obtained from the SLACK rule were compared to that determined by heuristic H1. The same comparison is carried out in this CASE 2. It has been found that similar operations schedules exist in only 4 examples, and in fact there is only 1 example offering an exact job sequence on each machine (example number 5). This means that the schedules which have been determined from heuristic H 1 and the SLACK rule are very different from each other. This can be explained by analysing the development of the heuristic H 1 (section 4.2.1) as follows :STEP $1-$ STEP2 : a job is selected according to the simple SLACK rule. STEP 3 : this is checked to see if it will make another job "critical". Therefore, if the due dates are set very tightly, critical jobs are most likely to exist. Hence the mechanism of revoking occurs frequently, and consequently a job is selected which will be different from the original decision.

The performance of heuristics on these 16 examples are summarised in table 4.16. Heuristic H 2 out performs the SLACK rule in determining the minimum cost of tardiness. In fact, heuristic H 2 provides 14 times the minimum cost of tardiness in 16 FMS static due
date problems. Because the problems and constraints differ significantly from those of conventional flow or job shops, it might be expected that the most applicable scheduling policies would differ also. The fact that they do differ indicate the need to be careful in any attempt to apply classical job shop results to these newer manufacturing systems. For example, the SLACK rule, which is generally accepted to be an efficient rule to deal with due date problems ( Panwalkar and Iskander 1977 and Conway 1965) only produced three times the best solution in the above analysis. In the static flow shop due date problem, heuristics H 2 has been employed to produce 5 times the optimal cost of tardiness in 6 examples. Therefore, heuristic H 2 is a promising algorithm to solve the due date problem in both dedicated and flexible manufacturing environments§1. Furthermore, the execution times are very short even for the FMS scheduling problems with such complicated routings. The average execution times are 1.482 cp second for heuristic $\mathrm{H} 1,1.549 \mathrm{cp}$ second for heuristic $\mathrm{H} 2,1.431 \mathrm{cp}$ second for SLACK rule and 1.333 cp second for SIP rule.

In the analysis of static $F M S$ due date problems, two different due date assumptions have been considered,
i.e. $d_{j}=1.5 \times \sum_{k=1}^{k_{j}} p_{j, k}$ and $d_{j}=1.3 \times \sum_{k=1}^{k_{j}} p_{j, k}$

It is expected that the assumption with tighter due date will develop the result of higher cost of tardiness. This can be recognised when a comparison is made between the results in table 4.11 and table 4.14. It can be observed that when applying either the SLACK rule or the SIP rule, the cost is always higher for the case of tighter due date
assumption. However, this is not true when the cost of tardiness has been determined from heuristic H 1 and H 2 , for instance, result in example 3. The reason for the reduction of the tardy cost with the tighter due date assumption is due to the provision of a shorter makespan as well as a shorter average lead time. However, the reduction of average lead time is not guaranteed to reduce the tardy cost, for instance, example 2 with heuristic H 2 . This can be explained by examining the tardy cost function, i.e. tardy cost of each job $j=$ $\max .\left\{\left(\mathrm{lj}-\mathrm{d}_{\mathrm{j}}\right), 0\right\}$ where $\mathrm{l}_{\mathrm{j}}=$ lead time of job j .

With the tighter due date assumption, reducing the lead time $l_{j}$ would reduce the tardy cost. On the other hand, the due date $\mathrm{d}_{\mathrm{j}}$ will be decreased accordingly, and the overall effect on the tardy cost is adverse. Table 4.17 and table 4.18 represent the dependence of the system performance ( makespan and average lead time) on the assumption of the due dates. As a result, the tighter due date assumption provides better makespan and average lead time. Therefore, it is necessary to further investigate how the due dates should be assumed, such that optimal system performance can be achieved. This further investigation will be discussed in the next chapter.

## TABLES ( Chapter 4 )

$\mathrm{m} . \mathrm{s} .=$ makespan
$\mathrm{I}=$ average lead time
$\mathrm{C}=$ cost of tardiness
$\mathrm{n}=$ number of jobs
$\mathrm{NOP}=$ number of operations
J.S. $=$ job sequence
O.S. $=$ operation schedule

Note: (1) The asterisk (*) denotes the best method in each example for obtaining the corresponding objective measure.
(2) The asterisk ( **) denotes the best method for each objective measure.
(3) When there is an arrow, result is the same as the arrow pointed.

| Example number | M/C no. | Jo | sequence o | each machine |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Heuristic H1 | Heuristic H2 | SLACK | SIP |
| 1 | M1 | 645123 | 645123 | 645132 | 456123 |
|  | M2 | " | " | " | " |
|  | M3 | " | " | " | " |
|  | M4 | " | " | " | " |
| 2 | M1 | 342165 | 342165 | 346152 | 324165 |
|  | M2 | " | " | " | " |
|  | M3 | " | " | " | " |
|  | M4 | " | " | " | " |
| 3 | M1 | 164352 | 164352 | 123456 | 643152 |
|  | M2 | 143526 | 135246 | 123465 | 631524 |
|  | M3 | " | " | " | 631254 |
|  | M4 | " | " | " | " |
| 4 | M1 | 132564 | 132564 | 134625 | 231564 |
|  | M2 | 132645 | 136542 | 134265 | 216345 |
|  | M3 | " | " | " | " |
|  | M4 | " | " | " | " |
| 5 | M1 | 153462 | 153462 | 135624 | 531426 |
|  | M2 |  | " | " | " |
|  | M3 | " | " | " | " |
|  | M4 | " | " | " | " |
| 6 | M1 | 625314 | 625314 | 625134 | 562314 |
|  | M2 | " | 625134 | 652134 | 526314 |
|  | M3 | " |  | , |  |
|  | M4 | " | " | " | " |

Table 4.6 Schedules for the static flow shop due-date problems

| Example number | Performance measure | Heuristic H1 | Heuristic H2 | SLACK | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | m.s. | 71 | 71 | 87 | 68 |
|  | 1 | 39.67 | 39.67 | 40.5 | 39.5 |
|  | c | *12.5 | *12.5 | 22.5 | 19 |
| 2 | m.s. | 70 | 70 | 88 | 72 |
|  | , | 48.33 | 48.33 | 49 | 51.67 |
|  | c | *65.5 | *65.5 | 66 | 89.5 |
| 3 | m.s. | 67 | 73 | 76 | 60 |
|  | 1 | 43.17 | 42.83 | 44.5 | 43.67 |
|  | c | 73.5 | *70.5 | 83.5 | 81.5 |
| 4 | m.s. | 70 | 76 | 70 | 68 |
|  | 1 | 44.17 | 43.17 | 42.33 | 44.33 |
|  | c | 73 | 67 | *63.5 | 78.5 |
| 5 | m.s. | 75 | 75 | 77 | 75 |
|  | 1 | 46.83 | 46.83 | 47.33 | 48 |
|  | c | *73.5 | *73.5 | 75 | 82.5 |
| 6 | m.s. | 86 | 82 | 82 | 86 |
|  | 1 | 48.33 | 45 | 46.17 | 51.33 |
|  | c | 37.5 | *17.5 | 25.5 | 55.5 |

Table 4.7 Comparative evaluation of the heuristics on the static flow shop due date problems

Total number of tests $=6$

|  |  | Heuristic <br> H 1 | Heuristic <br> H 2 | SLACK | SIP |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Number of best | m.s. | 2 | 3 | 1 | 4 |
| performance of | I | 2 | 4 | 1 | 1 |
|  | c | 3 | 5 | 1 | 0 |
|  |  |  | 2.42 | 3.33 | ${ }^{* * 1.92}$ |
| Ranking | m.s. | 2.33 | $* * 1.58$ | 2.83 | 3.33 |
|  | I | 2.25 | $* 1.417$ | 2.833 | 3.667 |
|  | c | 2.083 |  |  |  |

Table 4.8 Ranking of heuristics on static flow shop due date problems

| $\begin{gathered} \mathrm{Job} \\ \text { j } \end{gathered}$ | Sequence of operations <br> machine number) | Duration of operations | Total mean processing time $\sum_{k=1}^{5} p_{j, k}$ | Due-date $d_{j}=1.5 \times \sum_{k=1}^{5} p_{j, k}$ |
| :---: | :---: | :---: | :---: | :---: |
|  | $\begin{aligned} & 41416 \\ & 2 \end{aligned}$ | $\begin{array}{rrrrr} 3 & 4 & 11 & 3 & 1 \\ 5 & & & \end{array}$ | 22.5 | 33.75 |
| 2 | 31236 | 971241 | 33 | 49.5 |
| 3 | $\begin{aligned} & 54546 \\ & 12 \end{aligned}$ | $\begin{array}{llll} 811 & 13 & 5 & 1 \\ & 15 & 14 & \end{array}$ | 40.5 | 60.75 |
| 4 | $\begin{array}{rl} 2 & 3 \\ 4 & 25 \end{array}$ | $\begin{array}{lllll} 5 & 21 & 11 & 6 & 1 \\ 16 & 7 & & \end{array}$ | 39.5 | 59.25 |
| 5 | 31426 | 47271 | 21 | 31.5 |
| 6 | $\begin{array}{lllll} \hline 2 & 1 & 4 & 2 & 6 \\ 5 & 3 & 5 \end{array}$ | $\begin{array}{lllll} \hline 5 & 5 & 24 & 8 & 1 \\ 2 & 10 & 25 & \end{array}$ | 44.5 | 66.75 |
| 7 | $\begin{array}{lllll} \hline 3 & 4 & 3 & 4 & 6 \\ 1 & 5 & 1 & 5 & \end{array}$ | $\begin{array}{ccccc} \hline 6 & 6 & 7 & 9 & 1 \\ 9 & 8 & 5 & 10 \end{array}$ | 31 | 46.5 |

Table 4.9 Data for static FMS due date problem ( CASE 1, example 6)
Note : Alternative routing is permissible for some jobs, e.g. job 1 has two options in its second operation.

Job sequence (J.S.) on each machine and operation schedule (O.S.) for each job

| Example number |  |  | Heuristic H1 | $\begin{gathered} \text { Heuristic } \\ \mathrm{H} 2 \end{gathered}$ | SLACK | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M1 | 6523 | $\longleftarrow$ | $\longleftarrow$ | 6532 |
|  |  | M2 | 41273 | $\longleftarrow$ | - | 41372 |
|  |  | M3 | 274 |  |  | 724 |
|  | J.S. | M4 | 1546 | 1564 | 1546 | 5146 |
|  |  | M5 | 63157 |  | 63175 | 63157 |
| 1 |  | M6 | 1524673 | 6152473 | 1246573 | 1546372 |
| (DATA B1) |  | Job1 | 4256 |  |  |  |
|  |  | Job2 | 3126 |  |  |  |
|  |  | Job3 | 5126 |  |  |  |
|  | O.S. | Job4 | 2436 | (same as H1) | (same as H 1 ) | (same as H1) |
|  |  | Job5 | 4156 |  |  | (sameas H) |
|  |  | Job6 | 5146 |  |  |  |
|  |  | job 7 | 3526 |  |  |  |
|  |  | M1 | 632 | 6234 |  | 6532 |
|  |  | M2 | 415723 | 41527 |  | 41732 |
|  |  | M3 | 2574 | 2573 |  | 5724 |
|  | J.S. | M4 | 146 | 164 | (same as H 1 ) | $\leftarrow$ |
|  |  | M5 | 63175 |  |  | 63715 |
| 2 |  | M6 | 1675243 | 6125374 |  | 1756342 |
| (DATA B2) |  | Job1 | 4256 | $\leftarrow$ |  | $\leftarrow$ |
|  |  | Job2 | 3126 | $\longleftarrow$ |  | - |
|  |  | Job3 | 5126 | 5136 |  | $\leftarrow$ |
|  | O.S. | Job4 | 2436 | 2416 |  | $\leftarrow$ |
|  |  | Job5 | 3256 | $\leftarrow$ | (same as H 1 ) | 3156 |
|  |  | Job6 | 5146 | $\leftarrow$ |  |  |
|  |  | job 7 | 3526 | $\longleftarrow$ |  | $\leftarrow$ |
|  |  | M1 | 71362 |  | 71632 | 762 |
|  |  | M2 | 4572 |  | 45732 | 415732 |
|  |  | M3 | 243 |  | 24 | $\leftarrow$ |
|  | J.S. | M4 | 51476 |  | $\leftarrow$ | 154763 |
|  |  | M5 | 3651 | (same as H1) | $\leftarrow$ | 6315 |
| 3 |  | M6 | 4573162 |  | 4571632 | 4617532 |
| (DATA B3) |  | Job1 | 4156 |  | $\leftarrow$ | 4256 |
|  |  | Job2 | 3126 |  |  |  |
|  |  | Job3 | 5136 |  | 5126 | 5426 |
|  | O.S. | Job4 | 2436 | (same as H1) | $\longleftarrow$ | $\leftarrow$ |
|  |  | Job5 | 4256 |  | $\leftarrow$ | $\leftarrow$ |
|  |  | Job6 | 5146 |  | $\longleftarrow$ | $\leftarrow$ |
|  |  | job 7 | 1426 |  | - | $\leftarrow$ |

Table 4.10 Schedules for the static FMS due date problems (CASE 1)

|  |  | M1 | 6234 |  | $\leftarrow$ | $\leftarrow$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M2 | 136247 |  | 136274 | 136247 |
|  |  | M3 | 752 |  | $\longleftarrow$ |  |
|  | J.S. | M4 | 154 | (same as H 1 ) | $\longleftarrow$ | 514 |
|  |  | M5 | 36157 |  | 36175 | 36157 |
| 4 |  | M6 | 1652347 |  | 1623574 | 1652347 |
| (DATA B4) |  | Job1 | 4256 |  |  |  |
|  |  | Job2 | 1326 |  |  |  |
|  |  | Job3 | 5216 |  |  |  |
|  | O.S. | Job4 | 4216 | (same as H1) | (same as H1) | (same as H 1 ) |
|  |  | Job5 | 4356 |  |  |  |
|  |  | Job6 | 1526 |  |  |  |
|  |  | job 7 | 3526 |  |  |  |
|  |  | M1 | 35121 |  |  | 563241 |
|  |  | M2 | 4634562 |  |  | 645612 |
|  |  | M3 | 72762 |  |  | 7272 |
|  | J.S. | M4 | 1547531 | (same as H1) | (same as H 1 ) | 5156431 |
|  |  | M5 | 3764 |  |  | 37734 |
| 5 |  | M6 | 7354612 |  |  | 5764312 |
| (DATA C1) |  | Job1 | 41416 |  |  | 42416 |
|  |  | Job2 | 31236 |  |  |  |
|  |  | Job3 | 51246 |  |  | 51546 |
|  | O.S. | Job4 | 24256 | (same as H 1 ) | (same as H1) | 24156 |
|  |  | Job5 | 41426 |  |  |  |
|  |  | Job6 | 23526 |  |  | 21426 |
|  |  | job 7 | 35346 |  |  | 35356 |
|  |  | M1 | 15231 | 152134 | 15231 | 65321 |
|  |  | M2 | 425436 | 45236 | 424536 | 414562 |
|  |  | M3 | 527672 |  | $\leftarrow$ | 57272 |
|  | J.S. | M4 | 145173 | 115473 | 141573 | 1457173 |
|  |  | M5 | 36764 |  |  | 63643 |
| 6 |  | M6 | 1527436 | 1527346 | 1275436 | 5416732 |
| (DATA C2) |  | Job1 | 41416 | $\longleftarrow$ |  | 42416 |
|  |  | Job2 | 31236 | $\leftarrow$ |  | $\leftarrow$ |
|  |  | Job3 | 51246 | $\longleftarrow$ |  | 51546 |
|  | O.S. | Job4 | 24256 | 24156 | (same as H1) | $\leftarrow$ |
|  |  | Job5 | 31426 | $\leftarrow$ |  | $\leftarrow$ |
|  |  | Job6 | 53526 | $\longleftarrow$ |  | 51526 |
|  |  | job 7 | 35346 | $\leftarrow$ |  | 34346 |

Table 4.10 ( continued)

|  |  | M1 | 127614 |  | 127164 | 162714 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M2 | 456256 |  | 452656 | 6453265 |
|  |  | M3 | 275425 |  | 275452 | 257452 |
|  | J.S. | M4 | 13173 | (same as H 1 ) | $\longleftarrow$ |  |
|  |  | M5 | 37364 |  | $\longleftarrow$ | 3764 |
| 7 |  | M6 | 1273546 |  | 1732546 | 1734265 |
| (DATA C3) |  | Job1 | 41416 |  |  | $\leftarrow$ |
|  |  | Job2 | 31236 |  |  | $\leftarrow$ |
|  |  | Job3 | 54546 |  |  | 54246 |
|  | O.S. | Job4 | 23156 | (same as H 1 ) | (same as H1) | $\leftarrow$ |
|  |  | Job5 | 32326 |  |  | $\leftarrow$ |
|  |  | Job6 | 21526 |  |  | $\leftarrow$ |
|  |  | job 7 | 35146 |  |  | $\leftarrow$ |
|  |  | M1 | 1621 | $\leftarrow$ | 1261 | 1621 |
|  |  | M2 | 6454265 | 6456254 | 6452564 | 6454625 |
|  |  | M3 | 2574572 | $\leftarrow$ | $\longleftarrow$ | $\leftarrow$ |
|  | J.S. | M4 | 171373 | - | 1713673 | 171373 |
|  |  | M5 | 3634 | $\leftarrow$ | 334 | 3634 |
| 8 |  | M6 | 1627453 | 1625734 | 1526734 | 1672453 |
| (DATA C4) |  | Job1 | 41416 |  | $\longleftarrow$ |  |
|  |  | Job2 | 31236 |  | $\longleftarrow$ |  |
|  |  | Job3 | 54546 | (same as H1) | $\longleftarrow$ | (same as H 1) |
|  | O.S. | Job4 | 23256 |  | $\leftarrow$ |  |
|  |  | Job5 | 32326 |  | $\leftarrow$ |  |
|  |  | Job6 | 21526 |  | 21426 |  |
|  |  | job 7 | 34346 |  |  |  |

Table 4.10 ( continued)

| Example | $n \times N O P$ |  | Heuristic H1 | Heuristic H2 | SLACK | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $7 \times 4$ | m.s. | 42 | 42 | 41 | 45 |
|  |  | 1 | 28.43 | 27.71 | 28.71 | 30.71 |
|  |  | c | 7.8 | *3.5 | 8 | 26 |
| 2 | $7 \times 4$ | m.s. | 78 | 77 | 78 | 72 |
|  |  | 1 | 60.71 | 55.14 | 60.71 | 54.43 |
|  |  | c | 37.3 | *16.3 | 37.3 | 23.8 |
| 3 | $7 \times 4$ | m.s. | 92 | 92 | 92 | 69 |
|  |  | 1 | 47.14 | 47.14 | 47.43 | 45 |
|  |  | c | 23.5 | 23.5 | 24.3 | *9.5 |
| 4 | $7 \times 4$ | m.s. | 38 | 38 | 43 | 38 |
|  |  | I | 26 | 26 | 27.57 | 26.57 |
|  |  | c | *2.8 | *2.8 | 6.3 | *2.8 |
| 5 | $7 \times 5$ | m.s. | 80 | 80 | 80 | 74 |
|  |  | 1 | 50.57 | 50.57 | 50.57 | 49 |
|  |  | c | *5 | *5 | *5 | 11.5 |
| 6 | $7 \times 5$ | m.s. | $74$ |  |  | 64 |
|  |  | I | 53.57 | 46.57 | 55 | 49.71 |
|  |  | c | 35 | *1.8 | 46 | 36.8 |
| 7 | $7 \times 5$ | m.s. | 61 | 61 |  | 56 |
|  |  | 1 | 42.86 | 42.86 | 45.86 | 41.86 |
|  |  | c | *1.3 | *1.3 | 14.3 | 13.8 |
| 8 | $7 \times 5$ | m.s. | 37 | 44 | 42 | 37 |
|  |  | 1 | 31.14 | 31.14 | 30.71 | 31.14 |
|  |  | c | 20.3 | *14 | 14.5 | 19.3 |

Table 4.11 Comparative evaluation of the heuristics on the static FMS due date problems ( CASE 1)

Total number of tests $=8$

|  |  | Heuristic H1 | Heuristic H2 | SLACK | SIP |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Number of best | m.s. | 2 | 2 | 1 | 6 |
| performance of | 1 | 1 | 3 | 1 | 4 |
|  | c | 3 | 7 | 1 | 2 |
| Ranking | m.s. | 2.688 | 2.5 | 3.125 | ${ }^{* * 1.688}$ |
|  | I | 2.625 | 2.063 | 3.313 | ${ }^{* * 2.0}$ |
|  | c | 2.438 | $* * 1.5$ | 3.313 | 2.75 |

Table 4.12 Ranking for the heuristics on the static FMS due date problems (CASE 1)


Table 4.13 Schedules for the static FMS due date problems (CASE 2 )

|  |  | M1 | 6234 |  | $\longleftarrow$ | $\leftarrow$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M2 | 136247 |  | 136274 | 136247 |
|  |  | M3 | 752 |  |  |  |
|  | J.S. | M4 | 154 | (same as H 1 ) | $\longleftarrow$ | 514 |
|  |  | M5 | 36157 |  | 36175 | 36157 |
| 4 |  | M6 | 1652347 |  | 1623574 | 1652347 |
| (DATA B4) |  | Job1 | 4256 |  |  |  |
|  |  | Job2 | 1326 |  |  |  |
|  |  | Job3 | 5216 |  |  |  |
|  | O.S. | Job4 | 4216 | (same as H 1 ) | (same as H1) | (same as H 1 ) |
|  |  | Job5 | 4356 |  |  |  |
|  |  | Job6 | 1526 |  |  |  |
|  |  | job 7 | 3526 |  |  |  |
|  |  | M1 | 35121 |  |  | 563241 |
|  |  | M2 | 4634562 |  |  | 645612 |
|  |  | M3 | 72762 |  |  | 7272 |
|  | J.S. | M4 | 1547531 | (same as H 1 ) | (same as H 1 ) | 5156431 |
|  |  | M5 | 3764 |  |  | 37734 |
| 5 |  | M6 | 7354612 |  |  | 5764312 |
| (DATA C1) |  | Job1 | 41416 |  |  | 42416 |
|  |  | Job2 | 31236 |  |  |  |
|  |  | Job3 | 51246 |  |  | 51546 |
|  | O.S. | Job4 | 24256 | (same as $\mathrm{H}^{\prime}$ ) | (same as H 1 ) | 24156 |
|  |  | Job5 | 41426 |  |  | $\leftarrow$ |
|  |  | Job6 | 23526 |  |  | 21426 |
|  |  | job 7 | 35346 |  |  | 35356 |
|  |  | M1 | 153712 | 151234 | 15321 | 65321 |
|  |  | M2 | 44526 | 45236 | 44526 | 414562 |
|  |  | M3 | 57262 | 572672 | 527672 | 57272 |
|  | J.S. | M4 | 145173 | 115473 | 141573 | 1457173 |
|  |  | M5 | 367346 | 36764 | 367634 | 63643 |
| 6 |  | M6 | 1574326 | 1527436 | 1572634 | 5416732 |
| (DATA C2) |  | Job1 | 41416 | $\leftarrow$ | $\longleftarrow$ | 42416 |
|  |  | Job2 | 31236 | $\leftarrow$ | $\longleftarrow$ | $\leftarrow$ |
|  |  | Job3 | 51546 | 51246 | 51546 | $\leftarrow$ |
|  | O.S. | Job4 | 24256 | 24156 | 24256 | - |
|  |  | Job5 | 31426 | $\ldots$ | $\longleftarrow$ | $\leftarrow$ |
|  |  | Job6 | 53526 | $\leftarrow$ | $\longleftarrow$ | 51526 |
|  |  | job 7 | 35146 | 35346 | $\longleftarrow$ | 34346 |

Table 4.13 ( continued)

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|  |  | M1 | 127614 |  | 127164 | 162714 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M2 | 456256 |  | 452656 | 6453265 |
|  |  | M3 | 275425 |  | 275452 | 257452 |
|  | J.S. | M4 | 13173 | (same as H 1 ) | $\longleftarrow$ |  |
|  |  | M5 | 37364 |  |  | 3764 |
| 7 |  | M6 | 1273546 |  | 1732546 | 1734265 |
| (DATA C3) |  | Job1 | 41416 |  |  | $\leftarrow$ |
|  |  | Job2 | 31236 |  |  |  |
|  |  | Job3 | 54546 |  |  | 54246 |
|  | O.S. | Job4 | 23156 | (same as H 1 ) | (same as H 1 ) | $\leftarrow$ |
|  |  | Job5 | 32326 |  |  | $\leftarrow$ |
|  |  | Job6 | 21526 |  |  | $\leftarrow$ |
|  |  | job 7 | 35146 |  |  | $\leftarrow$ |
|  |  | M1 | 1621 | $\leftarrow$ | 1261 | 1621 |
|  |  | M2 | 6454265 | 6456245 | 6452465 | 6454625 |
|  |  | M3 | 2574572 |  | 2574752 | 2574572 |
|  | J.S. | M4 | 171373 | $\leftarrow$ | 1713673 | 171373 |
|  |  | M5 | 3634 |  | 334 | 3634 |
| 8 |  | M6 | 1627453 | 1627354 | 1267453 | 1672453 |
| (DATA C4) |  | Job1 | 41416 |  | $\leftarrow$ |  |
|  |  | Job2 | 31236 |  | $\longleftarrow$ |  |
|  |  | Job3 | 54546 | (same as H1) | $\leftarrow$ | (same as H1) |
|  | O.S. | Job4 | 23256 |  | $\leftarrow$ |  |
|  |  | Job5 | 32326 |  |  |  |
|  |  | Job6 | 21526 |  | 21426 |  |
|  |  | job 7 | 34346 |  | $\longleftarrow$ |  |

Table 4.13 ( continued)

| Example | $n \times N O P$ |  | Heuristic H1 | Heuristic H2 | SLACK | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $7 \times 4$ | $\begin{aligned} & \hline \text { m.s. } \\ & \text { I } \\ & c \end{aligned}$ | $\begin{aligned} & \hline 42 \\ & 28.43 \\ & 21.3 \end{aligned}$ | $\begin{aligned} & \hline 42 \\ & 27.71 \\ & * 14.6 \end{aligned}$ | $\begin{aligned} & \hline 41 \\ & 28.71 \\ & 22.5 \end{aligned}$ | $\begin{aligned} & \hline 45 \\ & 30.71 \\ & 38 \end{aligned}$ |
| 2 | $7 \times 4$ | $\begin{aligned} & \hline \text { m.s. } \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 72 \\ & 55.14 \\ & 37.2 \end{aligned}$ | $\begin{aligned} & 78 \\ & 54.29 \\ & * 32.3 \end{aligned}$ | $\begin{aligned} & \hline 80 \\ & 64.43 \\ & 95.7 \end{aligned}$ | $\begin{aligned} & 72 \\ & 54.43 \\ & 43.7 \end{aligned}$ |
| 3 | $7 \times 4$ | $\begin{aligned} & \hline \mathrm{m} . \mathrm{s} . \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 69 \\ & 45.57 \\ & * 21.3 \end{aligned}$ | $\begin{aligned} & 69 \\ & 45.57 \\ & * 21.3 \end{aligned}$ | $\begin{aligned} & 92 \\ & 47.43 \\ & 48.7 \end{aligned}$ | $\begin{aligned} & 69 \\ & 45 \\ & 21.7 \end{aligned}$ |
| 4 | $7 \times 4$ | $\begin{aligned} & \hline \text { m.s. } \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 38 \\ & 26 \\ & { }^{7} 7.5 \end{aligned}$ | $\begin{aligned} & \hline 38 \\ & 26 \\ & { }^{7} 7.5 \end{aligned}$ | $\begin{aligned} & 43 \\ & 27.57 \\ & 17.6 \end{aligned}$ | $\begin{aligned} & 38 \\ & 26.57 \\ & 9.3 \end{aligned}$ |
| 5 | $7 \times 5$ | $\begin{gathered} \mathrm{m} . \mathrm{s} . \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 80 \\ & 50.57 \\ & * 26.1 \end{aligned}$ | $\begin{aligned} & 80 \\ & 50.57 \\ & * 26.1 \end{aligned}$ | $\begin{aligned} & 80 \\ & 50.57 \\ & * 26.1 \end{aligned}$ | $\begin{aligned} & 74 \\ & 49 \\ & 34.6 \end{aligned}$ |
| 6 | $7 \times 5$ | $\begin{aligned} & \hline \text { m.s. } \\ & \mathrm{I} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & \hline 82 \\ & 52 \\ & 67.4 \end{aligned}$ | $\begin{aligned} & \hline 66 \\ & 47.29 \\ & * 36.7 \end{aligned}$ | $\begin{aligned} & 74 \\ & 56.57 \\ & 94.4 \end{aligned}$ | $\begin{aligned} & \hline 64 \\ & 49.71 \\ & 65.6 \end{aligned}$ |
| 7 | $7 \times 5$ | $\begin{gathered} \text { m.s. } \\ 1 \\ c \end{gathered}$ | $\begin{aligned} & 61 \\ & 42.86 \\ & * 21.7 \end{aligned}$ | $\begin{aligned} & \hline 61 \\ & 42.86 \\ & * 21.7 \end{aligned}$ | $\begin{aligned} & 65 \\ & 45.86 \\ & 41.2 \end{aligned}$ | $\begin{aligned} & \hline 56 \\ & 41.86 \\ & 27.2 \end{aligned}$ |
| 8 | $7 \times 5$ | $\begin{gathered} \mathrm{m} . \mathrm{s} . \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 37 \\ & 31.14 \\ & 38.1 \end{aligned}$ | $\begin{aligned} & 39 \\ & 31.14 \\ & 38 \end{aligned}$ | $\begin{aligned} & 37 \\ & 30.57 \\ & * 35 \end{aligned}$ | $\begin{aligned} & 37 \\ & 31.14 \\ & 38 \end{aligned}$ |

Table 4.14 Comparative evaluation of the heuristics on the static FMS due date problems (CASE 2 )

Total number of tests $=8$

|  |  | Heuristic H1 | Heuristic H2 | SLACK | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Number of best performance of | m.s. | 4 | 2 | 2 | 7 |
|  | 1 | 1 | 4 | 1 | 3 |
|  | c | 4 | 7 | 2 | 0 |
| Ranking | m.s. | 2.438 | 2.625 | 3.125 | **1.813 |
|  | 1 | 2.563 | **1.938 | 3.375 | 2.125 |
|  | c | 2.188 | **1.5 | 3.25 | 3.063 |

Table 4.15 Ranking for the heuristics on the static FMS due date problems (CASE 2)

Total number of tests $=16$

|  |  | Heuristic H 1 | Heuristic H2 | SLACK | SIP |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Number of best | m.s. | 6 | 4 | 3 | 13 |
| performance of | 1 | 2 | 7 | 2 | 7 |
|  | c | 7 | 14 | 3 | 2 |
| Ranking | m.s. | 2.563 | 2.563 | 3.125 | $* * 1.75$ |
|  | 1 | 2.594 | $* * 2.0$ | 3.344 | 2.063 |
|  | c | 2.313 | $* 1.5$ | 3.282 | 2.906 |

Table 4.16 Summary of performance of the heuristics on the static FMS due date problems

| Example | $n \times N O P$ | Heuristic H 1 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $d_{j}=1$ | $p_{j, k}$ | $\mathrm{d}_{\mathrm{j}}=1.3 \times \sum_{\mathrm{k}=1}^{\mathrm{K}_{\mathrm{j}}} \mathrm{p}_{\mathrm{j}, \mathrm{k}}$ |  |
|  |  | m.s. | 1 | m.s. | 1 |
| 1 | $7 \times 4$ | 42 | 28.43 | 42 | 28.43 |
| 2 | $7 \times 4$ | 78 | 60.71 | 72 | 55.14 |
| 3 | $7 \times 4$ | 92 | 47.14 | 69 | 45.57 |
| 4 | $7 \times 4$ | 38 | 26 | 38 | 26 |
| 5 | $7 \times 5$ | 80 | 50.57 | 80 | 50.57 |
| 6 | $7 \times 5$ | 74 | 53.57 | 82 | 52 |
| 7 | $7 \times 5$ | 61 | 42.86 | 61 | 42.86 |
| 8 | $7 \times 5$ | 37 | 31.14 | 37 | 31.14 |
| Total |  | 502 | 340.42 | *481 | *331.71 |

Table 4.17 Comparative study on different due date assumptions with heuristic H 1

| Example | $n \times N O P$ | Heuristic H2 |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $d_{j}=1.5 \times \sum_{k=1}^{k_{j}} p_{j, k}$ |  | $d_{j}=1.3 \times \sum_{k=1}^{k_{j}} p_{j, k}$ |  |
|  |  | m.s. | 1 | m.s. | 1 |
| 1 | $7 \times 4$ | 42 | 27.71 | 42 | 27.71 |
| 2 | $7 \times 4$ | 77 | 55.14 | 78 | 54.29 |
| 3 | $7 \times 4$ | 92 | 47.14 | 69 | 45.57 |
| 4 | $7 \times 4$ | 38 | 26 | 38 | 26 |
| 5 | $7 \times 5$ | 80 | 50.57 | 80 | 50.57 |
| 6 | $7 \times 5$ | 63 | 46.57 | 66 | 47.29 |
| 7 | $7 \times 5$ | 61 | 42.86 | 61 | 42.86 |
| 8 | $7 \times 5$ | 44 | 31.14 | 39 | 31.14 |
| Total |  | 497 | 327.13 | *473 | *325.43 |

Table 4.18 Comparative study on different due date assumptions with heuristic H 2
CHAPTER 5 : APPROXIMATE METHODS FOR MINIMUM MAKESPAN AND AVERAGE LEAD TIME PROBLEMS
5.1 Phase 1 : Assumption of Due-Dates
5.1.1 An example problem
5.1.2 Application of heuristics to static flow shop problems
5.2 Phase 2 : Modification of Due-Dates
5.2.1 Solution improvements in static flow shop problems
5.2.2 Comparative study
5.3 Application For The Static FMS
5.3.1 An FMS example problem
5.3.2 Evaluation of heuristics on static FMS
5.3.2.1 makespan analysis
5.3.2.2 lead time analysis
5.4 Approximate Methods For Dynamic SchedulingProblems
5.4.1 Dynamic FMS with due-date problem
5.4.2 Dynamic FMS with makespan and average lead time problems

## 5 APPROXIMATE METHODS FOR MINIMUM MAKESPAN AND AVERAGE LEAD TIME PROBLEMS

As economies grow and societies become affluent, the desire of the individual to possess special goods different from those of other people rises, and the demand for specially ordered products increases, while the life cycle of these products decreases. This tendency results in a wide variety of products with low volume. In addition, lead time from the receipt of the order to the shipment of the product is expected to be as small as possible in order to win in a competitive situation. Furthermore, if the manufacturing lead times can be reduced, a variety of products can be delivered to customers without storing a large amount of products and hence reducing the inventory cost. Therefore, lead time is a very important performance measure which must be considered in a manufacturing system.

It has been mentioned in the previous chapter that the makespan and average lead time determined from the heuristics are highly dependent on the assumptions of due dates. Since the entire heuristical scheduling mechanism depends on the proposed due date values, therefore, determination of the optimal values of these due dates associated with the minimum makespan and minimum average lead time are carried out in this context for both static and dynamic situations.

### 5.1 Phase 1: Assumption of Due -Dates

A production schedule is to be calculated to meet defined objectives. There are four factors which need to be considered in industrial practice ( Nicholson and Pullen 1971), these are
(1) meeting due dates of the jobs,
(2) minimising work-in-progress inventory,
(3) using resources fully, and
(4) distributing the workload across the alternative resources.

The static due date problem and workload distribution for alternative resources in FMS was considered in the previous chapter. The minimisation of the work-in-progress inventories and the maximisation of the resource utilisation in an FMS are now considered. In general, the fulfilment of one factor does not automatically imply the fulfilment of the other. It has been shown previously that heuristic $\mathrm{H} 2($ Alternate Operation + Look Back heuristic ) provides good schedules for obtaining minimum cost of tardiness, but unsatisfactory values of makespan (table 4.8, table 4.12 and table 4.15). It has been pointed out by Nicholson and Pullen (1971) that the meeting of due dates may imply full use of resources if due dates are set tightly, but for static situations, reducing the makespan may also imply higher utilisation of resources. Hence a short makespan may be expected to be obtained by meeting the due dates which are set tightly. On the other hand, minimising the work-in-progress may imply minimising the lead times of jobs. However, how tight these due dates should be is not known. Therefore, it is proposed to set the due dates equal to the mean total processing times (for flow-shop or job-shop, the mean total processing times are equivalent to the earliest completion times), then determine the values of makespan and lead times by applying the heuristics.

### 5.1.1 An example problem

In order to obtain satisfactory results of the makespan and average lead time, it has been suggested that the due dates are set equal to the mean total processing times for static system. This can be illustrated by the following 6 - job, 3 - machine flow shop problem taken from Stinson and Smith (1982). Data are presented in table 5.1. For clarity, all the tables have been presented at the back of this chapter. The detail procedures of obtaining the schedules are not presented, but only the Gantt chart representation of the results are shown in figure 5.1 - figure 5.4 ( which includes the optimum schedule as well as the schedule predicted by Stinson et al.). The results are summarised in table 5.2.

In this example, the makespan is shortest if heuristic H 1 is employed as compared with heuristic H 2 and Stinson's heuristic. This method results in the job sequence of $4,5,6,1,2,3$, (figure 5.3) which is the same for all three machines. The makespan is 65 and compares well with the optimal makespan for this problem of 64 ( figure 5.1, with the sequence of $4,1,2,3,6,5$ ). The sequence obtained from Stinson et al. ( figure 5.2) which is $1,2,3,6,4,5$ had a makespan equal to 66 (but there was a typing error in the original paper such that the makespan was printed as 67). Heuristic H 2 gives the lowest value of average lead time (the average lead time from the optimal makespan sequence $4,1,2,3,6,5$ is 45 ). This is mainly due to the machine $M_{2}$ which has been forced to wait for the job 6 at $t=7$ (figure 5.4), hence job 6 has left the system with a very short lead time. Because of the machining process which has been delayed by 2 units at $M_{2}$, the makespan obtained by heuristic H 2 is 67 . This is the main disadvantage of applying heuristic H 2 , since there may be several queue jobs delayed by the look-back-job for several hours in excess


Figure 5.1 Gantt cnart of Stinson's example (optimum solution)


Figure 5.2 Gantt cnart of Stinson's example witn Stinson's neuristic


Figure 5.3 Gantt cnart of Stinson's example witn heuristic Hl


TIME

Macnine idling time due to awalting of job 6

Figure 5.4 Gantt chart of Stinson's example witn neuristic in
of the processing time alone.

### 5.1.2 Application of heuristics to static flow shop problems

In the previous example, the developed heuristics out performs Stinson's method in obtaining both makespan and average lead time. Furthermore, they have produced the best result of average lead time even compared with the given optimal schedule. In order to test the heuristics are reliable and suitable for solving the scheduling problems, and they are potentially capable of dealing with the flexible manufacturing environment, the heuristics will be applied to solve some static flow shop problems, and the results compared with the optimal solutions.

Six examples of 6 - job, 3 - machine flow shop problems are taken from Giglio and Wagner (1964). The basic manufacturing data is presented in table 5.3. The simulation results are shown in table 5.4 and table 5.5.

According to the results which have been shown in table 5.4, the optimal schedules have the same job sequence on each machine, i.e. job passing is not allowed. However, job passing is permitted for the heuristics ( $\mathrm{H}_{1}$ and H 2 ), hence job sequence on machines may be different from each other in some examples. Since the heuristics are approximate methods, it is expected that the makespans predicted by them will be longer than those calculated from the optimal schedule. However, the important thing that should be examined is the deviation of the approximate results from the optimal solutions. Therefore, the average percentage deviations of the simulation results from the
optimal solutions are presented in table 5.5. It can be observed that the percentage deviation of the makespan is less than $9 \%$. On the other hand, the heuristics give an excellent prediction of average lead time and this has been reflected by the positive percentage deviation as shown in table 5.5. If the performance of heuristic H 1 is compared to heuristic H 2 in these flow shop problems, heuristic H 1 offers a better estimation of makespan, and heuristic H 2 produces excellent results of average lead time. In examples 1, 3, 4 and 6, the job sequences obtained from heuristics H 1 and H 2 are different from each other. The deviation is mainly because of the 'look back' mechanism from heuristic H 2 . Consequently, it has been used to develop schedules with shorter lead times. However, the penalty that it has paid is a long makespan.

### 5.2 Phase 2 : Modification of Due - Dates

It has been mentioned that heuristic H 2 always produces a schedule with a long makespan which is caused by the 'look back' mechanism. In order to reduce the long makespan, rescheduling may be required, so that unnecessary machine idling time will be kept to a minimum. For the Stinson's example( see section 5.1.1), this can be done by sequencing job 6 before job 5 in its first operation on $M_{1}$. The improvement produced is shown in figure 5.5 . This modified schedule not only improves the makespan but also the average lead time, and is equivalent to increasing the utilisation of machines and decreasing the work-in-progress inventory (improved results: makespan $=66$, average lead time $=37.2$ ) .

The above modification is easy and obvious because of the simplicity of the system. For complicated systems such as job-shop with revisit of machines or FMS, it requires a considerable amount of computation to find out the effect on the performance of a system if a job has changed its position in the sequence. Since the entire heuristical scheduling mechanism depends on the proposed due date values, therefore, an alternative solution for this problem is to re-adjust the due dates, then apply the heuristic algorithms to find another schedule. It is believed that optimal or near optimal solutions may be obtained by a special choice of due dates (Gere 1966). Since the optimal values of these due dates are unknown, it is proposed that due dates are selected equal to the corresponding completion times which are calculated from the first schedule. If there is no improvement from the second schedule, then the original schedule will be retained. Otherwise, the due dates will be


Figure $\mathbf{j . 5}$ jantt chart of Stinson's example with neuristic $n 2$ and due dates adjustment
re-adjusted equal to the completion times which have been given from the second schedule. This iterative procedure is repeated until there is no further improvement of the objective measure of performance of the system. Consequently, the final proposed due dates which will produce the minimum makespan are defined as "the optimal due dates for makespan" and the due dates which give the shortest average lead time are defined as "the optimal due dates for average lead time". As it has been mentioned before, the optimal due dates for makespan are not necessarily the same as the optimal due dates for average lead time.

### 5.2.1 Solution improvements in static flow shop problems

Heuristics H 1 and H 2 have been employed to solve the flow shop problems obtained from Giglio and Wagner (1964). In general, the results are good compared with the optimal solutions. In this section, the same flow shop problems are considered as before, applying both heuristics H 1 and H 2 but this time the iterative due dates adjustment method is considered.

The objectives of the iteration technique can be divided into two areas, The first one is the minimisation of makespan, and the second area is the minimisation of average lead time. These two main goals will be considered separately. Simulation results of applying the iterative procedures for the makespan and average lead time problems are presented in table 5.6 and table 5.7 respectively.

According to table 5.6, a nought appears under the column of Iteration number, this means that the corresponding makespan is
obtained from the original schedule. For the iteration number to equal one indicates the first iteration, and so on. In the last column, the optimal job sequence on each machine that has been obtained from each heuristic is presented. For example, the makespan of 68 (example 1) is obtained from heuristic H 2 with the job sequence of $4,6,5,1,2,3$ on each machine. The percentage deviation of makespan from the optimal solution is negative in each example as was expected. It can be observed that the heuristic H 2 with this iterative procedure produced three improved results out of six examples. Furthermore, this method applied has improved the average lead time in four of the examples ( see table 5.7). The average percentage deviation of makespan and average lead time from the optimal schedule are presented in table 5.8. From this table, it can be found that improved results are only as a result of applying heuristic H 2 . On the other hand, heuristic H 1 has not received any benefit from this iterative procedure of due dates adjustment when the results are compared to those in table 5.5.

Heuristic H2 works successfully together with the method of due dates adjustment because it always provides a 'time gap', which may be eliminated by the suggested method. For example, the 'time gaps' in figure 5.7 are eliminated after applying the method. The improved schedule is shown in figure 5.8. On the other hand, the job sequence obtained from heuristic H 1 is usually packed tightly as shown in figure 5.6. Therefore, improvement is difficult even when the method of due dates adjustment has been employed.

When examining the job sequences presented in table 5.6 and table 5.7 , it can be observed that they are identical to each other when


TIME

Figure j. 6 Gantt cnart of Giglio's example 4 witn neuristic Hl


TIME

Machine idling time due to awalting of job 3

韭睍 Machıne idling time due to awaiting of job 6

Figure 5.7 Gantt cnart of Giglio's example 4 with neuristic $\begin{gathered}\text { H2 }\end{gathered}$


TIME

Figure 5.8 Gantt cnart of Giglio's example 4 with neuristic H2 and due dates adjustment
heuristic H 1 is applied. This indicates that for simple flow shop scheduling problems, the best makespan as well as the shortest average lead time that have been predicted by this heuristic are determined from the same job sequence. Similarly, if only heuristic H 2 is considered, the generated job sequences always produce the shortest makespan and average lead time simultaneously, except in example 6. However, the above coincidental job sequences may not occur so frequently in other complex manufacturing environment such as FMS. Therefore, further investigation of the technique of due dates adjustment on FMS will be presented in section 5.3.

The approximate method gives reasonable results of makespan and average lead time, the required computational effort is another major attractive feature. For example, when the simulation has been run in the Cyber 855 computer system, the average execution time for heuristic H 1 is 1.82 cp second. For heuristic H 2 , it has taken into account the 'look back' mechanism, therefore the average execution time is a little longer, i.e. 2.5 cp second.

### 5.2.2 Comparative study

It was shown in the previous section that the determination of optimal makespan and optimal average lead time is equivalent to defining their corresponding optimal due dates. In this section, some of the published techniques are used to evaluate this method. Twelve problems have been examined, most of them are flow shop systems because of their widely quoted optimisation techniques in the literature. In these problems, jobs are varied from 3 to 9 , machines are varied from 3 to 5 , and one of them is a job shop problem with
revisiting of machine. Results are shown in Table 5.9 where the optimal values of makespan and average lead time obtained from the literature and the developed heuristics are given. Table 5.10 presents a comparison between the heuristics and other published methods according to two measures of performance. The first measure is the number of best performances produced by each technique, and the second measure is a simple ranking.

An examination of the performances which have been shown in Table 5.10 suggests that the heuristic H 1 and heuristic H 2 are the best performers in obtaining the makespan and the average lead time respectively. Upon this examination, it would appear that our heuristics out performed the others.

### 5.3 Application For The Static FMS

The developed heuristics have out performed the other published techniques in obtaining minimum makespan and average lead time. However, most of the examples that have been tested are flow shop problems. It is essential to consider more complicated systems such as FMS.

### 5.3.1 An FMS example problem

The basic manufacturing data obtained from lwata et al. (1978) has been presented in table 5.11. This FMS consists of three machines which produced two different part types each of a batch size equal to four. There are two alternative machines that can be scheduled for each operation of each part type. The total number of operations on each part type is equal to three, and re-visiting of machine is permitted.

The optimum makespan obtained by lwata et al. (1978) was used to compare with the other scheduling methods, i.e. the SIP rule, heuristics H 1 and H 2 . The results are presented in table 5.12. The Gantt charts for these different scheduling techniques have been shown in figure 5.9.

From the previous assumption (section 4.2.2, STEP 9), heuristic H 2 will not consider those future critical jobs which have alternative routes in their next operation. Since alternative operations existed for each process of each part type, therefore application of heuristic H 2 is equivalent to that of heuristic H 1 . Consequently, both

Figure 5.9 Scnedules of an FMS with different technıques
(a) IWATA's method


TIME
(b) Shortest Imminent Process time rule (SIP)

tIME
(c) Heuristic Hl or H2 ( objective measure $=$ minımum makespan )


TIME
(d) Heuristic H1 or H2 ( objectıve measure = mınımum average lead time )

time
Part type 1
$\square$ Part type 2
heuristics produced the same schedule in this example.

Upon examination of table 5.12, the schedule which has been obtained by Iwata et al. (1978) produced the worst measures of performance in makespan, average lead time and average machine utilisation. The reason for these unsatisfactory results is that Iwata et al. have assumed all of the parts are loaded and processed continuously as a batch ( see figure 5.9). This kind of batch processing mechanism is economical if the tool changeover time is considerably long. Otherwise, this will reduce the flexibility of production.

In this example, theoretically there are two alternative machines that can be scheduled for each operation of each job. However, due to the assumption of batch production made by Iwata et al., this flexibility can only be attained by the first job of each part type. Stecke and Solberg (1981) have mentioned that a common practice in non-automated job shops and flow shops is to assign each operation to one and only one machine and sometimes to assign to each machine only one operation. In the case of a fully developed FMS , such practices are unnecessary restrictions that can limit the system's capabilities. The versatility of the machines in an FMS allows considerable flexibility in assigning operation along with associated required tooling among machines. With the concept of group technology, the machine tools in an FMS do not require drastic changeovers in set up because of the similarity in the workpieces processed on them, Hence, set up time is saved. Thus the machines can switch from one part to another with a minimum loss of time, and it is usually negligible when compared to the processing times. The expense and capabilities of such equipment indicate the desirability
and possibilities of increased output and utilisation, as well as decreased lead time and makespan. These improved measures of performance are reflected in table 5.12.

In this analysis, the machine tool changeover time is negligible. Unlike Iwata et al., where there are two alternative machines as there are in our problem, we have considered a batch of jobs that can be subdivided among the two machine alternatives. The schedules determined by these two approaches can be seen in table 5.12 and figure 5.9. For example, when the SIP rule is applied, the operations schedule for the first job of part type 2 is $M_{2} \rightarrow M_{1} \rightarrow M_{1}$, and that for the second job of part type 2 is $M_{2} \rightarrow M_{1} \rightarrow M_{2}$ etc. As a result of the machining flexibility, these three scheduling techniques (i.e. SIP, heuristics H 1 and H 2 ) out perform the Iwata's method.

The results which have been shown in table 5.12 suggest that the heuristics produce the schedules associated with the optimal makespan and the optimal average lead time respectively. This agrees with the previous analysis of flow shop and job shop problems.

Upon examination of the machine utilisation, machine $M_{2}$ is highly utilised when the SIP rule, or heuristic H 1 or heuristic H 2 is applied. This is mainly due to the "shortest waiting time rule" being applied to solve the problem of alternative operations when the transportation time is assumed to be negligible. From the initial condition, i.e. at time $=0$, all the jobs will be transferred to station 2 due to $M_{2}$ which offers the shortest processing time for the first operation of both part 1 and part 2. Consequently, $\mathrm{M}_{2}$ is heavily loaded. In addition, $\mathrm{M}_{2}$
offers the shorter processing time when compared to $M_{3}$ in the second operation of part 1 . This means that $M_{2}$ has a relatively higher priority to process part 1 for its second operation. Furthermore, $\mathrm{M}_{2}$ is again more competitive than $M_{1}$ for processing part 2 in its last operation. As a result, $\mathrm{M}_{2}$ is highly utilised.

When the developed heuristics H 1 and H 2 are applied to optimise the makespan and the average lead time, the computational effort required for obtaining the optimal makespan is less than that necessary for determining the optimal average lead time. This is because the former objective measure requires only three iterations, but the latter one needs five in order to make it converge to the optimal value. It is expected that the SIP rule offers the shortest computing time due to its simplest dispatching algorithm.

The results of this simple FMS example show that the methods used to assign operations to machines in real time affect the performance of the system (as measured in makespan, average lead time, machine utilisation, for example).

### 5.3.2 Evaluation of heuristics on static FMS

In the previous section, each job was given an equal opportunity to select its processing path provided that the tool changeover set up time is negligible. Eventually, this assumption performs satisfactorily using the heuristics. However, only one example of FMS has been studied. In order to evaluate the heuristics in a static FMS, 16 hypothetical examples were analysed. The number of jobs varied
from 7 to 10, the number of operations varied from 4 to 6 , the number of machines was 6 for all examples. Re-visiting of machines was permissible for some of the jobs. Data will not be presented here, but it can be found in Appendix B (DATA B1 - B4), Appendix C (DATA C1 C4), Appendix D (DATA D1 - D4) and Appendix E (DATA E1 - E4). Since the optimal solutions for these examples are unknown, the results are compared with those obtained from two dispatching rules. The First In First Out (FIFO) rule and the SIP rule are employed for comparison, and it is generally accepted that the FIFO rule is the simplest rule for scheduling, whereas the SIP rule always provides a short makespan. The results are presented in table 5.13 - table 5.18 where the analysis is divided into two parts. The first part is mainly for the static FMS makespan problems (table 5.13 -table 5.15), and the second part is for the static FMS average lead time problems ( table 5.16 - table 5.18).

### 5.3.2.1 makespan analysis

For the first part of this analysis, the schedule corresponding to the optimal makespan which has been obtained from each scheduling technique is presented in table 5.13. The intermediate iterative values of makespan are shown in table 5.14. It can be observed that the methods for sequencing the jobs on each machine (called job sequencing) affect the performance of the system( as measured in the makespan here). In conventional flow shops and job shops problems, sometimes more than one optimal schedule can exist. This is also true in the case of FMS scheduling problems. For instance, the optimal makespan for example 7 is 56 which can be obtained using heuristic H 1 , heuristic H 2 , or the SIP rule ( see table 5.14). However,
if the job sequencing presented in table 5.13 is examined, it is found that the sequence of jobs determined by the SIP rule is different from the other two heuristics. For example, the job sequence on $M_{1}$ which has been obtained from heuristic H 1 or heuristic H 2 is $1,6,7,2,1,4$ but it is $1,6,2,7,1,4$ for the SIP rule. Similarly, the job sequence on $M_{3}$ obtained by the SIP rule is again different from the heuristics H 1 and H 2 . This means that more than one optimal schedule can exist. It can be observed that there is also more than one optimal schedule in example 9 and example 10. In example 9, although heuristics H 1 and $H 2$ produce different job sequences on machines $M_{4}, M_{5}$ and $M_{6}$, they have the same optimal makespan, i.e. 82. Furthermore, in example 10, heuristic H 1 and the FIFO rule offer the same optimal makespan (i.e. 84), but with different job sequence on machines $M_{1}, M_{4}, M_{5}$ and $M_{6}$. It should be stressed here that although sometimes different job sequences still provide the same makespan, the average lead times determined from each schedule will differ. This will be verified later in this section.

Considering the computational effort, the FIFO rule offers the fastest execution time due to its simplest dispatching algorithm, resulting in an average execution time of 1.55 cp second. The second fastest algorithm is the SIP rule which requires an average execution time of 1.601 cp second. When comparing the execution times which are required by both heuristics H 1 and H 2 , two factors must be considered. The first factor is the complication of the heuristic procedure, and the second one is the number of iterations necessary for each heuristic. In this study, the total number of iterations that have been computed by heuristic H 1 and heuristic H 2 are 37 and 35
respectively. However, the heuristic H 2 requires even a longer execution time ( 2.23 cp second) than heuristic H 1 ( 2.06 cp second) due to its more complicated scheduling procedure.

From table 5.14, it can be observed that the original makespan (i.e. without iteration) obtained from heuristic H 1 is always equal to that determined from the SIP rule, except in examples 15 and 16. This can be explained by analysing the initial due dates assumption which has been made by the heuristic as follows : -

At time $=0$, assuming there are 3 jobs $\left(J_{1}, J_{2}, J_{3}\right)$ awaiting to be loaded onto machine $M$. Let the processing times of $J_{1}, J_{2}$ and $J_{3}$ are $p_{1,1}, p_{2,1}$ and $p_{3,1}$ respectively, where it is assumed that $p_{1,1}<p_{2,1}<$ $p_{3,1}$.

## The SIP rule

When this rule is applied, the job sequence on the machine $M$ will be $J_{1}$ first, $J_{2}$ the second and the last $J_{3}$.

## The heuristic H1

When this heuristic is employed, due dates will be assumed equal to their corresponding mean total processing time,

$$
K_{1}
$$

i.e. $\quad d_{1}=\sum_{k=1} p_{1, k}$

$$
d_{2}=\sum_{k=1}^{k_{2}} p_{2, k}
$$

$$
d_{3}=\sum_{k=1}^{k_{3}} p_{3, k}
$$

The slack time for each job is, $\mathrm{K}_{1}$

$$
S_{1}=d_{1}-\sum_{k=1} p_{1, k}-t
$$

$$
S_{2}=d_{2}-\sum_{k=1}^{k_{2}} p_{2, k}-t
$$

$$
\mathrm{K}_{3}
$$

$$
S_{3}=d_{3}-\sum_{k=1} p_{3, k}-t
$$

$\therefore \mathrm{S}_{1}=\mathrm{S}_{2}=\mathrm{S}_{3}=0($ at $\mathrm{t}=0)$
If job 1 is assumed to be loaded onto the machine, then
$S_{1}=0$
$S_{2}=0-p_{1,1}$
$S_{3}=0-p_{1,1}$
If the cost per unit lateness for any job is equal to unity, then

Total cost of lateness with job 1 being loaded onto the machine $=2 p_{1,1}$

Similarly, the following results are obtained :
Total cost of lateness with job 2 being loaded onto the machine $=2 p_{2,1}$

Total cost of lateness with job 3 being loaded onto the machine $=2 p_{3,1}$

Obtain $2 p_{1,1}<2 p_{2,1}<2 p_{3,1}$
By comparing the cost of lateness, job 1 will be actually loaded onto the machine, then followed by job 2 and job 3 . This is exactly the same sequence which has been determined by the SIP rule. Therefore, the makespan which is calculated from heuristic H 1 (without iteration) will be most likely to match the makespan which obtained from the SIP rule.

From table 5.14, it can be observed that heuristic H 1 with the iteration procedure improves the makespan values. There are five improvements in this analysis( examples 1, 5, 8, 10 and 11 ). In general, heuristic H 1 performs as good as the SIP rule, but usually it out performs the SIP rule.

The ranking analysis of the heuristics are shown in table 5.15 . It can be seen that heuristic H 1 ranks highest (i.e. best) again in the analysis of the makespan. In addition, it provides 11 times the minimum makespan in 16 tests. These concluding results are similar to those obtained from the previous comparison of the heuristics with other published methods as recorded in table 5.10. Therefore, heuristic H 1 is a promising algorithm to solve the static makespan problem in both dedicated and flexible manufacturing environments.

### 5.3.2.2 lead time analysis

Considering the second part of this analysis, the schedule corresponding to the optimal average lead time which has been determined from each scheduling technique is presented in table 5.16.

The intermediate iterative values of average lead time are shown in table 5.17.

In this lead time analysis, there is also more than one optimal schedule in some examples. For instance, the optimal average lead time for example 8 is 30.57 which can be obtained from heuristic H 1 , or heuristic H 2 ( see table 5.17 ). However, by examinaton of the job sequence as well as the operations schedule which have been presented in table 5.16, it can be found that these two heuristics result in different predictions. In example 8, the operations schedules on job 5 and job 6 are $M_{3} \rightarrow M_{2} \rightarrow M_{3} \rightarrow M_{2} \rightarrow M_{6}$ and $M_{2} \rightarrow M_{1} \rightarrow M_{4} \rightarrow M_{2} \rightarrow M_{6}$ respectively, as predicted by heuristic $H 1$. However, the operations schedules of these two jobs which have been obtained by heuristic $\mathrm{H}_{2}$ are $\mathrm{M}_{3} \rightarrow \mathrm{M}_{2} \rightarrow \mathrm{M}_{4} \rightarrow \mathrm{M}_{2} \rightarrow \mathrm{M}_{6}$ and $M_{2} \rightarrow M_{1} \rightarrow M_{5} \rightarrow M_{2} \rightarrow M_{6}$. Furthermore, the job sequence on each machine depends on which heuristic is used. Similarly, in example 8, the FIFO rule and the SIP rule give different configurations in both the job sequence and operations schedule, but they produce the same value of average lead time. Furthermore, example 11 also provides two different optimal schedules for obtaining the optimal average lead time. Here only the job sequences on machines $M_{3}$ and $M_{6}$ are different when they are calculated by heuristics H 1 and H 2 .

It has already mentioned that the same makespan can be obtained from two different schedules, but the same value of average lead time is not guaranteed. According to table 5.13 and table 5.14, in the example 7, the optimal makespan is 56 which has been determined by two different schedules obtained from heuristic H 1 and the SIP rule.

However, the corresponding average lead times are 41.71 and 41.86 shown in table 5.17. Similarly, the optimal makespan in example 9 is 82 which can be calculated by applying heuristic H 1 , heuristic H 2 or the SIP rule. However, the corresponding average lead times are 59, 57.57 and 59 ( see table 5.17 ). Obviously, the schedule which should be selected is the one which provides both the optimal makespan as well as the shortest average lead time.

Considering the computing time required to solve those static FMS average lead time problems, the FIFO rule and the SIP rule again rank highest. Since the average lead time is obtained from the same simulation which has been computed to give the makespan, the average execution time is exactly the same as in the makespan problem, i.e. 1.55 cp second for the FIFO rule, and 1.601 cp second for the SIP rule. On the other hand, the execution times required by heuristics H 1 and H 2 will depend on the number of iterations necessary to converge to the optimal value. The average execution times which have been used by heuristic H 1 and heuristic H 2 are 2.501 cp second and 2.689 cp second respectively. They are both greater than those required for obtaining the optimal makespans. This is mainly due to the fact that the number of iterations which have been computed to provide the optimal average lead times is more than that necessary to provide the optimal makespans. In this optimal average lead time analysis, the total number of iterations computed by either heuristic H 1 or heuristic H 2 is 43 , which is more than the previous requirement (i.e. 37 and 35 iterations for heuristic H 1 and heuristic H 2 respectively).

In the makespan analysis, it has already mentioned that most of the
makespans predicted by the SIP rule are equal to the original makespan ( i.e. without iteration) computed from the heuristic H 1 . Similarly, here only examples 5, 7, 15 and 16 give different original average lead times (see table 5.17). It can be observed that heuristic H 1 with the iterative procedure improves the average lead time in seven examples, i.e. examples 1, 4, 8, 9, 10, 11 and 12.

The ranking analysis of these scheduling techniques are shown in table 5.18. It is found that heuristic H 2 produces excellent results again. It ranks highest in the analysis of the average lead time, and it also provides 13 times the minimum average lead time out of 16 tests. This result agrees with the previous analysis of flow shops and job shops problems. Hence heuristic H 2 is a promising algorithm to solve the static average lead time problem in both dedicated and flexible manufacturing environments.

In the process of iteration, computation will be stopped whenever there is no further improvement of the desired performance measure ( i.e. either makespan or average lead time). This stopping criterion helps the heuristics to provide competitive execution time as well as the best measure of performance. These have been already verified in this chapter. However, there is no guarantee that further improved results will not appear in the next further iterations. From table 5.14 ( example 10 ), the makespan obtained from heuristic H 1 is 89 after the first iteration. According to the assumed stopping criterion, this should be the best result that can be achieved by heuristic H 1 . Actually, the computation will be stopped after the first iteration with a makespan of 89. However, in the analysis of average lead time problems as presented in table 5.17, the computation is extended and
it has been terminated after the second iteration in the same example. The average lead time in this iteration is found to be 57.29 with a makespan of 84 which is better than before. For this example, it should be noted that the optimal makespan (i.e. 84) appearing under the heuristic H 1 is actually obtained during the consideration of optimal average lead time. Alternatively, it can be obtained by relaxing the stopping criterion. This can be done by terminating the simulation if there is no further improvement of the desired objective measure within a pre-determined number of iterations.

It has been mentioned that two different schedules may provide the same makespan, but different in the average lead time. If the objective measure of performance is the makespan, then the one which offers the optimal makespan as well as the shortest average lead time should be selected. For instance, in example 9, although heuristic H 1 , heuristic H 2 and the SIP rule predict the same optimal makespan ( see table 5.14 ), heuristic H 2 is selected due to its better performance in the examination of the average lead time ( see table 5.17 ). This is reflected by the average lead time values obtained in the second iteration, i.e. 55 ( from H 1 ), 54.86 ( from H 2 ) and 59 ( from the SIP rule ). Similarly, if the objective performance measure is the average lead time, then the optimal schedule should be the one which offers the minimum average lead time. In the case of a tie, the schedule which also provides the shortest makespan will be chosen. For instance, in example 8, the optimal average lead time is 30.57 which can be determined from either heuristic H 1 or heuristic H 2 . As a result, heuristic H 1 is selected due to its better performance in the analysis of makespan, i.e. 36 from heuristic H 1 , and 38 from heuristic H 2 .

In this chapter, optimal makespan and average lead time are determined by applying the heuristics associated with the corresponding optimal due dates. These optimal due dates can be obtained iteratively through simulations. If the due dates are pre-determined, one might suspect that the values of due dates would affect the system performance ( i.e. makespan and average lead time). In the last section of chapter 4, it was mentioned that better system performance can be obtained from the tighter due date assumption. Therefore, it is necessary to make a comparison between the results which have been determined from the optimal due dates with those calculated from the pre-determined due dates. Here eight examples are analysed, the comparisons have been shown in table 5.19 and table 5.20. Since these eight examples have already been considered before, the results can be extracted from previous tables ( see tables $4.17,4.18,5.14$ and 5.17 ). The results of this comparison suggest that the heuristics with the corresponding optimal due dates out perform the pre-determined due date assumption in obtaining the schedules associated with minimum makespan and minimum average lead time.

### 5.4 Approximate Methods For Dynamic Scheduling Problems

Static FMS with due date, makespan and average lead time problems have already been considered. The heuristics appear to out perform some of the single dispatching rules and published methods. In practice, the behaviour of FMS is not static due to the rapid change of demands or breakdown of machines. In this chapter, the breakdown of machines will not be considered, but the developed simulation program has taken into account machine failure. A dynamic FMS is a system in which there is some work-in-progress initially and where new jobs will arrive at a later time. The problem is separated into two parts which is similar to the static case. The first part is the due date problem, and the second part is the makespan and average lead time problems.

### 5.4.1 Dynamic FMS with due-date problem

In the static case, the due date of each job is assumed to be proportional to its mean total processing time inside the system, $k_{j}$
i.e. $d_{j}=F_{j} \times \sum_{k=1} p_{j, k}$
where $F_{j}=$ a safety factor for job $j$ to account for the congestion in the system, and $\mathrm{F}_{\mathrm{j}} \geq 1$.

In the dynamic system, $d_{j}=t_{a j}+F_{j} \times \sum_{k=1}^{k_{j}} p_{j, k}$, is assumed, where $t_{a j}=$ arrival time of job j. In order to compare the performance of the heuristics with some other methods, the computation will be
terminated if a pre-determined production has been met. The assumptions made are summarised as follows : -
(a) due date $d_{j}=t_{a j}+F_{j} \times \sum_{k=1}^{K_{j}} p_{j, k}$,
(b) a batch of job is input periodically,
(c) production demand is pre-determined( i.e. number of batches required to be produced is known in advance), and
(d) the cost per unit tardiness for each job is equal to unity.

Several simulations have been done for evaluating the performance of the heuristics on the dynamic due date problems. 48 hypothetical examples in total (TEST A - TEST D) were analysed. The number of operations varied from 4 to 6 , the number of part-mix was 7 and the number of machines was 6 for all examples. Re-visiting of machines was permissible for some of the jobs. The safety factor, $F_{j}$, varied from 1.5 to 2. The batch input period varied from 20 to 30 time units, and the pre-determined production demand varied from 3 jobs to 5 jobs of each part-mix. The assumptions that have been made for these simulations are summarised in table 5.21. The manufacturing data can be found in Appendix B (DATA B1 - B4), Appendix C (DATA C1 - C4 ) and Appendix D ( DATA D1 - D4 ). Since the optimal solutions for these examples are unknown, the results are again compared with those obtained from the SLACK rule and SIP rule which have already been employed for comparison in the static due date problems.

Comparative evaluations of the heuristics are presented in table 5.22 - table 5.25, and the ranking analysis is shown in table 5.26.

Although the cost of tardiness is the prime objective, the corresponding makespan and average lead time are also presented as additional information which has been produced from the simulations. Unlike the static case, where detailed configurations of the job sequence and operations schedule are presented for each example, only one example with detailed scheduling will be presented for clarity, due to limited space available in this context. For instance, the operations schedule on each job and the job sequence on each machine for example 3 - TEST D are presented in table 5.27 and table 5.28 respectively.

Upon examination of table 5.27 and table 5.28 , it can be observed that heuristic H 1 , heuristic H 2 and the SLACK rule produce the same operations schedule for each job. However, the job sequences on machines are different when they have been determined from these three methods, except the one appearing on machine $M_{3}$. Hence these scheduling methods produce different lead times of the products, and eventually deviations in the cost of tardiness are obtained. For this example, heuristic H 2 is the best performer to obtain the optimal cost of tardiness, i.e. 246. In the static case, it has already been mentioned that equal makespan can be obtained from different schedules. This is also applied on the dynamic situation. For instance, in example 3 - TEST D, similar makespan (i.e. 177 ) with different job sequences have been computed from heuristic H 1 , the SLACK rule and the SIP rule. According to the results in table 5.22 table 5.25, the schedules which have been calculated from each scheduling method are always different from each other and this can be reflected from the deviations in the results of cost of tardiness. However, there are some exceptions in these 48 examples, such as
example 12 - TEST A , examples 4 and 12 in TEST B , example 5 TEST C, and examples 4 and 5 in TEST D. In the static case, it has been shown that there is a high possibility of having exactly the same schedules predicted by different scheduling techniques. It has been accepted that scheduling is a combinatorial problem whose complexity increases with the number of jobs. In the dynamic case, the small possibility of having exactly the same schedules is due to the large number of jobs involved inside the manufacturing system.

From the result of example 4 - TEST $B$ as shown in table 5.23 , even the schedules which produce similar results of makespan and the average lead time, will not guarantee to give the same cost of tardiness. This can be observed from the table where the costs of tardiness are 1 unit and 3 units. These have been calculated from heuristic H 1 ( or heuristic H 2 ) and the SLACK rule respectively. On the other hand, sometimes two different schedules offer similar results of the average lead time and the cost of tardiness, but the makespan is different from each other. This can be recognized from the result of example 7 - TEST $D$ as shown in table 5.25. Both heuristics H 1 and H 2 produce the same values of the average lead time and the cost of tardiness,i.e. 68.81 and 221 respectively. However, the makespans which have been determined from these heuristics are 162 and 169. In this example, although the desired objective performance measure is the cost of tardiness and both heuristics give the same value, heuristic H 1 is preferred due to its better performance in the analysis of makespan.

The computational effort required for simulating these examples is summarised in table 5.29. If TEST A is compared to TEST B, or TEST

C is compared to TEST D, results suggested that the assumed due date values have very little effect on the execution time. However, if TEST A or TEST B is compared to TEST C or TEST D, it can be seen that the execution time is affected by the production demand as well as the input rate of new components. In general, whenever optimising the cost of tardiness, the SIP rule offers the shortest execution time due to its simple dispatching mechanism whereas it is generally accepted that heuristic H 2 requires the largest computional effort.

Performance of the heuristics on these dynamic FMS due date problems is summarised in table 5.30. Results suggest that heuristic H 2 is a promising technique to determine the schedule associates with minumum cost of tardiness. In the analysis of tardy cost , heuristic H 2 ranks highest again, and it provides 23 times the minimum cost out of 48 tests. These concluding results are similar to the analysis of static case ( see table 4.16 ).

The SIP rule ranks highest again in the analysis of makespan as was expected. In the analysis of average lead time, heuristic H 1 has improved its performance as compared to the static case. This suggests that heuristic H 1 may be a potential technique to obtain optimal average lead time in dynamic systems. Therefore, further investigation of the heuristic on the analysis of average lead time will be presented in the next section. In addition, the outstanding performance of the heuristics is highlighted in table 5.31. By applying these heuristics, the minimum tardy cost is achieved in 34 cases out of 48 problems ( $70.83 \%$ ).

In the static case, system performance such as makespan and average
lead time is affected by the due date values. This is also true in the analysis of dynamic system. A comparative study of altering the due date values on dynamic FMS is presented in table 5.32. For applying heuristic H 2 , the system performance seems not very sensitive to the change of due dates. When heuristic H 1 is applied, better makespan can be achieved by tightening the due dates, but a penalty will be paid in the form of increased average lead time. Hence it is a fruitful direction to further investigate the heuristics in order to determine the optimal makespan and average lead time in a dynamic system.

### 5.4.2 Dynamic FMS with makespan and average lead time problems

In the static system, makespan represents the time length from the beginning of the first operation of the first job to the end of the last operation of the last job. If a dynamic system is assumed to be a non-stop manufacturing plant, then the term makespan is not applicable since new jobs will arrive from time to time. In this chapter, the dynamic system is defined as follows :

1. some jobs are available at the beginning, but new jobs will arrive at some later time, and
2. production demand is pre-determined and once the production demand is met, production is stopped.

Hence the heuristics can still be compared with other methods by comparing their values of makespan and average lead time.

In a static system, due dates of jobs are initially set very close to their mean total processing time. Then after the first simulation trail, due dates are adjusted to the corresponding completion times and followed by a second simulation trail. This procedure will
continue until there is no further improvement in the desired measure of performance, i.e. makespan or average lead time. In a dynamic system, a new job will arrive in some future time, and the initial $\mathrm{K}_{\mathrm{j}}$
due date $d_{j}=t_{a j}+\sum_{k=1} p_{j, k}$. This can be illustrated by the following example.

Example: Dynamic flow-shop with makespan or average lead time problems (figure 5.10)

Job 1 and job 2 are available at $t=0$, job 3 and job 4 will arrive at time $t_{a 3}$ and $t_{a 4}$ respectively. There are only two operations for each job. The pre-determined production demand is the manufacturing of these 4 jobs. Hence the due date for each job in the first simulation is as follows :

$$
d_{1}=0+\sum_{k=1} p_{1, k}=\sum_{k=1} p_{1, k}
$$

$$
d_{2}=0+\sum_{k=1}^{2} p_{2, k}=\sum_{k=1}^{2} p_{2, k}
$$

$$
d_{3}=t_{3}+\sum_{k=1}^{2} p_{3, k}
$$

$$
2
$$

$$
d_{4}=t_{4}+\sum_{k=1} p_{4, k}
$$



Figure 5.10 Gantt cnart of dynamic flow-shop with makespan/average lead tıme problem

The assumed results are presented in figure 5.10. After the first trail, a set of completion times has been obtained, i.e. $L_{1}, L_{2}, L_{3}$ and $\mathrm{L}_{4}$. The next step is to adjust the due dates and then run the simulation again. Two methods of due date adjustment are now proposed.
(1) This method has already been shown for the static case, i.e. due dates are adjusted to the corresponding completion times which have been determined from the previous schedule,
i.e. $\left(\begin{array}{l}d_{1} \\ d_{2} \\ d_{3} \\ d_{4}\end{array}\right)=\left(\begin{array}{l}L_{1} \\ L_{2} \\ L_{3} \\ L_{4}\end{array}\right)$

This approach entirely depends on the previous completion times, hence this method is known as " full adjustment " of due date.
(2) The second method of due date adjustment is simpler than the method of " full adjustment ". During the iteration procedure, this method only adjusts the due dates of those components which are available at $t=0$, i.e. job 1 and job 2, hence due dates of job 1 and job 2 are adjusted to $d_{1}=L_{1}$ and $d_{2}=L_{2}$ respectively. For the components which will arrive in future time, i.e. job 3 and job 4, due date is assumed such that :
$d_{j}=t_{a j}+\sum_{k=1} p_{j, k}$ which is equal to the initial value appearing in the first simulation trail. Since only part of the components will be adjusted, this method is known as " partial adjustment " of due date.

These two methods of due date adjustment are evaluated by applying
the heuristics to several dynamic FMS with different input rate of new components and varied production demands. In order to compare the performance of the heuristics with some other methods, the computation will be terminated if a pre-determined production has been met. The following assumptions are made : -
(a) a batch of jobs is input periodically, or the rate of input is assumed equal to the rate of output, and
(b) a production demand is decided.

64 hypothetical examples in total (STUDY 1 - STUDY 4 ) were examined. The number of operations varied from 4 to 6 , the number of part-mix varied from 7 to 10 and the number of machines was 6 for all examples. Re-visiting of machines was permissible for some of the jobs. The assumptions that have been made for these simulations are summarised in table 5.33. The manufacturing data can be found in Appendix B (DATA B1 - B4 ), Appendix C (DATA C1 - C4 ), Appendix D ( DATA D1 - D4 ) and Appendix E (DATA E1 - E4 ). Since the optimal solutions for these problems are not known, the results are again compared with those determined from the FIFO rule and the SIP rule which have already been applied for comparison in the static makespan and average lead time problems.

Comparative evaluations of the heuristics on these dynamic FMS makespan and average lead time problems are presented in table 5.34 - table 5.37 and table 5.38 - table 5.41 respectively. Ranking analysis of the different schedule techniques are summarised in table 5.42 - table 5.45.

Upon examination of table 5.34 - table 5.37, similar makespan can
also be determined from different schedules. For instance, in the analysis of example 13 - STUDY 1 ( see table 5.34 ), both heuristic H1 and the SIP rule produce the same optimal makespan (i.e. 242 ). However, the associated schedules are different from each other. This is reflected in the different values of average lead time which have been presented in table 5.38 , i.e. 93.8 for heuristic $\mathrm{H} 1,94.17$ for the SIP rule. There are many such examples appearing in this analysis, such as example 7 - STUDY 2, example 13 - STUDY 2, etc. Therefore, lead time analysis must be considered before a decision is made.

According to the results shown in table 5.38 - table 5.41, similar average lead time can be obtained from different schedules. For instance, results from example 8 - STUDY 1 ( see table 5.38 ) suggested that the optimal average lead time can be developed from either the heuristic H 1 with the full adjustment of aue dates or heuristic H 2 with the due dates being again fully adjusted. These two heuristics actually produced two different schedules which can be proved by examining the associated makespan as shown in table 5.34, i.e. 116 for heuristic H 1 , and 118 for heuristic H 2 . Obviously the technique of heuristic H 1 with the full adjustment of due dates would be selected to optimise the average lead time for this example. This is not only because of its achievement of optimal lead time, but also due to its better performance in the analysis of makespan. Several similar examples can also be found in the analysis of average lead time problems, such as example 8 - STUDY 2 , example 11 - STUDY 3 , etc. As a result, the corresponding makespan analysis should be taken into account even when the desired objective performance measure is the average lead time.

In the analysis of static case, it has already been mentioned that it is not always necessary for the iterative procedure to coincide with the optimal value. Sometimes the value of the performance measure (i.e. makespan or average lead time ) diverges to another stage and then converges back to the optimal value. This fluctuation mechanism can also be observed in the dynamic analysis. For instance, in the analysis of optimal makespan (see table 5.34 - table 5.37 ), the fluctuation has occurred in the following examples : example 5 STUDY 1, example 10 - STUDY 3, example 5 - STUDY 4, example 12 STUDY 4 and example 13 - STUDY 4. It should be mentioned here that those re-improved makespans are obtained from the schedules which have been developed during the optimising procedure of the average lead time. For instance, the re-improved makespan in example 5 STUDY 1 ( i.e. 174, see table 5.34 ) has been determined from the schedule associates with an average lead time of 70.76 ( see table 5.38 ). Hence, the study of the dynamic case further confirms that the relaxation of the stopping criterion needs further research.

The ranking analysis can be divided into two groups which are classified by the condition of dispatching new jobs into the manufacturing system. The first group consists of STUDY 1, STUDY 2 and STUDY 3, such that the jobs will enter the system periodically. The second group consists of STUDY 4 where the input rate of new jobs is equal to the corresponding output rate.

## GROUP 1

The ranking evaluations of the heuristics for this group are presented in table 5.42 - table 5.44, and the results have been summarised in
table 5.46 .

Upon examination of table 5.46 , heuristic H 1 , with the method of full adjustment of due dates, appears to be the best technique in obtaining the optimal makespan. This can be observed from the results, which show that the technique offers 27 times the optimal values of makespan out of 48 tests and it also ranks the highest in this analysis.

In the analysis of average lead time, heuristic H 1 with the method of full adjustment of due dates again ranks highest in this study. However, heuristic H 2 , again with the technique of due dates being fully adjusted, provides the maximum number of best performances of the average lead time (i.e. 30 ) and it also ranks the second highest in this analysis. Therefore, in the analysis of average lead time, there is no clear cut conclusion to be made about which heuristic out performs another. Hence, it is generally accepted that both heuristics H 1 and H 2 , with the method of full adjustment of due dates appear to be the best techniques to develop the schedule for the optimal average lead time. According to the results which have been presented in table 5.15, table 5.18 and table 5.46, heuristic H 1 and heuristic H 2 always provide the best solution of the makespan and average lead time in both the static and dynamic systems respectively. In addition to heuristic H 2 , heuristic H 1 appears to be a promising technique to obtain the optimal average lead time.

For the technique of partial adjustment of due dates, only those components which are available initially will be adjusted. Hence the optimal solution will not be expected to be obtained by this technique.

This has been proved by the results which have been presented in table 5.46 where the technique of full adjustment of due date works better than the partial adjustment of due date in determining both of the optimal makespan and average lead time.

## GROUP 2

According to the results shown in table 5.45, the heuristics which use the techniques of due date adjustment again out perform the other dispatching rules. For GROUP 2, the technique of partial adjustment of due date appears to improve the system performance as compared to that in GROUP 1. This is reflected by the ranking which the technique has been granted, i.e. 2.594 for the makespan (the best one ), and 1.906 for the average lead time (the best one ). This seems to contradict the previous statement, i.e. full adjustment of due date is better than the partial adjustment. Further analysis of the results of GROUP 2 will be followed in this section.

For the technique of partial adjustment of due date, due dates for future arrival jobs are governed by the relation of $d_{j}=t_{a j}+\sum_{k=1} p_{j, k}$.

In GROUP $1, t_{a j}$ values are exactly the same in each iteration. Hence $\mathrm{d}_{\mathrm{j}}$ values for the future jobs will not be adjusted by the technique of partial adjustment of due date. Consequently, results which have been obtained by this technique are unsatisfactory. However, in GROUP 2, it has been assumed that whenever there is a job leaving the system, a job of the same part-mix will be launched. Hence the arrival time for a future job is dependent upon the completion time of
the corresponding job with the same part-mix. This is best illustrated by the Gantt chart as shown in figure 5.11 and figure 5.12.

From figure 5.11, job 1 and job 2 are available at $t=0$, and job 1 is assumed to have higher priority to load on the machine. According to the previous assumption of inputing new jobs, $t_{a 3}=L_{1}$ and $t_{a 4}=L_{2}$ are obtained, and the resulting schedule is $1,2,3,4$. In the second iteration, the due dates of job 1 and job 2 are adjusted to $d_{1}=L_{1}$ and $d_{2}=L_{2}$ (where $L_{1}$ and $L_{2}$ are taken from figure 5.11 ). From figure 5.12 job 2 has been assumed to be loaded on the machine first, hence the arrival times for job 3 and job 4 are different from the first schedule. As a result, the due dates for future jobs may also be adjusted even though the technique of partial adjustment of due dates only has been applied. Consequently, this technique performs satisfactorily as seen in table 5.45 .

The results shown in table 5.47 highlight the performance of the heuristics on the dynamic system. By applying the heuristics, the minimum makespan occurs on 43 occasions which accounts for 67.19 \% in these 64 problems. Results also suggest that the heuristics are excellent performers in obtaining the schedule associated with the minimum average lead time. This is reflected by the greater frequency of occurrence of minimum average lead time, i.e. 58, which accounts for $90.63 \%$ in this analysis. In contrast, the SIP rule only accounts for $37.5 \%$ and $15.63 \%$ in determining the optimal makespan and average lead time respectively. The FIFO rule performs even worse, as was expected. It gives only $26.56 \%$ in obtaining the optimal makespan, but none in determining the optimal average lead time.


Figure 5.11 Results from tne first simulation


TIME

Figure 5.12 Results from the second simulation with the partial adjustment of due dates

The computational effort required for simulating the above dynamic systems is presented in table 5.48. Both the FIFO rule and the SIP rule provide very economical methods as was expected. However, they produce very poor results. It was expected that the computational effort required by heuristic H 2 would be greater than that of heuristic H 1 , and this can be observed in table 5.48. The longest average execution time has been granted to the examples in STUDY 4. This is partly due to the highest demand which has been assumed in this study (i.e. 5 jobs per part-mix ), and partly due to the assumption made for launching the new jobs into the system. When the pre-determined production demand is increased, it means that the simulated time will be increased accordingly in order to produce the required production. In STUDY 4, the input condition of new jobs has been governed by the relation such that the input rate is equal to the output rate. This is not a practical method of launching new jobs into the system, and some of the machines may be under utilised due to insufficient supply of jobs to feed the system. Consequently, the simulation time will be extended in order to meet the production demand. Results suggested that the computational effort required by the heuristics compares well with those obtained using simple dispatching rules, i.e. FIFO and SIP . In addition, the heuristics perform satisfactorily in optimising various performance measures in both the static and dynamic situations as shown in table 5.49. Hence the heuristics could be practically implemented to each station for the scheduling calculation. The practical implementation of the system will be discussed in the next chapter.

## TABLES ( Chapter 5 )

$$
\begin{aligned}
& \mathrm{m} . \mathrm{s} . \\
& \mathrm{I}=\text { makespan } \\
& \mathrm{c}=\text { average lead time } \\
& \mathrm{n}=\text { cost of tardiness } \\
& \mathrm{n}_{\mathrm{p}}=\text { number of jobs } \\
& \mathrm{m}=\text { number of part types } \\
& \mathrm{NOP}=\text { number of machines } \\
& \text { J.S. }=\text { job sequence } \\
& \text { O.S. }=\text { operation schedule }
\end{aligned}
$$

Note: (1) The asterisk ( ${ }^{*}$ ) denotes the best method in each example for obtaining the corresponding objective measure.
(2) The asterisk ( **) denotes the best method for each objective measure.
(3) When there is an arrow, result is the same as the arrow pointed.

| Job | Machine |  |  | Earliest completion <br> time |
| :---: | :--- | :--- | :--- | :---: |
| j | 1 | 2 | 3 |  |
| 1 | 5 | 6 | 20 | 31 |
| 2 | 6 | 30 | 6 | 42 |
| 3 | 30 | 4 | 5 | 39 |
| 4 | 2 | 5 | 5 | 12 |
| 5 | 3 | 10 | 4 | 17 |
| 6 | 4 | 1 | 4 | 9 |

Table 5.1 Operation time in a 6-job, 3-machine Stinson's example

|  | Heuristic <br> H 1 | Heuristic <br> H 2 | Stinson and <br> Smith | Optimum <br> solution |
| :--- | :---: | :---: | :---: | :---: |
| Makespan 65 67 66 64 <br> Average <br> lead time 38 37.8 52.2 45 l |  |  |  |  |

Table 5.2 Results of Stinson's example

| Example number | Job j | Machine number |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  |  | I | II | III |
| 1 | 1 | 5 | 8 | 20 |
|  | 2 | 6 | 30 | 6 |
|  | 3 | 30 | 4 | 5 |
|  | 4 | 2 | 5 | 3 |
|  | 5 | 3 | 10 | 4 |
|  | 6 | 4 | 1 | 4 |
| 2 | 1 | 9 | 13 | 6 |
|  | 2 | 7 | 7 | 20 |
|  | 3 | 6 | 4 | 8 |
|  | 4 | 8 | 3 | 10 |
|  | 5 | 20 | 7 | 2 |
|  | 6 | 10 | 2 | 13 |
| 3 | 1 | 6 | 7 | 3 |
|  | 2 | 12 | 2 | 3 |
|  | 3 | 4 | 6 | 8 |
|  | 4 | 3 | 11 | 7 |
|  | 5 | 6 | 8 | 10 |
|  | 6 | 2 | 14 | 12 |
| 4 | 1 | 4 | 5 | 5 |
|  | 2 | 2 | 17 | 7 |
|  | 3 | 2 | 10 | 4 |
|  | 4 | 10 | 8 | 2 |
|  | 5 | 7 | 15 | 6 |
|  | 6 | 9 | 4 | 11 |
| 5 | 1 | 9 | 1 | 5 |
|  | 2 | 12 | 1 | 13 |
|  | 3 | 8 | 6 | 7 |
|  | 4 | 11 | 9 | 10 |
|  | 5 | 5 | 13 | 6 |
|  | 6 | 12 | 3 | 9 |
| 6 | 1 | 15 | 5 | 14 |
|  | 2 | 7 | 4 | 2 |
|  | 3 | 9 | 14 | 18 |
|  | 4 | 28 | 11 | 9 |
|  | 5 | 1 | 17 | 4 |
|  | 6 | 1 | 8 | 3 |

Table 5.3 Table of processing times for flow shop problems (Giglio and Wagner 1964)

| Example | Method | Makespan | Average lead time | Job sequence on each machine |
| :---: | :---: | :---: | :---: | :---: |
| 1 | optimum solution | 64 | 46 | $\begin{aligned} & \text { M1: } 412365 \\ & \text { M2 : } \\ & \text { M3: } \end{aligned}$ |
|  | H1 | $\begin{aligned} & 67 \\ & (-4.69 \%) \end{aligned}$ | $\begin{aligned} & 38.5 \\ & (+16.3 \%) \end{aligned}$ | $\begin{aligned} & \text { M1: } 456123 \\ & \text { M2: } \end{aligned}$ |
|  | H2 | $\begin{aligned} & 69 \\ & (-7.81 \%) \end{aligned}$ | $\begin{aligned} & 38.2 \\ & (+16.96 \%) \end{aligned}$ | M3 : <br> M1: 456123 <br> M2: 465123 <br> M3 : |
| 2 | optimum solution | 69 | 47.3 | $\begin{aligned} & \text { M1: } 342165 \\ & \text { M2 } \\ & \text { M3: } \end{aligned}$ |
|  | H | $\begin{aligned} & 71 \\ & (-2.9 \%) \end{aligned}$ | $\begin{aligned} & 50.7 \\ & (-7.19 \%) \end{aligned}$ | $\begin{aligned} & \text { M1 : } 324165 \\ & \text { M2 : } \\ & \text { M3: } \end{aligned}$ |
|  | H2 | $\begin{aligned} & 71 \\ & (-2.9 \%) \end{aligned}$ | $\begin{aligned} & 50.7 \\ & (-7.19 \%) \end{aligned}$ | M1:324165 <br> M2 : <br> M3 : |
| 3 | optimum solution | 57 | 41.3 | $\begin{aligned} & \text { M1: } 356241 \\ & \text { M2: } \\ & \text { M3: } \end{aligned}$ |
|  | H1 | $\begin{aligned} & 59 \\ & (-3.51 \%) \end{aligned}$ | $\begin{aligned} & 42.7 \\ & (-3.39 \%) \end{aligned}$ | M1: 643152 <br> M2 : 631524 <br> M3 : 631254 |
|  | H2 | $\begin{aligned} & 60 \\ & (-5.26 \%) \end{aligned}$ | $\begin{aligned} & 42.7 \\ & (-3.39 \%) \end{aligned}$ | M1: 643152 <br> M2 : 631524 <br> M3 : 613254 |

Table 5.4 Comparison of performance of the developed heuristics with optimum solutions

Note : +ve \% denotes better result as compared to the optimum solution and vise versa.

|  | optimum solution | 63 | 44.7 | $\begin{aligned} & \text { M1:213654 } \\ & \text { M2: " } \\ & \text { M3: " } \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: |
| 4 | H1 | $67$ | 43.3 | M1:231564 |
|  |  | $(-6.35 \%)$ | ( + 3.13\%) | $\begin{aligned} & \text { M2 : } 216345 \\ & \text { M3: } \end{aligned}$ |
|  | H2 |  | 43 | M1 : 231564 |
|  |  | (-19.05\%) | ( + 3.8\%) | M2 : 316542 |
|  |  |  |  | M3 : " |
| 5 | optimum solution | 68 | 48.8 | M1:524361 |
|  |  |  |  | M2 : " |
|  |  |  |  | M3: " |
|  | H1 | 74 | 47 | M1:531426 |
|  |  | (-8.82\%) | ( + $3.69 \%$ ) | M2 : " |
|  |  |  |  | M3: " |
|  | H2 | 74 | 47 | M1:531426 |
|  |  | (-8.82\%) | ( + 3.69\%) | M2 : " |
|  |  |  |  | M3: " |
| 6 | optimum solution | 76 | 61.2 | M1:315642 |
|  |  |  |  | M2: ${ }^{\text {a }}$ |
|  |  |  |  | M3: " |
|  | H1 |  | 50.3 | M1:562314 |
|  |  | (-11.84\%) | ( + 17.81\%) | M2 : 526314 |
|  |  |  |  | M3 : "' |
|  | H2 |  | 44.5 | M1:562314 |
|  |  | (-6.58\%) | ( + 27.29\%) | M2 : 625134 |
|  |  |  |  | M3 : |

Table 5.4 ( continued)

| Heuristic | Average \% deviation from the optimal schedule |  |
| :---: | :---: | :---: |
|  | Makespan | Average lead time |
| H 1 | -6.35 | +5.06 |
| H 2 | -8.40 | +6.86 |

Table 5.5 Comparative study of heuristics on flow shop problems

| Example | Heuristic method | Iteration number | Makespan | ence corresponding to the optimal from each heuristic |
| :---: | :---: | :---: | :---: | :---: |
| 1 | H1 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 67(-4.69 \%) \\ & 67 \end{aligned}$ | M1: 456123 M2 : ${ }^{n}$ M3: |
|  | H2 | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 69 \\ & \# 68(-6.25 \%) \\ & 68 \end{aligned}$ | M1: 465123 M2: M3: |
| 2 | H1 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $71(-2.9 \%)$ | $\begin{aligned} & \text { M1:324165 } \\ & \text { M2: } \\ & \text { M3: } \end{aligned}$ |
|  | H2 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 71(-2.9 \%) \\ & 71 \end{aligned}$ | $\begin{aligned} & \text { M1: } 324165 \\ & \text { M2 : } \\ & \text { M3: } \end{aligned}$ |
| 3 | H1 | $\begin{aligned} & \hline 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 59(-3.51 \%) \\ & 59 \end{aligned}$ | $\begin{aligned} & \text { M1: } 643152 \\ & \text { M2 }: 631524 \\ & \text { M3: } 631254 \end{aligned}$ |
|  | H2 | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 60 \\ & \# 59(-3.51 \%) \\ & 59 \end{aligned}$ | M1: 613254 M2 : M3: |
| 4 | H1 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 67(-6.35 \%) \\ & 67 \end{aligned}$ | $\begin{aligned} & \text { M1: } 231564 \\ & \text { M2: } 216345 \\ & \text { M3: } n \end{aligned}$ |
|  | H2 | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 75 \\ & \# 69(-9.52 \%) \\ & 69 \end{aligned}$ | $\begin{aligned} & \text { M1: } 316542 \\ & \text { M2: } \\ & \text { M3: } \end{aligned}$ |
| 5 | H1 | $\begin{aligned} & \hline 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 74(-8.82 \%) \\ & 74 \end{aligned}$ | $\begin{aligned} & \text { M1:531426 } \\ & \text { M2: } \quad " \\ & \text { M3: } \quad " \end{aligned}$ |
|  | H2 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 74 \text { (-8.82\%) } \\ & 74 \end{aligned}$ | $\begin{aligned} & \text { M1:531426 } \\ & \text { M2: " } \\ & \text { M3: } \end{aligned}$ |
| 6 | H1 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $85(-11.84 \%)$ | $\begin{aligned} & \text { M1:562314 } \\ & \text { M2:526314 } \\ & \text { M3: } \end{aligned}$ |
|  | H2 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 81(-6.58 \%) \\ & 81 \end{aligned}$ | M1: 562314 M2 $: 625134$ M3: |

Table 5.6 Improved results with iterative procedures for the flow shop makespan problems Note : The asterisk (\#) denotes improved result.

| Example | Heuristic method | Iteration number | average lead Jo time | sequence corresponding to the optima ge lead time from each heuristic |
| :---: | :---: | :---: | :---: | :---: |
| 1 | H 1 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 38.5(+16.3 \%) \\ & 38.5 \end{aligned}$ | $\begin{aligned} & \text { M1:456123 } \\ & \text { M2: } \\ & \text { M3: } \end{aligned}$ |
|  | H2 | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 38.2 \\ & \# 37.5(+18.48 \%) \\ & 37.5 \end{aligned}$ | $\begin{aligned} & \text { M1: } 465123 \\ & \text { M2 : } \\ & \text { M3: } \end{aligned}$ |
| 2 | H1 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 50.7(-7.19 \%) \\ & 50.7 \end{aligned}$ | $\begin{aligned} & \text { M1: } 324165 \\ & \text { M2 : } \\ & \text { M3: } \end{aligned}$ |
|  | H2 | $\begin{aligned} & \hline 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 50.7(-7.19 \%) \\ & 50.7 \end{aligned}$ | $\begin{aligned} & \text { M1:324165 } \\ & \text { M2: } 1 \\ & \text { M3: } \end{aligned}$ |
| 3 | H 1 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 42.7(-3.39 \%) \\ & 42.7 \end{aligned}$ | $\begin{aligned} & \text { M1 : } 643152 \\ & \text { M2 }: 631524 \\ & \text { M3 }: 631254 \end{aligned}$ |
|  | H2 | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 42.7 \\ & \# 41.8(-1.21 \%) \\ & 41.8 \end{aligned}$ | M1: 613254 M2: M3 : |
| 4 | H1 | $\begin{aligned} & \hline 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 43.3(+3.13 \%) \\ & 43.3 \end{aligned}$ | $\begin{aligned} & \text { M1:231564 } \\ & \text { M2: } 216345 \\ & \text { M3: } \end{aligned}$ |
|  | H2 | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & \hline 43 \\ & \# 38.3(+14.32 \%) \\ & 38.3 \end{aligned}$ | M1: 316542 M2: M3: |
| 5 | H1 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 47(+3.69 \%) \\ & 47 \end{aligned}$ | M1: 531426 M2: M3: |
|  | H2 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 47(+3.69 \%) \\ & 47 \end{aligned}$ | M1: 531426 M2: M3: |
| 6 | H1 | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 50.3(+17.81 \%) \\ & 50.3 \end{aligned}$ | M1: 562314 M2 : 526314 M3: |
|  | H2 | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 44.5 \\ & \# 43(+29.74 \%) \\ & 43 \end{aligned}$ | M1: 625134 M2: M3: |

Table 5.7 Improved results with iterative procedures for the flow shop lead time problems
Note : The asterisk (\#) denotes improved result.

| Heuristic | Average \% deviation from the optimal schedule |  |
| :---: | :---: | :---: |
|  | Makespan | Average lead time |
| H 1 | -6.35 | +5.06 |
| H 2 | $\#-6.26$ | $\#+9.64$ |

Table 5.8 Comparative study of heuristics on flow shop problems (with iterative procedures )

Note : The asterisk ( \# ) denotes the improved result


Table 5.9 Comparison of performance of the developed heuristics with other published methods

|  | $\begin{aligned} & \text { Palmer } \\ & \text { (1965) } \end{aligned}$ | 75 | 55.14 | $\begin{aligned} & \text { M1: } \\ & \text { M2 : } 1,4,5,2,6,7,3 \\ & \text { M3: } \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: |
| $\begin{gathered} 7 \times 3 \\ (\text { flow }- \text { shop }) \end{gathered}$ | H1 | *72 | 43 | M1 : <br> M2 : 4,5,6,1,2,7,3 <br> M3 : |
|  | H2 | 75 | *39.14 | $\begin{aligned} & \text { M1 : } \\ & \text { M2 : 4,6,5,7,1,2,3 } \\ & \text { M3 : } \end{aligned}$ |
|  | $\begin{aligned} & \text { Palmer } \\ & \text { (1965) } \end{aligned}$ | 85 | 63.5 | $\begin{aligned} & \text { M1 : } \\ & \text { M2 : } 2,6,8,3,4,7,1,5 \\ & \text { M3 : } \end{aligned}$ |
| $\begin{gathered} 8 \times 3 \\ \text { (flow }- \text { shop }) \end{gathered}$ | $\begin{aligned} & \mathrm{H} 1 \\ & \mathrm{H} 2 \end{aligned}$ | $* 81$ $* 81$ | *52.13 | $\begin{aligned} & \text { M1: } \\ & \text { M2 : 8,3,2,7,4,1,6,5 } \\ & \text { M3 : } \end{aligned}$ |
|  | $\begin{aligned} & \hline \text { Palmer } \\ & \text { (1965) } \end{aligned}$ | *59 | 46.33 | $\begin{aligned} & \text { M1 : } \\ & \text { M2 : } 6,3,5,4,1,2 \\ & \text { M3 : } \end{aligned}$ |
| $\begin{gathered} 6 \times 3 \\ \text { ( flow }- \text { shop ) } \end{gathered}$ | H1 | *59 | 42.67 | $\begin{aligned} & \text { M1 : } 6,4,3,1,5,2 \\ & \text { M2 : } 6,3,1,5,2,4 \\ & \text { M3 : } 6,3,1,2,5,4 \end{aligned}$ |
|  | H2 | *59 | *41.83 | $\begin{aligned} & \text { M1 : } \\ & \text { M2 : } 6,1,3,2,5,4 \\ & \text { M3 : } \end{aligned}$ |
|  | $\begin{aligned} & \hline \text { Palmer } \\ & \text { (1965) } \end{aligned}$ | *84 | 53.33 | $\begin{aligned} & \text { M1 : } \\ & \text { M2 : } 8,7,2,3,6,1,9,5,4 \\ & \text { M3 : } \end{aligned}$ |
| $\begin{gathered} 9 \times 3 \\ \text { (flow }- \text { shop }) \end{gathered}$ | H1 | 88 | 47.44 | $\begin{aligned} & \text { M1 : } 7,2,3,8,1,5,9,6,4 \\ & \text { M2 :7,8,1,3,9,6,5,4,2 } \\ & \text { M3:7,8,1,3,9,6,5,4,2 } \end{aligned}$ |
|  | H2 | 88 | *47.22 | ```M1 : M2 :7,8,1,3,9,6,4,5,2 M3 :``` |

Table 5.9 ( continued)

| $\begin{gathered} 4 \times 3 \\ (\text { flow }- \text { shop }) \end{gathered}$ | $\begin{aligned} & \hline \text { Palmer } \\ & \text { (1965) } \end{aligned}$ | *54 | 42.75 | $\begin{aligned} & \text { M1: } \\ & \text { M2 : } 2,4,3,1 \\ & \text { M3 : } \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: |
|  | H 1 H 2 | 60 60 | *38.5 | $\begin{aligned} & \text { M1 : } \\ & \text { M2 : } 3,1,4,2 \\ & \text { M3 : } \end{aligned}$ |
| $\begin{gathered} 5 \times 3 \\ \text { (flow }- \text { shop }) \end{gathered}$ | $\begin{aligned} & \hline \text { Palmer } \\ & \text { (1965) } \end{aligned}$ | *80 | 49.2 | $\begin{aligned} & \text { M1: } \\ & \text { M2: } 3,5,1,2,4 \\ & \text { M3 } \end{aligned}$ |
|  | H 1 H 2 | *80 | *43.6 | $\begin{aligned} & \text { M1 : } \\ & \text { M2 : 5,2,3,1,4 } \\ & \text { M3 : } \end{aligned}$ |
| $\begin{gathered} 3 \times 3 \\ \text { ( job-shop ) } \end{gathered}$ | Nicholson (1971) <br> H1 | $* 15$ $* 15$ | $* 13$ $* 13$ | $\begin{aligned} & \text { M1 : } 3,1,2 \\ & \text { M2 }: 2,1,3 \\ & \text { M3 :2,3,1 } \end{aligned}$ |
|  | H2 | *15 | *13 |  |

Table 5.9 ( continued)

Total number of tests $=12$

|  |  | Heuristic <br> H 1 | Heuristic <br> H 2 | Other methods |
| :--- | :---: | :---: | :---: | :---: |
|  |  |  |  |  |
| Number of best | m.s. | ${ }^{* *} 9$ | 8 | 8 |
| performance of | 1 | 8 | ${ }^{* * 11}$ | 4 |
| Ranking | m.s. | ${ }^{* * 1.917}$ | 2.042 | 2.042 |
|  | 1 | 1.833 | ${ }^{* * 1.583}$ | 2.583 |

Table 5.10 Ranking of performance for the heuristics and other published methods

| Part type | Batch size | Sequence of operations <br> ( machine number) | Duration of <br> operations |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | ---: |
| 1 | 4 | 1 | 2 | 1 | 5 | 4 | 2 |
|  | 2 | 3 | 3 | 3 | 5 | 3 |  |
| 2 | 4 | 2 | 1 | 1 | 3 | 2 | 5 |
|  |  | 3 | 3 | 2 | 7 | 4 | 4 |

Table 5.11 Basic manufacturing data for an FMS (IWATA's example )

| IWATA's method |  | SIP | ristic H 1 or Heuristic $\mathrm{H}^{\prime}$ |  |
| :---: | :---: | :---: | :---: | :---: |
|  |  | Objective measure |
|  |  | minimum makespan | minimum average lead time |
| Makespan | 38 |  | 35 | *34 | *34 |
| Average lead time | 32.5 |  | 24.5 | 23.875 | *22.75 |
| Machine |  |  |  |  |
| Utilization (\%) |  |  |  |  |
| $U_{1}$ | 94.74 | 68.57 | 64.71 | 70.59 |
| $\mathrm{U}_{2}$ | 73.68 | 91.43 | 94.12 | 94.12 |
| $U_{3}$ | 52.63 | 68.57 | 76.47 | 67.65 |
| mean utilization : | 73.68 | 76.19 | *78.43 | 77.45 |
| Operation scheduling |  |  |  |  |
| $\begin{array}{r} \text { Part } 1:(1,1) \\ (1,2) \end{array}$ | 131 | 231 <br> 1 | $\begin{aligned} & 231 \\ & 231 \end{aligned}$ | $\begin{aligned} & 231 \\ & 233 \end{aligned}$ |
| $(1,3)$ | " | " | 233 | 231 |
| $(1,4)$ | " | " | 233 | 231 |
| Part $2:(2,1)$ | 212 | 211 | 211 | 211 |
| (2,2) | " | 212 | 211 | 211 |
| ( 2,3 ) | " | 232 | 212 | 212 |
| ( 2,4 ) | " | 211 | 212 | 212 |
| Computing time ( cp second) | $\begin{aligned} & \text { ( not } \\ & \text { available ) } \end{aligned}$ | 0.765 | 1.376 | 1.871 |

Table 5.12 Evaluation of the heuristics on an FMS example

Job sequence( J.S. ) on each machine and operation schedule( O.S. ) for each job corresponding to the optimal makespan obtained from each scheduling technique

| Example number |  |  | Heuristic H1 | Heuristic H2 | FIFO | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1(DATA B1) | J.S. | M1 | 1362 | 6523 | 1326 | 6532 |
|  |  | M2 | 45372 | 41273 | 45372 | 41372 |
|  |  | M3 | 724 | $\longleftarrow$ | 274 | 724 |
|  |  | M4 | 1546 | 1564 | 15476 | 5146 |
|  |  | M5 | 31657 | 63157 | 3615 | 63157 |
|  |  | M6 | 1543672 | 6152473 | 1543726 | 1546372 |
|  | O.S. | Job 1 | 4156 | 4256 | 4156 | (same as H2) |
|  |  | Job 2 | 3126 | $\longleftarrow$ | $\longleftarrow$ |  |
|  |  | Job 3 | 5126 | $\leftarrow$ | $\longleftarrow$ |  |
|  |  | Job 4 | 2436 |  |  |  |
|  |  | Job 5 | 4256 | 4156 | 4256 |  |
|  |  | Job 6 | 5146 |  |  |  |
|  |  | Job 7 | 3526 | $\longleftarrow$ | 3426 |  |
| 2 | J.S. | M1 | 6532 | 6324 | 362 |  |
|  |  | M2 | 41732 | 41752 | 415372 |  |
|  |  | M3 | 5724 | 7523 | 2574 |  |
|  |  | M4 | 146 | 164 | 146 | (same as $\mathrm{H}^{\prime}$ ) |
|  |  | M5 | 63715 | $\leftarrow$ | 36175 |  |
|  |  | M6 | 1756342 | 6173254 | 1357462 |  |
| (DATA B2) | O.S. | Job 1 | 4256 | $\leftarrow$ | $\leftarrow$ | (same as H1) |
|  |  | Job 2 | 3126 |  |  |  |
|  |  | Job 3 | 5126 | 5136 | 5126 |  |
|  |  | Job 4 | 2436 | 2416 | 2436 |  |
|  |  | Job 5 | 3156 | 3256 |  |  |
|  |  | Job 6 | 5146 | $\longleftarrow$ | $\leftarrow$ |  |
|  |  | Job 7 | 3526 | $\longleftarrow$ | $\longleftarrow$ |  |
| 3 | J.S. | M1 | 762 |  | 72536 |  |
|  |  | M2 | 415732 |  | 41723 |  |
|  |  | M3 | 24 |  |  |  |
|  |  | M4 | 154763 | (same as H1) | 15476 | (same as H1) |
|  |  | M5 | 6315 |  | 3615 |  |
|  |  | M6 | 4617532 |  | 4712536 |  |
| (DATA B3) | O.S. | Job 1 | 4256 | (same as H 1 ) | $\longleftarrow$ | (same as H 1 ) |
|  |  | Job 2 | 3126 |  |  |  |
|  |  | Job 3 | 5426 |  | 5126 |  |
|  |  | Job 4 | 2436 |  |  |  |
|  |  | Job 5 | 4256 |  | 4156 |  |
|  |  | Job 6 | 5146 |  | $\longleftarrow$ |  |
|  |  | Job 7 | 1426 |  | $\longleftarrow$ |  |

Table 5.13 Schedules for the static FMS makespan problems

| 4 | J.S. | $\begin{aligned} & \text { M1 } \\ & \text { M2 } \\ & \text { M3 } \\ & \text { M4 } \\ & \text { M5 } \\ & \text { M6 } \end{aligned}$ | $\begin{aligned} & \hline 6234 \\ & 136247 \\ & 752 \\ & 514 \\ & 36157 \\ & 1652347 \end{aligned}$ | (same as H 1 ) | $\begin{aligned} & \hline 2634 \\ & 132746 \\ & 725 \\ & 145 \\ & 37165 \\ & 2137546 \end{aligned}$ | (same as $\mathrm{H1}$ ) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| (DATA B4) | O.S. | Job 1 Job 2 Job 3 Job 4 Job 5 Job 6 Job 7 | 4256 1326 5216 4216 4356 1526 3526 | (same as H 1 ) | (same as H 1 ) | (same as H 1 ) |
| 5 | J.S. | M1 M2 M3 M4 M5 M6 | $\begin{aligned} & 53121 \\ & 465426 \\ & 72762 \\ & 5154713 \\ & 37364 \\ & 5741362 \end{aligned}$ | $\begin{aligned} & \hline 53241 \\ & 461562 \\ & 27672 \\ & 5154613 \\ & 37374 \\ & 5746132 \end{aligned}$ | 3211 <br> 46542651543651 <br> 33774 <br> 3741625 | 563241 645612 7272 5156431 37734 5764312 |
| (DATA C1) | O.S. | $\begin{aligned} & \text { Job } 1 \\ & \text { Job } 2 \\ & \text { Job } 3 \\ & \text { Job } 4 \\ & \text { Jcb } 5 \\ & \text { Job } 6 \\ & \text { Job } 7 \end{aligned}$ | 41416 <br> 31236 <br> 51546 <br> 24256 <br> 41426 <br> 23526 <br> 35346 | 42416 $\leftarrow$ $\leftarrow 24156$ $\leftarrow$ 23426 35356 | 41416 $\leftarrow$ $\stackrel{24256}{ }$ 42426 $\leftarrow$ | 42416 $\leftarrow$ $\leftarrow 24156$ 41426 21426 $\leftarrow$ |
| 6 | J.S. | M1 M2 M3 M4 M5 M6 | 65321 414562 57272 1457173 63643 5416732 | (same as H1) | $\begin{aligned} & 13251 \\ & 44265 \\ & 257672 \\ & 141653 \\ & 367347 \\ & 1427365 \end{aligned}$ | (same as H1) |
| (DATA C2) | O.S. | Job 1 Job 2 Job 3 Job 4 Job 5 Job 6 Job 7 | 42416 <br> 31236 <br> 51546 <br> 24256 <br> 31426 <br> 51526 <br> 34346 | (same as H1) | 41416 $\leftarrow$ $\leftarrow$ 53426 35356 | (same as H 1 ) |

Table 5.13 ( continued)

|  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M1 | 167214 6453265 |  | 216714 465256 | $\begin{aligned} & 162714 \\ & 6453265 \end{aligned}$ |
|  |  | M3 | 275452 |  | 257452 |  |
|  | J.S. | M4 | 13173 | (same as H 1 ) | 13163 | $\begin{aligned} & 13173 \\ & 3764 \\ & 1734265 \end{aligned}$ |
|  |  | M5 | 3764 |  | 37374 |  |
| 7 |  | M6 | 1734265 |  | 1742536 | $1734265$ |
|  | O.S. | Job 1 | 41416 | (same as H 1 ) | $\stackrel{ }{ }$ | (same as H 1 ) |
| (DATA C3) |  | Job 2 | 31236 |  |  |  |
|  |  | Job 3 | 54246 |  | 54546 |  |
|  |  | Job 4 | 23156 |  | $\longleftarrow$ |  |
|  |  | Job 5 | 32326 |  |  |  |
|  |  | Job 6 | 21526 |  | 21426 |  |
|  |  | Job 7 | 35146 |  | 35156 |  |
|  | J.S. | M1 | 1261 | 1621 | 2161 | 1621 |
|  |  | M2 | 4654265 | 6456245 | 4652456 | 6454625 |
|  |  | M3 | 7254752 | 725472 | 2574752 | 2574572 |
|  |  | M4 | 1713673 | 1713573 | 1731673 | 171373 |
|  |  | M5 | 334 | 3634 | 334 | 3634 |
| 8 |  | M6 | 1627435 | 1627345 | 1274563 | 1672453 |
| (DATA C4) | O.S. | Job 1 | 41416 | $\longleftarrow$ | (same as H 1 ) | $\longleftarrow$ |
|  |  | Job 2 | 31236 | $\longleftarrow$ |  | $\longleftarrow$ |
|  |  | Job 3 | 54546 | $\longleftarrow$ |  | $\longleftarrow$ |
|  |  | Job 4 | 23256 | $\longleftarrow$ |  | $\longleftarrow$ |
|  |  | Job 5 | 32326 | 32426 |  |  |
|  |  | Job 6 | 21426 | 21526 |  | 21526 |
|  |  | Job 7 | 34346 | $\longleftarrow$ |  | $\leftarrow$ |
|  |  | M1 | 23156 | $\stackrel{ }{2}$ | 123576 |  |
|  |  | M2 | 4217 | - | 1427 |  |
|  |  | M3 | 241636 |  | 214636 |  |
|  | J.S. | M4 | 463271 | 463217 | 467312 | (same as H 1 ) |
|  |  | M5 | 235471 | 235147 | 23541 |  |
| 9 |  | M6 | 2543176 | 2514376 | 5472136 |  |
|  |  | Job 1 | 123456 |  | $\longleftarrow$ |  |
| (DATA D1) |  | Job 2 | 153246 |  | $\longleftarrow$ |  |
|  |  | Job 3 | 15436 |  | $\leftarrow$ |  |
|  | O.S. | Job 4 | 42356 | (same as H1) | $\leftarrow$ | (same as H 1 ) |
|  |  | Job 5 | 156 |  | - |  |
|  |  | Job 6 | 43136 |  |  |  |
|  |  | Job 7 | 4526 |  | 4126 |  |

Table 5.13 ( continued)

| 10 | J.S. | M1 <br> M2 <br> M3 <br> M4 <br> M5 <br> M6 | $\begin{aligned} & \hline 12537 \\ & 14267 \\ & 124636 \\ & 461732 \\ & 25314 \\ & 5142376 \end{aligned}$ | $\begin{aligned} & 213567 \\ & 1427 \\ & 216346 \\ & 4631274 \\ & 2351 \\ & 5132467 \end{aligned}$ | $\begin{aligned} & 12357 \\ & 14267 \\ & 124636 \\ & 467132 \\ & 23541 \\ & 5412376 \end{aligned}$ | $\begin{aligned} & 213567 \\ & 1427 \\ & 214636 \\ & 463127 \\ & 23514 \\ & 5124367 \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| (DATA D2) | O.S. | Job 1 <br> Job 2 <br> Job 3 <br> Job 4 <br> Job 5 <br> Job 6 <br> Job 7 | $\begin{aligned} & 123456 \\ & 153246 \\ & 15436 \\ & 42356 \\ & 156 \\ & 43236 \\ & 4126 \end{aligned}$ | $\begin{aligned} & \leftarrow \\ & \leftarrow \\ & \leftarrow \\ & \leftarrow 42346 \\ & \leftarrow \\ & \leftarrow 43136 \\ & \leftarrow \end{aligned}$ | (same as H1) |  |
| 11 | J.S. | M1 <br> M2 <br> M3 <br> M4 <br> M5 <br> M6 | $\begin{aligned} & 21537 \\ & 4126 \\ & 4216763 \\ & 467123 \\ & 24531 \\ & 4512763 \end{aligned}$ | $\begin{aligned} & 12537 \\ & 14267 \\ & 142636 \\ & 461723 \\ & 24513 \\ & 4512376 \end{aligned}$ | $\begin{aligned} & 12357 \\ & 1426 \\ & 1426376 \\ & 467132 \\ & 24351 \end{aligned}$ | (same as H2) |
| (DATA D3) | O.S. | Job 1 <br> Job 2 <br> Job 3 <br> Job 4 <br> Job 5 <br> Job 6 <br> Job 7 | $\begin{aligned} & 123456 \\ & 153246 \\ & 15436 \\ & 42356 \\ & 156 \\ & 43236 \\ & 4136 \end{aligned}$ |  | (same as H1) | (same as H 2 ) |
| 12 | J.S. | $\begin{aligned} & \text { M1 } \\ & \text { M2 } \\ & \text { M3 } \\ & \text { M4 } \\ & \text { M5 } \\ & \text { M6 } \end{aligned}$ | $\begin{aligned} & 5123 \\ & 41762 \\ & 461236 \\ & 4764312 \\ & 57231 \\ & 5473216 \end{aligned}$ | (same as H 1 ) | $\begin{aligned} & \hline 1235 \\ & 41672 \\ & 642163 \\ & 4674312 \\ & 27351 \\ & 4756231 \end{aligned}$ | (same as H 1 ) |
| (DATA D4) | O.S. | Job 1 <br> Job 2 <br> Job 3 <br> Job 4 <br> Job 5 <br> Job 6 <br> Job 7 | $\begin{aligned} & 123456 \\ & 153246 \\ & 15436 \\ & 42346 \\ & 156 \\ & 43236 \\ & 4526 \end{aligned}$ | (same as H1) | (same as H1) | (same as H1) |

Table 5.13 ( continued)

|  |  | M1 | 29310158 | $\leftarrow$ | 12358910 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M2 | 42101687 | $\leftarrow$ | 142867 |  |
|  |  | M3 | 246136 | $\stackrel{\sim}{2}$ | 21463106 |  |
|  | J.S. | M4 | 104632718 |  | 467103128 | (same as $\mathrm{H}_{1}$ ) |
|  |  | M5 | 2931045718 | 2931045178 | 2357419108 |  |
| 13 |  | M6 | 91024531768 | 91024513768 | 52431791086 |  |
|  |  | Job 1 | 123456 |  | $\longleftarrow$ |  |
| (DATA E1) |  | Job 2 | 153246 |  | $\leftarrow$ |  |
|  |  | Job 3 | 15436 |  | $\longleftarrow$ |  |
|  | O.S. | Job 4 | 42356 |  | $\longleftarrow$ |  |
|  |  | Job 5 | 156 |  | $\longleftarrow$ |  |
|  |  | Job 6 | 43236 | (same as H1) | $\leftarrow$ | (same as $\mathrm{H}^{\prime}$ ) |
|  |  | Job 7 | 4526 |  | $\longleftarrow$ |  |
|  |  | Job 8 | 12456 |  | $\longleftarrow$ |  |
|  |  | Job 9 | 156 |  |  |  |
|  |  | Job 10 | 41256 |  | 41356 |  |
|  |  | M1 | 258931061 | $\longleftarrow$ | 12358910 |  |
|  |  | M2 | 872341 |  | 147682 |  |
|  |  | M3 | 26106341 | 26103461 | 62143106 |  |
|  | J.S. | M4 | 7106842341 | $\longleftarrow$ | 4671031482 | (same as H 1 ) |
|  |  | M5 | 27598101 | 27985101 | 273591108 |  |
| 14 |  | M6 | 75928106341 | 97825310461 | 75934110268 |  |
|  |  | Job 1 | 123456 |  | $\longleftarrow$ |  |
| (DATA E2) |  | Job 2 | 153246 |  |  |  |
|  |  | Job 3 | 12436 |  | 15436 |  |
|  | O.S. | Job 4 | 42346 |  | $\longleftarrow$ |  |
|  |  | Job 5 | 156 |  |  |  |
|  |  | Job 6 | 43136 | (same as H1) | 43236 | (same as H1) |
|  |  | Job 7 | 4526 |  |  |  |
|  |  | Job 8 | 12456 |  | - |  |
|  |  | Job 9 | 156 |  | $\longleftarrow$ |  |
|  |  | Job 10 | 41356 |  | $\longleftarrow$ |  |

Table 5.13 ( continued)

|  |  | M1 | 13259841010 |  | 12358961010 | 12359841010 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M2 | 1368102 |  | 1348210 | 1368102 |
|  |  | M3 | 1676423 |  | 1462763 | 1676432 |
|  | J.S. | M4 | 764103812 | (same as $\mathrm{H}_{1}$ ) | 467103182 | 764103812 |
|  |  | M5 | 7592481 |  | 2574918 | 7592481 |
| 15 |  | M6 | 57964810321 |  | 54769310218 | 75964381012 |
| (DATA E3) | O.S. | Job 1 | 123456 | (same as H1) | $\leftarrow$ | (same as H 1 ) |
|  |  | Job 2 | 153246 |  | $\leftarrow$ |  |
|  |  | Job 3 | 12436 |  | $\leftarrow$ |  |
|  |  | Job 4 | 41356 |  | 42356 |  |
|  |  | Job 5 | 156 |  |  |  |
|  |  | Job 6 | 43236 |  | 43136 |  |
|  |  | Job 7 | 4536 |  | $\leftarrow$ |  |
|  |  | Job 8 | 12456 |  | $\leftarrow$ |  |
|  |  | Job 9 | 156 |  | $\leftarrow$ |  |
|  |  | Job 10 | 41216 |  | $\leftarrow$ |  |
|  |  | M1 | 2315981010 | $\leftarrow$ | 1235891010 | 2135981010 |
|  |  | M2 | 31624810 | $\leftarrow$ | 13468210 | 13624810 |
|  |  | M3 | 6217643 | $\leftarrow$ | 1642673 | 6127643 |
|  | J.S. | M4 | 761043128 | 761043182 | 467103182 | 671043128 |
|  |  | M5 | 2759418 | 2759481 | 2574918 | 2759418 |
| 16 |  | M6 | 57694321018 | 57694381021 | 54679311028 | 75694321108 |
|  |  | Job 1 | 123456 |  |  |  |
| (DATA E4) |  | Job 2 | 153246 |  |  |  |
|  |  | Job 3 | 12436 |  |  |  |
|  | O.S. | Job 4 | 42356 |  |  |  |
|  |  | Job 5 | 156 |  |  |  |
|  |  | Job 6 | 43236 | (same as H 1 ) | (same as H1) | (same as H 1 ) |
|  |  | Job 7 | 4536 |  |  |  |
|  |  | Job 8 | 12456 |  |  |  |
|  |  | Job 9 | 156 |  |  |  |
|  |  | Job 10 | 41216 |  |  |  |

Table 5.13 ( continued)

| Example | $n_{p} \times N O P$ | Iteration number | Makespan |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | H1 | H2 | FIFO | SIP |
| 1 | $7 \times 4$ | 0 | 45 | 42 | 43 | 45 |
|  |  | 1 | *41 | 42 |  |  |
|  |  | 2 | 41 |  |  |  |
| 2 | $7 \times 4$ | 0 | *72 | 78 | 78 | *72 |
|  |  | 1 | 78 | 74 |  |  |
|  |  | 2 |  | 74 |  |  |
| 3 | $7 \times 4$ | 0 | *69 | *69 | 90 | *69 |
|  |  | 1 | 69 | 69 |  |  |
| 4 | $7 \times 4$ | 0 | *38 | *38 | 39 | *38 |
|  |  | 1 | 38 | 38 |  |  |
| 5 | $7 \times 5$ | 0 | 74 | 74 | 81 | 74 |
|  |  | 1 | *72 | 81 |  |  |
|  |  | 2 | 72 |  |  |  |
| 6 | $7 \times 5$ | 0 | *64 | *64 | 72 | *64 |
|  |  | 1 | 79 | 79 |  |  |
| 7 | $7 \times 5$ | 0 | *56 | *56 | 57 | *56 |
|  |  | 1 | 57 | 58 |  |  |
| 8 | $7 \times 5$ | 0 | 37 | 39 | 37 | 37 |
|  |  | 1 | *36 | 38 |  |  |
|  |  | 2 | 36 | 38 |  |  |

Table 5.14 Comparative evaluation of the heuristics on the static FMS makespan problems

| 9 | $7 \times 6$ | 0 | $\begin{aligned} & \hline \text { "82 } \\ & 82 \end{aligned}$ | $\begin{aligned} & \hline 82 \\ & 82 \end{aligned}$ | 88 | *82 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 10 | $7 \times 6$ | 0 1 2 | $\begin{aligned} & 89 \\ & 89 \\ & * 84 \end{aligned}$ | $\begin{aligned} & 89 \\ & 89 \end{aligned}$ | *84 | 89 |
| 11 | $7 \times 6$ | 0 1 2 | $\begin{aligned} & 97 \\ & 96 \\ & 96 \end{aligned}$ | $\begin{aligned} & 97 \\ & 97 \end{aligned}$ | *93 | 97 |
| 12 | $7 \times 6$ | 0 1 | $\begin{aligned} & 36 \\ & 36 \end{aligned}$ | $\begin{aligned} & 36 \\ & 36 \end{aligned}$ | *35 | 36 |
| 13 | $10 \times 6$ | 0 1 2 | $\begin{aligned} & 98 \\ & 104 \end{aligned}$ | $\begin{aligned} & 98 \\ & 97 \\ & 97 \end{aligned}$ | *95 | 98 |
| 14 | $10 \times 6$ | 0 1 | $\begin{aligned} & 66 \\ & 70 \end{aligned}$ | $\begin{aligned} & 67 \\ & 68 \end{aligned}$ | *59 | 66 |
| 15 | $10 \times 6$ | 0 1 | $\begin{aligned} & \text { *55 } \\ & 71 \end{aligned}$ | $\begin{aligned} & * 55 \\ & 71 \end{aligned}$ | 57 | 59 |
| 16 | $10 \times 6$ | 0 1 | $\begin{aligned} & 56 \\ & 61 \end{aligned}$ | $\begin{aligned} & 57 \\ & 77 \end{aligned}$ | 55 | *54 |

Table 5.14 ( continued)

Total number of tests $=16$

|  | Heuristic <br> H 1 | Heuristic <br> H 2 | FIFO | SIP |
| :--- | :---: | :---: | :---: | :---: |
| Number of best <br> performance measure <br> of makespan | ${ }^{* 11}$ | 6 | 5 | 7 |
| Ranking | ${ }^{* * 1.906}$ | 2.656 | 2.719 | 2.531 |

Table 5.15 Ranking for the heuristics on the static FMS makespan problems

|  |  |  | Job sequence( J.S. ) on each machine and operation schedule( O.S.) for each job corresponding to the optimal average lead time obtained from each scheduling technique |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Example number |  |  | Heuristic | Heuristic | FIFO | SIP |
|  |  |  | H1 | H2 |  |  |
| 1(DATA B1) | J.S. | M1 | 1362 | 6523 | 1326 | 6532 |
|  |  | M2 | 45372 | 41273 | 45372 | 41372 |
|  |  | M3 | 724 | 274 |  | 724 |
|  |  | M4 | 1546 | 1564 | 15476 | 5146 |
|  |  | M5 | 31567 | 63157 | 3615 | 63157 |
|  |  | M6 | 1543672 | 6152473 | 1543726 | 1546372 |
|  | O.S. | Job 1 | 4156 | 4256 | 4156 | (same as H 2 ) |
|  |  | Job 2 | 3126 |  |  |  |
|  |  | Job 3 | 5126 | $\leftarrow$ | $\longleftarrow$ |  |
|  |  | Job 4 | 2436 |  |  |  |
|  |  | Job 5 | 4256 | 4156 | 4256 |  |
|  |  | Job 6 | 5146 | $\leftarrow$ | $\leftarrow$ |  |
|  |  | Job 7 | 3526 | $\longleftarrow$ | 3426 |  |
|  |  | M1 | 6532 | 65324 | 362 |  |
|  |  | M2 | 41732 | 4172 | 415372 |  |
|  |  | M3 | 5724 | 5723 | 2574 |  |
|  | J.S. | M4 | 146 | 164 | 146 | (same as H1) |
|  |  | M5 | 63715 | $\leftarrow$ | 36175 |  |
| 2 |  | M6 | 1756342 | 6175324 | 1357462 |  |
|  |  | Job 1 | 4256 | $\leftarrow$ | $\leftarrow$ |  |
| (DATA B2) |  | Job 2 | 3126 |  |  |  |
|  |  | Job 3 | 5126 | 5136 | 5126 |  |
|  | O.S. | Job 4 | 2436 | 2416 | 2436 | (same as H1) |
|  |  | Job 5 | 3156 | - | 3256 |  |
|  |  | Job 6 | 5146 | - | $\longleftarrow$ |  |
|  |  | Job 7 | 3526 | $\leftarrow$ | $\leftarrow$ |  |
|  |  | M1 | 762 |  | 72536 |  |
|  |  | M2 | 415732 |  | 41723 |  |
|  |  | M3 | 24 |  |  |  |
|  | J.S. | M4 | 154763 | (same as H 1 ) | 15476 | (same as H1) |
|  |  | M5 | 6315 |  | 3615 |  |
| 3 |  | M6 | 4617532 |  | 4712536 |  |
|  |  | Job 1 | 4256 |  | $\leftarrow$ |  |
| (DATA B3) |  | Job 2 | 3126 |  | $\leftarrow$ |  |
|  |  | Job 3 | 5426 |  | 5126 |  |
|  | O.S. | Job 4 | 2436 | (same as H 1 ) |  | (same as H 1 ) |
|  |  | Job 5 | 4256 |  | 4156 |  |
|  |  | Job 6 | 5146 |  | $\longleftarrow$ |  |
|  |  | Job 7 | 1426 |  | $\longleftarrow$ |  |

Table 5.16 Schedules for the static FMS lead time problems


Table 5.16 ( continued)

|  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M1 M2 | 167214 <br> 6453265 |  | $216714$ | $162714$ $6453265$ |
|  |  | M3 | 275452 |  | 257452 |  |
|  | J.S. | M4 | 13173 | (same as H1) | 13163 | 13173 |
|  |  | M5 | 3764 |  | 37374 | 3764 |
| 7 |  | M6 | 1734265 |  | 1742536 | 1734265 |
|  | O.S. | Job 1 | 41416 | (same as H1) | $\longleftarrow$ | (same as H 1 ) |
| (DATA C3) |  | Job 2 | 31236 |  |  |  |
|  |  | Job 3 | 54246 |  | 54546 |  |
|  |  | Job 4 | 23156 |  | $\leftarrow$ |  |
|  |  | Job 5 | 32326 |  |  |  |
|  |  | Job 6 | 21526 |  | 21426 |  |
|  |  | Job 7 | 35146 |  | 35156 |  |
|  | J.S. | M1 | 1261 | 1621 | 2161 | 1621 |
|  |  | M2 | 4654265 | 6456245 | 4652456 | 6454625 |
|  |  | M3 | 7254752 | 725472 | 2574752 | 2574572 |
|  |  | M4 | 1713673 | 1713573 | 1731673 | 171373 |
|  |  | M5 | 334 | 3634 | 334 | 3634 |
| 8 |  | M6 | 1627435 | 1627345 | 1274563 | 1672453 |
| (DATA C4) | O.S. | Job 1 | 41416 | $\longleftarrow$ | (same as H1) | $\leftarrow$ |
|  |  | Job 2 | 31236 | $\leftarrow$ |  | $\longleftarrow$ |
|  |  | Job 3 | 54546 | $\leftarrow$ |  | $\leftarrow$ |
|  |  | Job 4 | 23256 |  |  | $\longleftarrow$ |
|  |  | Job 5 | 32326 | 32426 |  |  |
|  |  | Job 6 | 21426 | 21526 |  | 21526 |
|  |  | Job 7 | 34346 | $\longleftarrow$ |  | $\longleftarrow$ |
| (DATA D1) | J.S. | M1 | 25316 | 251367 | 123576 | 23156 |
|  |  | M2 | 42317 | 4217 | 1427 | 4217 |
|  |  | M3 | 246136 | 241636 | 214636 | 241636 |
|  |  | M4 | 462371 | 462317 | 467312 | 463271 |
|  |  | M5 | 25471 | 25341 | 23541 | 235471 |
|  |  | M6 | 5243176 | 5241376 | 5472136 | 2543176 |
|  | O.S. | Job 1 | 123456 | $\leftarrow$ | (same as H 2 ) | $\longleftarrow$ |
|  |  | Job 2 | 153246 | $\leftarrow$ |  | $\leftarrow$ |
|  |  | Job 3 | 12436 | 15436 |  | $\longleftarrow$ |
|  |  | Job 4 | 42356 |  |  | - |
|  |  | Job 5 | 156 | $\leftarrow$ |  | - |
|  |  | Job 6 | 43136 |  |  |  |
|  |  | Job 7 | 4526 | 4126 |  | 4526 |

Table 5.16 ( continued)

|  |  | M1 | 125367 | 213567 | 12357 | 213567 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M2 | 1427 | $\longleftarrow$ | 14267 | 1427 |
|  |  | M3 | 124636 | 216346 | 124636 | 214636 |
|  | J.S. | M4 | 461327 | 4631274 | 467132 | 463127 |
|  |  | M5 | 25314 | 2351 | 23541 | 23514 |
| 10 |  | M6 | 5124367 | 5132467 | 5412376 | 5124367 |
|  |  | Job 1 | 123456 | $\longleftarrow$ | $\longleftarrow$ |  |
| (DATA D2) |  | Job 2 | 153246 | $\longleftarrow$ | $\longleftarrow$ |  |
|  |  | Job 3 | 15436 | $\longleftarrow$ | $\leftarrow$ |  |
|  | O.S. | Job 4 | 42356 | 42346 | 42356 | (same as H1) |
|  |  | Job 5 | 156 | $\leftarrow$ | $\leftarrow$ |  |
|  |  | Job 6 | 43136 | $\longleftarrow$ | 43236 |  |
|  |  | Job 7 | 4126 | $\longleftarrow$ | $\longleftarrow$ |  |
|  |  | M1 | 21537 | $\leftarrow$ | 12357 | 12537 |
|  |  | M2 | 4126 | $\longleftarrow$ | 1426 | 14267 |
|  |  | M3 | 4216763 | 4216736 | 1426376 | 142636 |
|  | J.S. | M4 | 467123 | $\longleftarrow$ | 467132 | 461723 |
|  |  | M5 | $24531$ | $\leftarrow$ | $24351$ | $24513$ |
| 11 |  | M6 | $4512763$ | 4512736 | $4512376$ | $4512376$ |
|  |  | Job 1 | 123456 |  |  | $\longleftarrow$ |
| (DATA D3) |  | Job 2 | 153246 |  |  | $\longleftarrow$ |
|  |  | Job 3 | 15436 |  |  | $\longleftarrow$ |
|  | O.S. | $\text { Job } 4$ | 42356 | (same as H1) | (same as H1) | $\leftarrow$ |
|  |  | $\text { Job } 5$ | 156 |  |  | $\longleftarrow$ |
|  |  | Job 6 | 43236 |  |  |  |
|  |  | Job 7 | 4136 |  |  | 4126 |
|  |  |  | 5132 |  |  |  |
|  |  | M2 | 41762 |  | 41672 | 41762 |
|  |  | M3 | 461236 |  | 642163 | 461236 |
|  | J.S. | M4 | $4764312$ | (same as H1) | $4674312$ | $4764312$ |
|  |  | M5 | $57321$ |  | $27351$ | $57231$ |
| 12 |  | M6 | 5473216 |  | 4756231 |  |
|  |  |  |  |  |  |  |
| (DATA D4) |  | Job 2 | 153246 |  |  |  |
|  |  | Job 3 | 15436 |  |  |  |
|  | O.S. | Job 4 | 42346 | (same as H 1 ) | (same as H1) | (same as H1) |
|  |  | Job 5 | $156$ |  |  |  |
|  |  | $\text { Job } 6$ | $43236$ |  |  |  |
|  |  | Job 7 | 4526 |  |  |  |

Table 5.16 ( continued)

|  |  | M1 | 29310158 | $\leftarrow$ | 12358910 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M2 | 42101687 | $\longleftarrow$ | 142867 |  |
|  |  | M3 | 246136 | $\longleftarrow$ | 21463106 |  |
|  | J.S. | M4 | 104632718 |  | 467103128 | (same as H 1 ) |
|  |  | M5 | 2931045718 | 2931045178 | 2357419108 |  |
| 13 |  | M6 | 91024531768 | 91024513768 | 52431791086 |  |
| (DATA E1) |  | Job 1 | 123456 |  | $\leftarrow$ |  |
|  |  | Job 2 | 153246 |  | $\leftarrow$ |  |
|  |  | Job 3 | 15436 |  | $\longleftarrow$ |  |
|  | O.S. | Job 4 | 42356 |  | $\longleftarrow$ |  |
|  |  | Job 5 | 156 |  | $\leftarrow$ |  |
|  |  | Job 6 | 43236 | (same as H1) | $\leftarrow$ | (same as H 1 ) |
|  |  | Job 7 | 4526 |  | $\leftarrow$ |  |
|  |  | Job 8 | 12456 |  | $\longleftarrow$ |  |
|  |  | Job 9 | 156 |  |  |  |
|  |  | Job 10 | 41256 |  | 41356 |  |
| 14 |  | M1 | 258931061 | $\leftarrow$ | 12358910 |  |
|  |  | M2 | 872341 | $\leftarrow$ | 147682 |  |
|  |  | M3 | 26106341 | 26103461 | 62143106 |  |
|  | J.S. | M4 | 7106842341 | $\longleftarrow$ | 4671031482 | (same as H1) |
|  |  | M5 | 27598101 | 27985101 | 273591108 |  |
|  |  | M6 | 75928106341 | 97825310461 | 75934110268 |  |
| (DATA E2) |  | Job 1 | 123456 |  | $\longleftarrow$ |  |
|  |  | Job 2 | 153246 |  |  |  |
|  |  | Job 3 | 12436 |  | 15436 |  |
|  | O.S. | Job 4 | 42346 |  | $\leftarrow$ |  |
|  |  | Job 5 | 156 |  |  |  |
|  |  | Job 6 | 43136 | (same as H1) | 43236 | (same as H1) |
|  |  | Job 7 | 4526 |  | $\leftarrow$ |  |
|  |  | Job 8 | 12456 |  | $\longleftarrow$ |  |
|  |  | Job 9 | 156 |  | $\longleftarrow$ |  |
|  |  | Job 10 | 41356 |  | $\longleftarrow$ |  |

Table 5.16 ( continued )

|  |  | M1 | 13259841010 |  | 12358961010 | 12359841010 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | M2 | 1368102 |  | 1348210 | 1368102 |
|  |  | M3 | 1676423 |  | 1462763 | 1676432 |
|  | J.S. | M4 | 764103812 | (same as H 1 ) | 467103182 | 764103812 |
|  |  | M5 | 7592481 |  | 2574918 | 7592481 |
| 15 |  | M6 | 57964810321 |  | 54769310218 | 75964381012 |
|  |  | Job 1 | 123456 |  | $\longleftarrow$ |  |
| (DATA E3) |  | Job 2 | 153246 |  | $\longleftarrow$ |  |
|  |  | Job 3 | 12436 |  |  |  |
|  | O.S. | Job 4 | 41356 |  | 42356 |  |
|  |  | Job 5 | 156 |  |  |  |
|  |  | Job 6 | 43236 | (same as H 1 ) | 43136 | (same as H1) |
|  |  | Job 7 | 4536 |  |  |  |
|  |  | Job 8 | 12456 |  | $\leftarrow$ |  |
|  |  | Job 9 | 156 |  | $\leftarrow$ |  |
|  |  | Job 10 | 41216 |  | $\leftarrow$ |  |
|  |  | M1 | 25319861010 | 2315981010 | 1235891010 | 2135981010 |
|  |  | M2 | 3142810 | 31624810 | 13468210 | 13624810 |
|  |  | M3 | 2674613 | 6217643 | 1642673 | 6127643 |
|  | J.S. | M4 | 746103281 | 761043182 | 467103182 | 671043128 |
|  |  | M5 | 2759481 | $\leftarrow$ | 2574918 | 2759418 |
| 16 |  | M6 | 75964283101 | 57694381021 | 54679311028 | 75694321108 |
|  |  | Job 1 | 123456 | $\leftarrow$ |  |  |
| (DATA E4) |  | Job 2 | 153246 | $\leftarrow$ |  |  |
|  |  | Job 3 | 12436 | $\leftarrow$ |  |  |
|  | O.S. | Job 4 | 42356 | $\leftarrow$ |  |  |
|  |  | Job 5 | 156 | $\longleftarrow$ |  |  |
|  |  | Job 6 | 43136 | 43236 | (same as H 2 ) | (same as H 2 ) |
|  |  | Job 7 | 4536 |  |  |  |
|  |  | Job 8 | 12456 | $\longleftarrow$ |  |  |
|  |  | Job 9 | 156 | $\leftarrow$ |  |  |
|  |  | Job 10 | 41216 | - |  |  |

Table 5.16 ( continued)

| Example | $n_{p} \times$ NOP | Iteration number | Average lead time |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | H 1 | H2 | FIFO | SIP |
| 1 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 30.71 \\ & 29.43 \\ & 29.14 \\ & 29.14 \end{aligned}$ | $\begin{aligned} & 27.86 \\ & { }^{*} 27.71 \\ & 27.71 \end{aligned}$ | 30.14 | 30.71 |
| 2 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 54.43 \\ & 61 \end{aligned}$ | $\begin{aligned} & \text { *51.57 } \\ & 52.59 \end{aligned}$ | 62.57 | 54.43 |
| 3 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 45 \\ & 45 \end{aligned}$ | $\begin{aligned} & * 45 \\ & 45 \end{aligned}$ | 55.29 | *45 |
| 4 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 26.57 \\ & * 25.86 \\ & 25.86 \end{aligned}$ | $\begin{aligned} & 26.57 \\ & * 25.86 \\ & 25.86 \end{aligned}$ | 29.71 | 26.57 |
| 5 | $7 \times 5$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 52.71 \\ & 50.57 \\ & 50.29 \\ & 50.29 \end{aligned}$ | $\begin{aligned} & 52.71 \\ & 49.57 \\ & 49.14 \\ & 49.14 \end{aligned}$ | 63 | *49 |
| 6 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 49.71 \\ & 52.43 \end{aligned}$ | $\begin{aligned} & \text { *49.71 } \\ & 52.43 \end{aligned}$ | 56.43 | *49.71 |
| 7 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 41.71 \\ & 46.43 \end{aligned}$ | $\begin{aligned} & * 41.71 \\ & 46.71 \end{aligned}$ | 44.29 | 41.86 |
| 8 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 31.14 \\ & * 30.57 \\ & 30.57 \end{aligned}$ | $\begin{aligned} & 31.14 \\ & * 30.57 \\ & 30.57 \end{aligned}$ | 31.14 | 31.14 |

Table 5.17 Comparative evaluation of the heuristics on the static FMS lead time problems

| 9 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 1 \\ & 2 \\ & 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 59 \\ & 55 \\ & 55 \end{aligned}$ | $\begin{aligned} & 57.57 \\ & 54.86 \\ & 54.57 \\ & * 54.43 \\ & 54.43 \end{aligned}$ | 60.71 | 59 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 10 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 57.29 \\ & * 57.14 \\ & 57.29 \end{aligned}$ | $\begin{aligned} & 58.29 \\ & 58.57 \end{aligned}$ | 60.43 | 57.29 |
| 11 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & \hline 63 \\ & * 60 \\ & 60.29 \end{aligned}$ | $\begin{aligned} & 63 \\ & \text { *60 } \\ & 60.29 \end{aligned}$ | 62.71 | 63 |
| 12 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 24.14 \\ & * 23.86 \\ & 23.86 \end{aligned}$ | $\begin{aligned} & 24.14 \\ & { }^{2} 23.86 \\ & 23.86 \end{aligned}$ | 27.43 | 24.14 |
| 13 | $10 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 63.1 \\ & 63.2 \end{aligned}$ | $\begin{aligned} & 62.1 \\ & { }^{661} \\ & 61 \end{aligned}$ | 71.6 | 63.1 |
| 14 | $10 \times 6$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 37.5 \\ & 38.8 \end{aligned}$ | $\begin{aligned} & * 36.2 \\ & 36.4 \end{aligned}$ | 45.5 | 37.5 |
| 15 | $10 \times 6$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \star 36.5 \\ & 42.2 \end{aligned}$ | $\begin{aligned} & * 36.5 \\ & 42.2 \end{aligned}$ | 41.2 | 36.6 |
| 16 | $10 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 43.2 \\ & 41.6 \\ & 42.9 \end{aligned}$ | $\begin{aligned} & 43.2 \\ & 44.5 \end{aligned}$ | 42.9 | *41.5 |

Table 5.17 ( continued)

Total number of tests $=16$

|  | Heuristic <br> H1 | Heuristic <br> H2 | FIFO | SIP |
| :--- | :---: | :---: | :---: | :---: |
| Number of best <br> performance measure <br> of average lead time | 9 | $* * 13$ | 0 | 4 |
| Ranking | 1.906 | ${ }^{* * 1.688}$ | 3.781 | 2.625 |

Table 5.18 Ranking for the heuristics on the static FMS lead time problems

| Example | $n \times$ NOP | Performance measure | Heuristic H1 |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | $d_{j}=1.5 \times \sum_{k=1}^{K_{j}} p_{j, k}$ | $d_{j}=1.3 \times \sum_{k=1}^{K_{j}} p_{j, k}$ | optimal due date |
| 1 | $7 \times 4$ | m.s. | $\begin{aligned} & 42 \\ & 28.43 \end{aligned}$ | $\begin{aligned} & 42 \\ & 28.43 \end{aligned}$ | $\begin{aligned} & 41 \\ & 29.14 \end{aligned}$ |
| 2 | $7 \times 4$ | m.s. | $\begin{aligned} & 78 \\ & 60.71 \end{aligned}$ | $\begin{aligned} & 72 \\ & 55.14 \end{aligned}$ | $\begin{aligned} & 72 \\ & 54.43 \end{aligned}$ |
| 3 | $7 \times 4$ | m.s. | $\begin{aligned} & 92 \\ & 47.14 \end{aligned}$ | $\begin{aligned} & 69 \\ & 45.57 \end{aligned}$ | $\begin{aligned} & 69 \\ & 45 \end{aligned}$ |
| 4 | $7 \times 4$ | m.s. | $\begin{aligned} & 38 \\ & 26 \end{aligned}$ | $\begin{aligned} & 38 \\ & 26 \end{aligned}$ | $\begin{aligned} & 38 \\ & 25.86 \end{aligned}$ |
| 5 | $7 \times 5$ | m.s. | $\begin{aligned} & 80 \\ & 50.57 \end{aligned}$ | $\begin{aligned} & 80 \\ & 50.57 \end{aligned}$ | $\begin{aligned} & 72 \\ & 50.29 \end{aligned}$ |
| 6 | $7 \times 5$ | m.s. | $\begin{aligned} & 74 \\ & 53.57 \end{aligned}$ | $\begin{aligned} & 82 \\ & 52 \end{aligned}$ | $\begin{aligned} & 64 \\ & 49.71 \end{aligned}$ |
| 7 | $7 \times 5$ | m.s. | $\begin{aligned} & 61 \\ & 42.86 \end{aligned}$ | $\begin{aligned} & 61 \\ & 42.86 \end{aligned}$ | $\begin{aligned} & 56 \\ & 41.71 \end{aligned}$ |
| 8 | $7 \times 5$ | m.s. | $\begin{aligned} & 37 \\ & 31.14 \end{aligned}$ | $\begin{aligned} & 37 \\ & 31.14 \end{aligned}$ | $\begin{aligned} & 36 \\ & 30.57 \end{aligned}$ |
| Total valu correspon performan | of the ng measure | m.s. | $\begin{aligned} & 502 \\ & 340.42 \end{aligned}$ | $\begin{aligned} & 481 \\ & 331.71 \end{aligned}$ | $\begin{aligned} & * 448 \\ & * \end{aligned}$ |

Table 5.19 Comparative study of different due date assumptions on the system performance ( with heuristic H1 )

| Example | $n \times N O P$ | Performance measure | Heuristic H2 |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | $\mathrm{d}_{\mathrm{j}}=1.5 \times \sum_{\mathrm{k}=1} \mathrm{p}_{\mathrm{j}, \mathrm{k}}$ | $\mathrm{d}_{\mathrm{j}}=1.3 \times \sum_{\mathrm{k}=1}^{\mathrm{K}_{\mathrm{j}}} \mathrm{p}_{\mathrm{j}, \mathrm{k}}$ | optimal due date |
| 1 | $7 \times 4$ | m.s. | $\begin{aligned} & 42 \\ & 27.71 \end{aligned}$ | $\begin{aligned} & 42 \\ & 27.71 \end{aligned}$ | $\begin{aligned} & 42 \\ & 27.71 \end{aligned}$ |
| 2 | $7 \times 4$ | $\stackrel{\text { m.s. }}{ }$ | $\begin{aligned} & 77 \\ & 55.14 \end{aligned}$ | $\begin{aligned} & 78 \\ & 54.29 \end{aligned}$ | $\begin{aligned} & 74 \\ & 51.57 \end{aligned}$ |
| 3 | $7 \times 4$ | $\underset{1}{\text { m.s. }}$ | $\begin{aligned} & 92 \\ & 47.14 \end{aligned}$ | $\begin{aligned} & 69 \\ & 45.57 \end{aligned}$ | $\begin{aligned} & 69 \\ & 45 \end{aligned}$ |
| 4 | $7 \times 4$ | m.s. | $\begin{aligned} & 38 \\ & 26 \end{aligned}$ | $\begin{aligned} & 38 \\ & 26 \end{aligned}$ | $\begin{aligned} & 38 \\ & 25.86 \end{aligned}$ |
| 5 | $7 \times 5$ | m.s. | $\begin{aligned} & 80 \\ & 50.57 \end{aligned}$ | $\begin{aligned} & 80 \\ & 50.57 \end{aligned}$ | $\begin{aligned} & 74 \\ & 49.14 \end{aligned}$ |
| 6 | $7 \times 5$ | m.s. | $\begin{aligned} & \hline 63 \\ & 46.57 \end{aligned}$ | $\begin{aligned} & \hline 66 \\ & 47.29 \end{aligned}$ | $\begin{aligned} & 64 \\ & 49.71 \end{aligned}$ |
| 7 | $7 \times 5$ | m.s. | $\begin{aligned} & 61 \\ & 42.86 \end{aligned}$ | $\begin{aligned} & 61 \\ & 42.86 \end{aligned}$ | $\begin{aligned} & 56 \\ & 41.71 \end{aligned}$ |
| 8 | $7 \times 5$ | m.s. | $\begin{aligned} & 44 \\ & 31.14 \end{aligned}$ | $\begin{aligned} & 39 \\ & 31.14 \end{aligned}$ | $\begin{aligned} & 38 \\ & 30.57 \end{aligned}$ |
| Total value correspond performa | of the ng measure | m.s. | $\begin{aligned} & 497 \\ & 327.13 \end{aligned}$ | $\begin{aligned} & 473 \\ & 325.43 \end{aligned}$ | $\begin{aligned} & * 455 \\ & * 321.27 \end{aligned}$ |

Table 5.20 Comparative study of different due date assumptions on the system performance ( with heuristic H 2 )

Total number of tests $=48$


Table 5.21 Experimental data for the dynamic FMS due date problems

| Example | $n_{p} \times$ NOP | Performance measure | Heuristic H1 | Heuristic H2 | SLACK | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $7 \times 4$ | $\begin{aligned} & \text { m.s. } \\ & \text { l } \end{aligned}$ | $\begin{gathered} 180 \\ 33.833 \\ * 155.5 \end{gathered}$ | $\begin{aligned} & \hline 178 \\ & 35.11 \\ & 185.5 \end{aligned}$ | $\begin{aligned} & 177 \\ & 34.29 \\ & 177.8 \end{aligned}$ | $\begin{aligned} & \hline 168 \\ & 34.09 \\ & 164.8 \end{aligned}$ |
| 2 | $7 \times 4$ | $\begin{gathered} \hline \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 302 \\ & 117.86 \\ & 2018.5 \end{aligned}$ | $\begin{gathered} 314 \\ 109.17 \\ * 1742.5 \end{gathered}$ | $\begin{aligned} & \hline 320 \\ & 116.91 \\ & 2000 \end{aligned}$ | $\begin{aligned} & \hline 297 \\ & 113.26 \\ & 1887.3 \end{aligned}$ |
| 3 | $7 \times 4$ | $\begin{aligned} & \text { m.s. } \\ & \text { I } \\ & c \end{aligned}$ | $\begin{aligned} & 289 \\ & 91.26 \\ & 1467.3 \end{aligned}$ | $\begin{aligned} & 295 \\ & 91.71 \\ & 1483.3 \end{aligned}$ | $\begin{gathered} \hline 284 \\ 89.37 \\ * 1401.3 \end{gathered}$ | $\begin{aligned} & \hline 288 \\ & 90.91 \\ & 1435.3 \end{aligned}$ |
| 4 | $7 \times 4$ | $\begin{gathered} \hline \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 161 \\ & 29.17 \\ & 53 \end{aligned}$ | $\begin{gathered} 160 \\ 28.57 \\ * 39 \end{gathered}$ | $\begin{aligned} & 160 \\ & 29.77 \\ & 56.8 \end{aligned}$ | $\begin{aligned} & 158 \\ & 29.11 \\ & 58.8 \end{aligned}$ |
| 5 | $7 \times 5$ | $\begin{aligned} & \text { m.s. } \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 305 \\ & 104.06 \\ & 1659.5 \end{aligned}$ | $\begin{gathered} 295 \\ 103.51 \\ * 1643.5 \end{gathered}$ | $\begin{aligned} & 293 \\ & 107.43 \\ & 1777.5 \end{aligned}$ | $\begin{aligned} & 319 \\ & 112.06 \\ & 2006 \end{aligned}$ |
| 6 | $7 \times 5$ | $\begin{aligned} & \hline \mathrm{m} . \mathrm{s} . \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 267 \\ & 89.54 \\ & 1404 \end{aligned}$ | $\begin{gathered} 258 \\ 85.06 \\ * 1253.8 \end{gathered}$ | $\begin{aligned} & 261 \\ & 87.91 \\ & 1341.5 \end{aligned}$ | $\begin{aligned} & 264 \\ & 88.77 \\ & 1393 \end{aligned}$ |
| 7 | $7 \times 5$ | $\begin{aligned} & \text { m.s. } \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{gathered} 231 \\ 71.43 \\ * 889.5 \end{gathered}$ | $\begin{aligned} & 234 \\ & 72.4 \\ & 915 \end{aligned}$ | $\begin{aligned} & 244 \\ & 73.91 \\ & 957 \end{aligned}$ | $\begin{aligned} & 234 \\ & 74.14 \\ & 989.7 \end{aligned}$ |
| 8 | $7 \times 5$ | $\begin{aligned} & \text { m.s. } \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{gathered} 165 \\ 33.17 \\ * 141.3 \end{gathered}$ | $\begin{aligned} & 165 \\ & 34.4 \\ & 175.3 \end{aligned}$ | $\begin{aligned} & 160 \\ & 32.83 \\ & 141.5 \end{aligned}$ | $\begin{aligned} & 166 \\ & 33.46 \\ & 155.3 \end{aligned}$ |
| 9 | $7 \times 6$ | $\begin{aligned} & \hline \text { m.s. } \\ & \text { l } \\ & c \end{aligned}$ | $\begin{aligned} & 394 \\ & 131.09 \\ & 2728.5 \end{aligned}$ | $\begin{aligned} & \hline 407 \\ & 131.29 \\ & 2723.5 \end{aligned}$ | $\begin{aligned} & \hline 407 \\ & 126.69 \\ & 2595 \end{aligned}$ | $\begin{gathered} \hline 374 \\ 124.97 \\ * 2509 \end{gathered}$ |
| 10 | $7 \times 6$ | $\begin{gathered} \text { m.s. } \\ \text { I } \\ c \end{gathered}$ | $\begin{aligned} & 370 \\ & 139.6 \\ & 2314.6 \end{aligned}$ | $\begin{gathered} 365 \\ 132.74 \\ * 2221.7 \end{gathered}$ | $\begin{aligned} & 375 \\ & 120.6 \\ & 2359.5 \end{aligned}$ | $\begin{aligned} & 360 \\ & 128.89 \\ & 2635.5 \end{aligned}$ |
| 11 | $7 \times 6$ | $\begin{gathered} \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & \hline 376 \\ & 125.34 \\ & 2216 \end{aligned}$ | $\begin{aligned} & \hline 398 \\ & 128.46 \\ & 2325 \end{aligned}$ | $\begin{aligned} & 370 \\ & 139.34 \\ & 2695.8 \end{aligned}$ | $\begin{gathered} 365 \\ 120.29 \\ * 2051.3 \end{gathered}$ |
| 12 | $7 \times 6$ | $\begin{gathered} \hline \text { m.s. } \\ \text { l } \\ c \end{gathered}$ | $\begin{gathered} 157 \\ 24.8 \\ * 63 \end{gathered}$ | $\begin{gathered} 157 \\ 24.8 \\ * 63 \end{gathered}$ | $\begin{aligned} & 160 \\ & 28.17 \\ & 136.8 \end{aligned}$ | $\begin{aligned} & 157 \\ & 24.63 \\ & 66.5 \end{aligned}$ |

Table 5.22 Comparative evaluation of the heuristics on the dynamic FMS due date problems (TEST A )

| Example | $n_{p} \times$ NOP | Performance measure | Heuristic <br> H1 | Heuristic H2 | SLACK | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $7 \times 4$ | $\begin{aligned} & \mathrm{m} . \mathrm{s} . \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 179 \\ & 34.43 \\ & 33 \end{aligned}$ | $\begin{gathered} 180 \\ 34.49 \\ * 12 \end{gathered}$ | $\begin{aligned} & 179 \\ & 34.29 \\ & 42 \end{aligned}$ | $\begin{aligned} & 168 \\ & 34.09 \\ & 19 \end{aligned}$ |
| 2 | $7 \times 4$ | $\begin{gathered} \hline \text { m.s. } \\ \text { I } \\ c \end{gathered}$ | $\begin{aligned} & \hline 317 \\ & 116 \\ & 1317 \end{aligned}$ | $\begin{aligned} & \hline 313 \\ & 118.14 \\ & 1392 \end{aligned}$ | $\begin{aligned} & \hline 330 \\ & 118.14 \\ & 1387 \end{aligned}$ | $\begin{aligned} & 297 \\ & 113.26 \\ & * 1289 \end{aligned}$ |
| 3 | $7 \times 4$ |  | $\begin{aligned} & \hline 272 \\ & 87 \\ & 828 \end{aligned}$ | $\begin{gathered} 276 \\ 85.31 \\ * 772 \end{gathered}$ | $\begin{aligned} & 275 \\ & 87.71 \\ & 854 \end{aligned}$ | $\begin{aligned} & 288 \\ & 90.91 \\ & 941 \end{aligned}$ |
| 4 | $7 \times 4$ | $\begin{aligned} & \mathrm{m} . \mathrm{s} . \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{gathered} 161 \\ 29.69 \\ * 1 \end{gathered}$ | $\begin{aligned} & 161 \\ & 29.69 \\ & * 1 \end{aligned}$ | $\begin{aligned} & 161 \\ & 29.69 \\ & 3 \end{aligned}$ | $\begin{aligned} & 158 \\ & 29.11 \\ & 5 \end{aligned}$ |
| 5 | $7 \times 5$ |  | $\begin{aligned} & 304 \\ & 99.91 \\ & 1008 \end{aligned}$ | $\begin{aligned} & 308 \\ & 99.66 \\ & 997 \end{aligned}$ | $\begin{gathered} 281 \\ 99.57 \\ * 992 \end{gathered}$ | $\begin{aligned} & \hline 319 \\ & 112.06 \\ & 1547 \end{aligned}$ |
| 6 | $7 \times 5$ | $\begin{aligned} & \text { m.s. } \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 255 \\ & 86.71 \\ & * 788 \end{aligned}$ | $\begin{aligned} & 255 \\ & 86.43 \\ & 790 \end{aligned}$ | $\begin{aligned} & \hline 251 \\ & 89.03 \\ & 873 \end{aligned}$ | $\begin{aligned} & 264 \\ & 88.77 \\ & 895 \end{aligned}$ |
| 7 | $7 \times 5$ | $\begin{aligned} & \hline \text { m.s. } \\ & 1 \\ & c \end{aligned}$ | $\begin{aligned} & \hline 229 \\ & 72.34 \\ & 476 \end{aligned}$ | $\begin{gathered} \hline 231 \\ 71.26 \\ * 438 \end{gathered}$ | $\begin{aligned} & 244 \\ & 74.89 \\ & 572 \end{aligned}$ | $\begin{aligned} & 234 \\ & 74.14 \\ & 583 \end{aligned}$ |
| 8 | $7 \times 5$ | $\begin{aligned} & \hline \text { m.s. } \\ & 1 \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 169 \\ & 35.06 \\ & 25 \end{aligned}$ | $\begin{gathered} 166 \\ 33.86 \\ * 8 \end{gathered}$ | $\begin{aligned} & 164 \\ & 33 \\ & 15 \end{aligned}$ | $\begin{aligned} & 166 \\ & 33.46 \\ & 27 \end{aligned}$ |
| 9 | $7 \times 6$ | $\begin{aligned} & \mathrm{m} . \mathrm{s} . \\ & \mathrm{c} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 395 \\ & 124.8 \\ & 2018 \end{aligned}$ | $\begin{aligned} & \hline 406 \\ & 125.17 \\ & 1981 \end{aligned}$ | $\begin{aligned} & 407 \\ & 126.06 \\ & 2033 \end{aligned}$ | $\begin{aligned} & \hline 374 \\ & 124.97 \\ & * 1962 \end{aligned}$ |
| 10 | $7 \times 6$ | $\begin{aligned} & \mathrm{m} . \mathrm{s} . \\ & \mathrm{c} \\ & \mathrm{c} \end{aligned}$ | $\begin{gathered} 365 \\ 117 \\ * 1687 \end{gathered}$ | $\begin{aligned} & 374 \\ & 127 \\ & 2039 \end{aligned}$ | $\begin{aligned} & 375 \\ & 120.17 \\ & 1797 \end{aligned}$ | $\begin{aligned} & 360 \\ & 128.89 \\ & 2073 \end{aligned}$ |
| 11 | $7 \times 6$ | $\begin{aligned} & \text { m.s. } \\ & 1 \\ & c \end{aligned}$ | $\begin{aligned} & 379 \\ & 127.66 \\ & 1625 \end{aligned}$ | $\begin{aligned} & \hline 410 \\ & 132.51 \\ & 1798 \end{aligned}$ | $\begin{aligned} & 388 \\ & 138.77 \\ & 2015 \end{aligned}$ | $\begin{aligned} & \hline 365 \\ & 120.29 \\ & * 1467 \end{aligned}$ |
| 12 | $7 \times 6$ |  | $\begin{aligned} & 156 \\ & 25.91 \\ & * 0 \end{aligned}$ | $\begin{gathered} 156 \\ 25.91 \\ * 0 \end{gathered}$ | $\begin{gathered} 156 \\ 25.91 \\ { }^{0} \end{gathered}$ | $\begin{gathered} 157 \\ 24.63 \\ { }^{0} 0 \end{gathered}$ |

Table 5.23 Comparative evaluation of the heuristics on the dynamic FMS due date problems (TEST B )

| Example | $n_{p} \times$ NOP | Performance measure | Heuristic H1 | Heuristic H2 | SLACK | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $7 \times 4$ | $\begin{gathered} \hline \mathrm{m} . \mathrm{s} . \\ \mathrm{c} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 100 \\ & 41.24 \\ & 219.8 \end{aligned}$ | $\begin{array}{r} 100 \\ 40.1 \\ * 208 \end{array}$ | $\begin{aligned} & 103 \\ & 42.38 \\ & 239.5 \end{aligned}$ | $\begin{aligned} & 97 \\ & 41.43 \\ & 236 \end{aligned}$ |
| 2 | $7 \times 4$ | $\begin{gathered} \mathrm{m} . \mathrm{s} . \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 198 \\ & 104.14 \\ & 922 \end{aligned}$ | $\begin{aligned} & \hline 197 \\ & 99.71 \\ & 859.5 \end{aligned}$ | $\begin{aligned} & 192 \\ & 107.71 \\ & 997 \end{aligned}$ | $\begin{gathered} 181 \\ 91.76 \\ * 725.3 \end{gathered}$ |
| 3 | $7 \times 4$ | $\begin{aligned} & \text { m.s. } \\ & \text { I } \end{aligned}$ | $\begin{gathered} 190 \\ 74.29 \\ * 516.8 \end{gathered}$ | $\begin{aligned} & 174 \\ & 75.62 \\ & 552.5 \end{aligned}$ | $\begin{aligned} & 181 \\ & 80.71 \\ & 638.3 \end{aligned}$ | $\begin{aligned} & 177 \\ & 80.67 \\ & 649.5 \end{aligned}$ |
| 4 | $7 \times 4$ | $\begin{aligned} & \hline \text { m.s. } \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 98 \\ & 36 \\ & 143.8 \end{aligned}$ | $\begin{gathered} \hline 92 \\ 33.67 \\ * 101.3 \end{gathered}$ | $\begin{aligned} & 93 \\ & 35.52 \\ & 131 \end{aligned}$ | $\begin{aligned} & 94 \\ & 36.05 \\ & 144.8 \end{aligned}$ |
| 5 | $7 \times 5$ | $\begin{aligned} & \text { m.s. } \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{gathered} \hline 189 \\ 86.33 \\ * 614.5 \end{gathered}$ | $\begin{gathered} 189 \\ 86.33 \\ * 614.5 \end{gathered}$ | $\begin{aligned} & 193 \\ & 98.81 \\ & 874.3 \end{aligned}$ | $\begin{aligned} & 211 \\ & 92.1 \\ & 785.3 \end{aligned}$ |
| 6 | $7 \times 5$ | $\begin{gathered} \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 166 \\ & 85.48 \\ & 751 \end{aligned}$ | $\begin{gathered} 178 \\ 81.52 \\ * 680.8 \end{gathered}$ | $\begin{aligned} & 161 \\ & 86.9 \\ & 781 \end{aligned}$ | $\begin{aligned} & 175 \\ & 86.19 \\ & 786.8 \end{aligned}$ |
| 7 | $7 \times 5$ | $\begin{gathered} \mathrm{m} . \mathrm{s} . \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 143 \\ & 67.62 \\ & 447.5 \end{aligned}$ | $\begin{gathered} 143 \\ 66 \\ * 413.5 \end{gathered}$ | $\begin{aligned} & 156 \\ & 67.48 \\ & 447 \end{aligned}$ | $\begin{aligned} & 149 \\ & 71.48 \\ & 537.5 \end{aligned}$ |
| 8 | $7 \times 5$ | $\begin{gathered} \hline \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 92 \\ & 38.9 \\ & 202.8 \end{aligned}$ | $\begin{gathered} 105 \\ 39.05 \\ * 200.5 \end{gathered}$ | $\begin{aligned} & 95 \\ & 39.38 \\ & 211 \end{aligned}$ | $\begin{aligned} & 104 \\ & 39.48 \\ & 214.8 \end{aligned}$ |
| 9 | $7 \times 6$ | $\begin{aligned} & \mathrm{m} . \mathrm{s} . \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & \hline 248 \\ & 111.24 \\ & 1218.5 \end{aligned}$ | $\begin{aligned} & \hline 253 \\ & 111.86 \\ & 1225.5 \end{aligned}$ | $\begin{gathered} 249 \\ 103.9 \\ * 1069 \end{gathered}$ | $\begin{aligned} & 228 \\ & 105.71 \\ & 1096 \end{aligned}$ |
| 10 | $7 \times 6$ | $\begin{gathered} \hline \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & \hline 225 \\ & 101.33 \\ & * 1002 \end{aligned}$ | $\begin{aligned} & \hline 232 \\ & 104.62 \\ & 1071 \end{aligned}$ | $\begin{aligned} & 235 \\ & 103.38 \\ & 1045 \end{aligned}$ | $\begin{aligned} & \hline 220 \\ & 101.67 \\ & 1013.5 \end{aligned}$ |
| 11 | $7 \times 6$ | $\begin{aligned} & \hline \text { m.s. } \\ & \text { l } \end{aligned}$ | $\begin{aligned} & 248 \\ & 108.9 \\ & 993.5 \end{aligned}$ | $\begin{aligned} & 255 \\ & 110.71 \\ & 1031.5 \end{aligned}$ | $\begin{aligned} & 241 \\ & 121.05 \\ & 1238.3 \end{aligned}$ | $\begin{gathered} 241 \\ 104.14 \\ * 898.7 \end{gathered}$ |
| 12 | $7 \times 6$ | $\begin{gathered} \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 92 \\ & 30.38 \\ & 131.5 \end{aligned}$ | $\begin{gathered} 95 \\ 30.24 \\ * 128.5 \end{gathered}$ | $\begin{aligned} & 90 \\ & 30.1 \\ & 146.5 \end{aligned}$ | $\begin{aligned} & 92 \\ & 30.71 \\ & 145.8 \end{aligned}$ |

Table 5.24 Comparative evaluation of the heuristics on the dynamic FMS due date problems (TEST C )

| Example | $n_{p} \times N O P$ | Performance measure | Heuristic H1 | Heuristic H2 | SLACK | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $7 \times 4$ | $\begin{gathered} \hline \text { m.s. } \\ \text { i } \\ \text { c } \end{gathered}$ | $\begin{aligned} & 103 \\ & 40.67 \\ & 61 \end{aligned}$ | $\begin{aligned} & 109 \\ & 42.19 \\ & 68 \end{aligned}$ | $\begin{gathered} 103 \\ 40.52 \\ * 58 \end{gathered}$ | $\begin{aligned} & \hline 97 \\ & 41.43 \\ & 94 \end{aligned}$ |
| 2 | $7 \times 4$ | $\begin{aligned} & \hline \text { m.s. } \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{aligned} & 201 \\ & 103.81 \\ & 522 \end{aligned}$ | $\begin{aligned} & \hline 203 \\ & 101.1 \\ & 465 \end{aligned}$ | $\begin{aligned} & 188 \\ & 106.19 \\ & 573 \end{aligned}$ | $\begin{gathered} 181 \\ 91.76 \\ * 453 \end{gathered}$ |
| 3 | $7 \times 4$ | $\begin{gathered} \text { m.s. } \\ \text { l } \\ c \end{gathered}$ | $\begin{aligned} & 177 \\ & 76.9 \\ & 274 \end{aligned}$ | $\begin{gathered} 178 \\ 74.76 \\ * 246 \end{gathered}$ | $\begin{aligned} & 177 \\ & 77.62 \\ & 286 \end{aligned}$ | $\begin{aligned} & 177 \\ & 80.67 \\ & 357 \end{aligned}$ |
| 4 | $7 \times 4$ | $\begin{aligned} & \hline \text { m.s. } \\ & \text { l } \\ & c \end{aligned}$ | $\begin{aligned} & \hline 95 \\ & 35.14 \\ & * 15 \end{aligned}$ | $\begin{aligned} & \quad 95 \\ & 35.14 \\ & * 15 \end{aligned}$ | $\begin{aligned} & 94 \\ & 34.76 \\ & 17 \end{aligned}$ | $\begin{aligned} & 94 \\ & 36.05 \\ & 48 \end{aligned}$ |
| 5 | $7 \times 5$ | $\begin{gathered} \text { m.s. } \\ \text { I } \end{gathered}$ | $\begin{gathered} 202 \\ 87.62 \\ * 343 \end{gathered}$ | $\begin{gathered} 202 \\ 87.62 \\ * 343 \end{gathered}$ | $\begin{aligned} & 191 \\ & 91.76 \\ & 431 \end{aligned}$ | $\begin{aligned} & 211 \\ & 92.1 \\ & 453 \end{aligned}$ |
| 6 | $7 \times 5$ | $\begin{gathered} \mathrm{m} . \mathrm{s} . \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{gathered} 161 \\ 82.76 \\ * 366 \end{gathered}$ | $\begin{aligned} & \hline 172 \\ & 83 \\ & 371 \end{aligned}$ | $\begin{aligned} & 169 \\ & 87.29 \\ & 459 \end{aligned}$ | $\begin{aligned} & 175 \\ & 86.19 \\ & 489 \end{aligned}$ |
| 7 | $7 \times 5$ | $\begin{gathered} \hline \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & \hline 162 \\ & 68.81 \\ & * 221 \end{aligned}$ | $\begin{gathered} 169 \\ 68.81 \\ * 221 \end{gathered}$ | $\begin{aligned} & 155 \\ & 69.38 \\ & 242 \end{aligned}$ | $\begin{aligned} & 149 \\ & 71.48 \\ & 295 \end{aligned}$ |
| 8 | $7 \times 5$ | $\begin{gathered} \hline \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{gathered} 96 \\ 38.81 \\ * 39 \end{gathered}$ | $\begin{aligned} & 104 \\ & 40.33 \\ & 69 \end{aligned}$ | $\begin{aligned} & \hline 95 \\ & 39.24 \\ & 47 \end{aligned}$ | $\begin{aligned} & 104 \\ & 39.48 \\ & 70 \end{aligned}$ |
| 9 | $7 \times 6$ | $\begin{gathered} \hline \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & \hline 249 \\ & 107.52 \\ & 829 \end{aligned}$ | $\begin{aligned} & \hline 260 \\ & 104.57 \\ & 732 \end{aligned}$ | $\begin{aligned} & \hline 249 \\ & 101.81 \\ & * 686 \end{aligned}$ | $\begin{aligned} & 228 \\ & 105.71 \\ & 763 \end{aligned}$ |
| 10 | $7 \times 6$ | $\begin{gathered} \text { m.s. } \\ \text { l } \\ c \end{gathered}$ | $\begin{aligned} & 225 \\ & 98.19 \\ & * 606 \end{aligned}$ | $\begin{aligned} & 231 \\ & 101.48 \\ & 676 \end{aligned}$ | $\begin{aligned} & \hline 235 \\ & 101.24 \\ & 667 \end{aligned}$ | $\begin{aligned} & \hline 220 \\ & 101.67 \\ & 684 \end{aligned}$ |
| 11 | $7 \times 6$ | $\begin{gathered} \hline \text { m.s. } \\ \mathrm{l} \\ \mathrm{c} \end{gathered}$ | $\begin{aligned} & 265 \\ & 109.52 \\ & 641 \end{aligned}$ | $\begin{aligned} & 292 \\ & 109.76 \\ & 644 \end{aligned}$ | $\begin{aligned} & 264 \\ & 118.14 \\ & 810 \end{aligned}$ | $\begin{gathered} 241 \\ 104.14 \\ * 592 \end{gathered}$ |
| 12 | $7 \times 6$ | $\begin{aligned} & \hline \text { m.s. } \\ & \mathrm{l} \\ & \mathrm{c} \end{aligned}$ | $\begin{gathered} 90 \\ 29.81 \\ * 20 \end{gathered}$ | $\begin{aligned} & 90 \\ & 30.38 \\ & 24 \end{aligned}$ | $\begin{aligned} & 90 \\ & 30.14 \\ & 25 \end{aligned}$ | $\begin{aligned} & 92 \\ & 30.71 \\ & 48 \end{aligned}$ |

Table 5.25 Comparative evaluation of the heuristics on the dynamic FMS due date problems (TEST D)

|  | Performance measure | TEST A <br> (number of tests $=12$ ) |  |  |  | TEST B <br> (number of tests $=12$ ) |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | H2 SL | SLACK | SIP | H1 H2 |  | SLACK | SIP |
| Number of best performance of | m.s. | 2 | 2 | 3 | 7 | 31 |  | 4 | 6 |
|  | I | 2 | 4 | 3 | 3 | 23 |  | 2 | 5 |
|  | c | 4 | 6 | 1 | 2 | 46 |  | 2 | 4 |
| Ranking | m.s. | 2.792 | 2.667 | 2.583 | **1.958 | *2.25 | 2.833 | 32.625 | 2.292 |
|  | I | 2.625 | 2.542 | 2.583 | **2.25 | 2.333 | 2.542 | $2 \quad 2.875$ | **2.25 |
|  | c | 2.292 | 2 *2.208 | 82.75 | 2.75 | 2.167 | **2 | 2.875 | 2.958 |
|  | Performance <br> measure |  | TEST C <br> (number of tests $=12$ ) |  |  | TEST D <br> (number of tests = 12) |  |  |  |
|  |  | $\mathrm{H1}$ | H2 SL | SLACK | SIP | $\mathrm{H}_{1} \mathrm{H} 2$ |  | SLACK | SIP |
| Number of best performance of | m.s. | 3 | 4 | 3 | 5 | 31 |  | 5 | 8 |
|  |  | 4 | 6 | 1 | 2 | 63 | 3 | 3 | 2 |
|  | c | 3 | 7 | 1 | 2 | $7 \quad 4$ | 4 | 2 | 2 |
| Ranking | m.s. | 2.5 | 2.792 | 2.542 | *2.167 | 2.417 | 3.375 | 5 **2.042 | 2.083 |
|  | 1 | **2.042 | 1.958 | 3.25 | 2.75 | **1.875 | 2.458 | 2.5 | 3.167 |
|  | c | 2.125 | **1.875 | 35.083 | 2.917 | **1.792 | 2.125 | $25 \quad 2.667$ | 3.42 |

Table 5.26 Ranking for the heuristics on the dynamic FMS due date problems

| Job number | Operation schedule for each job |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Heuristic | Heuristic | SLACK | SIP |
|  | H 1 | H2 |  |  |
| $(1,1)$ | 4256 | $\leftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(1,2)$ | 4256 | $\leftarrow$ | $\leftarrow$ |  |
| $(1,3)$ | 4156 | $\leftarrow$ | $\leftarrow$ | 4256 |
| $(2,1)$ | 3126 | $\leftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(2,2)$ | 3126 | $\leftarrow$ | $\leftarrow$ |  |
| $(2,3)$ | 3126 | $\longleftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(3,1)$ | 5126 | $\leftarrow$ | $\leftarrow$ | 5426 |
| $(3,2)$ | 5436 | $\leftarrow$ | $\leftarrow$ |  |
| $(3,3)$ | 5436 | $\longleftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(4,1)$ | 2436 | $\leftarrow$ | $\leftarrow$ |  |
| $(4,2)$ | 2416 | $\leftarrow$ | $\leftarrow$ | 2436 |
| $(4,3)$ | 2436 | $\leftarrow$ | $\longleftarrow$ | $\leftarrow$ |
| $(5,1)$ | 4256 | $\leftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(5,2)$ | 3256 | $\leftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(5,3)$ | 4256 | $\longleftarrow$ | $\longleftarrow$ | 3256 |
| $(6,1)$ | 5146 | $\leftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(6,2)$ | 5146 | $\leftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(6,3)$ | 5146 | $\longleftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(7,1)$ | 1426 | $\longleftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(7,2)$ | 3426 | $\leftarrow$ | $\leftarrow$ | $\leftarrow$ |
| $(7,3)$ | 3426 | $\longleftarrow$ | $\leftarrow$ | $\leftarrow$ |

Table 5.27 Operation schedule for a dynamic FMS due date problem ( example 3 - TEST D)
Note : Job number (i,j) denotes the jth component of part-mix i.


Table 5.28 Job sequence for a dynamic FMS due date problem ( example 3-TEST D )

|  | Average execution time required for the <br> dynamic FMS due date problems (cp second) |  |  |  |
| :--- | :---: | :---: | :---: | :---: |
| Scheduling method | TEST A | TEST B | TEST C | TEST D |
| Heuristic H1 | 4.093 | 4.107 | 2.81 | 2.94 |
| Heuristic H2 | 4.596 | 4.653 | 3.064 | 3.174 |
| SLACK | 3.63 | 3.71 | 2.54 | 2.71 |
| SIP | 3.455 | 3.501 | 2.593 | 2.613 |

Table 5.29 Summary of computational effort on the dynamic FMS due date problems

Total number of tests $=48$

|  | Performance <br> measure | Heuristic <br> H 1 | Heuristic <br> H 2 | SLACK | SIP |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Number of      <br> best performance m.s. 11 8 15 26 <br> of c 14 16 9 12 <br> Ranking c.s. 18 23 6 10 | c | 2.49 | 2.917 | 2.448 | ${ }^{* * 2.125}$ |
|  | 2.094 | $* * 2.375$ | 2.802 | 2.604 |  |

Table 5.30 Summary of the performance of heuristics on dynamic FMS due date problems

Total number of tests $=48$

|  | Heuristics (H1+H2) | SLACK | SIP |
| :--- | :---: | :---: | :---: |
| Number of occurance of minimum <br> tardy cost | 34 | 6 | 10 |
| Percentage of best performance in <br> 48 problems | $70.83 \%$ | $12.5 \%$ | $20.83 \%$ |

Table 5.31 Performance of the heuristics on the measurement of tardy cost in dynamic FMS


Table 5.32 Comparative study of different due date assumptions on dynamic FMS

|  | STUDY 1 | STUDY 2 | STUDY 3 | STUDY 4 |
| :---: | :---: | :---: | :---: | :---: |
| Input rate : 1 job of each part-mix in every | 40 time units | 60 time units | 80 time units | $\begin{aligned} & \text { Input }=\text { Output } \\ & \text { rate } \\ & \text { rate } \end{aligned}$ |
| desired production: | $3 \text { jobs/ part- }$ | $\begin{gathered} 4 \text { jobs/part- } \\ \text { mix } \end{gathered}$ | $\begin{gathered} 3 \text { jobs/part- } \\ \text { mix } \end{gathered}$ | $5 \text { jobs/part- }$ |
| Data source : | DATA B1-B4 <br> DATA C1-C4 <br> DATA D1-D4 <br> DATAE1-E4 | $\leftarrow$ - | $\longleftarrow$ | $\leftarrow$ |
| $n_{p} \times$ NOP | $\begin{aligned} & 7 \times 4 \\ & 7 \times 5 \\ & 7 \times 6 \\ & 10 \times 6 \end{aligned}$ | $\leftarrow \sim$ | $\longleftarrow \sim$ | $\leftarrow \sim$ |

Table 5.33 Experimental data for the dynamic FMS makespan and average lead time problems

| Example | $n_{p} \times N O P$ | Iteration <br> number | MAKESPAN |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Heuristic H1 |  | Heuristic H2 |  | FIFO | SIP |
|  |  |  | MDYNA |  | MDYNA |  |  |  |
|  |  |  | 1 | 2 | 1 | 2 |  |  |
| 1 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & \hline 125 \\ & *_{1} 121 \\ & 121 \end{aligned}$ | $\begin{aligned} & 125 \\ & 131 \end{aligned}$ | $\begin{aligned} & \hline 122 \\ & 122 \end{aligned}$ | $\begin{aligned} & 122 \\ & 122 \end{aligned}$ | 125 | 125 |
| 2 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 192 \\ & 200 \end{aligned}$ | $\begin{aligned} & 192 \\ & 200 \end{aligned}$ | $\begin{aligned} & 189 \\ & 189 \end{aligned}$ | $\begin{aligned} & 189 \\ & 188 \\ & * 186 \\ & 186 \end{aligned}$ | 193 | 192 |
| 3 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 175 \\ & 175 \end{aligned}$ | $\begin{aligned} & 175 \\ & 179 \end{aligned}$ | $\begin{aligned} & 175 \\ & 186 \end{aligned}$ | $\begin{aligned} & 175 \\ & 186 \end{aligned}$ | *172 | 175 |
| 4 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \text { *118 } \\ & 118 \end{aligned}$ | $\begin{aligned} & * 118 \\ & 118 \end{aligned}$ | $\begin{aligned} & * 118 \\ & 118 \end{aligned}$ | $\begin{aligned} & * 118 \\ & 118 \end{aligned}$ | 119 | *118 |
| 5 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 188 \\ & 193 \\ & * 174 \end{aligned}$ | $\begin{aligned} & 188 \\ & 184 \\ & 177 \\ & 181 \end{aligned}$ | $\begin{aligned} & \hline 198 \\ & 193 \\ & 187 \\ & 187 \end{aligned}$ | $\begin{aligned} & 198 \\ & 199 \end{aligned}$ | 186 | 191 |
| 6 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 156 \\ & 156 \end{aligned}$ | $\begin{aligned} & * 156 \\ & 161 \end{aligned}$ | $\begin{aligned} & 160 \\ & 160 \end{aligned}$ | $\begin{aligned} & 160 \\ & 162 \end{aligned}$ | 164 | 164 |
| 7 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 146 \\ & 150 \end{aligned}$ | $\begin{aligned} & 146 \\ & 148 \end{aligned}$ | $\begin{aligned} & 155 \\ & 151 \\ & 155 \end{aligned}$ | $\begin{aligned} & \hline 155 \\ & 156 \end{aligned}$ | 149 | 164 |
| 8 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 117 \\ & 117 \end{aligned}$ | $\begin{aligned} & 117 \\ & * 116 \\ & 116 \end{aligned}$ | $\begin{aligned} & 119 \\ & 119 \end{aligned}$ | $\begin{aligned} & 119 \\ & 118 \\ & 118 \end{aligned}$ | 117 | 117 |

MDYNA $=1$, partial adjustment of due dates.
$=2$, full adjustment of due dates.

Table 5.34 Comparative evaluation of the heuristics on the dynamic FMS makespan problems (STUDY 1)

| 9 | $7 \times 6$ | 1 | $\begin{aligned} & * 228 \\ & 234 \end{aligned}$ | $\begin{aligned} & * 228 \\ & 234 \end{aligned}$ | $\begin{aligned} & 229 \\ & 246 \end{aligned}$ | $\begin{aligned} & 229 \\ & 235 \end{aligned}$ | 234 | *228 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 10 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & * 220 \\ & 224 \end{aligned}$ | $\begin{aligned} & \hline \text { *220 } \\ & 220 \\ & 229 \end{aligned}$ | $\begin{aligned} & 225 \\ & 229 \end{aligned}$ | $\begin{aligned} & 225 \\ & 225 \end{aligned}$ | 224 | *220 |
| 11 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 238 \\ & 238 \end{aligned}$ | $\begin{aligned} & 238 \\ & 244 \end{aligned}$ | $\begin{aligned} & 245 \\ & 252 \end{aligned}$ | $\begin{aligned} & 245 \\ & 242 \\ & 257 \end{aligned}$ | *231 | 238 |
| 12 | $7 \times 6$ | 0 1 | $\begin{aligned} & \hline 116 \\ & 116 \end{aligned}$ | $\begin{aligned} & 116 \\ & 116 \end{aligned}$ | $\begin{aligned} & \hline 116 \\ & 116 \end{aligned}$ | $\begin{aligned} & 116 \\ & 116 \end{aligned}$ | *115 | 116 |
| 13 | $10 \times 6$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \text { *242 } \\ & 242 \end{aligned}$ | $\begin{aligned} & \hline \text { *242 } \\ & 243 \end{aligned}$ | $\begin{aligned} & 247 \\ & 252 \end{aligned}$ | $\begin{aligned} & 247 \\ & 256 \end{aligned}$ | 244 | *242 |
| 14 | $10 \times 6$ | 0 1 | $\begin{aligned} & 150 \\ & 157 \end{aligned}$ | $\begin{aligned} & \hline 150 \\ & 158 \end{aligned}$ | $\begin{aligned} & 144 \\ & 151 \end{aligned}$ | $\begin{aligned} & \hline 144 \\ & 156 \end{aligned}$ | *142 | 147 |
| 15 | $10 \times 6$ | 1 | $\begin{aligned} & 165 \\ & 171 \end{aligned}$ | $\begin{aligned} & \hline 165 \\ & 175 \end{aligned}$ | $\begin{aligned} & \hline 167 \\ & 172 \end{aligned}$ | $\begin{aligned} & \hline 167 \\ & 185 \end{aligned}$ | 161 | *159 |
| 16 | $10 \times 6$ | 0 1 | $\begin{aligned} & * 151 \\ & 151 \end{aligned}$ | $\begin{aligned} & * 151 \\ & 162 \end{aligned}$ | $\begin{aligned} & 159 \\ & 171 \end{aligned}$ | $\begin{aligned} & 159 \\ & 183 \end{aligned}$ | 154 | *151 |

Table 5.34 (continued)

MAKESPAN

| Example | $n_{p} \times$ NOP | Iteration <br> number | MAKESPAN |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Heuristic H1 |  | Heuristic H2 |  | FIFO | SIP |
|  |  |  | MDYNA |  | MDYNA |  |  |  |
|  |  |  | 1 | 2 | 1 | 2 |  |  |
| 1 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 225 \\ & 225 \end{aligned}$ | $\begin{aligned} & 225 \\ & * 221 \\ & 221 \end{aligned}$ | $\begin{aligned} & 222 \\ & 222 \end{aligned}$ | $\begin{aligned} & 222 \\ & 222 \end{aligned}$ | 223 | 225 |
| 2 | $7 \times 4$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & \hline 272 \\ & 270 \\ & 270 \end{aligned}$ | $\begin{aligned} & 272 \\ & 269 \\ & 274 \end{aligned}$ | $\begin{aligned} & * 263 \\ & 267 \end{aligned}$ | $\begin{aligned} & \hline \text { *263 } \\ & 281 \end{aligned}$ | 269 | 264 |
| 3 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \text { *261 } \\ & 261 \end{aligned}$ | $\begin{aligned} & \text { "261 } \\ & 275 \end{aligned}$ | $\begin{aligned} & * 261 \\ & 261 \end{aligned}$ | $\begin{aligned} & * 261 \\ & 263 \end{aligned}$ | 268 | *261 |
| 4 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \text { *218 } \\ & 218 \end{aligned}$ | $\begin{aligned} & * 218 \\ & 218 \end{aligned}$ | $\begin{aligned} & * 218 \\ & 218 \end{aligned}$ | $\begin{aligned} & \text { *218 } \\ & 218 \end{aligned}$ | 219 | *218 |
| 5 | $7 \times 5$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 261 \\ & 252 \\ & 252 \end{aligned}$ | $\begin{aligned} & 261 \\ & 254 \\ & 257 \end{aligned}$ | $\begin{aligned} & 269 \\ & 259 \\ & 264 \end{aligned}$ | $\begin{aligned} & 269 \\ & 267 \\ & 270 \end{aligned}$ | 256 | *249 |
| 6 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 244 \\ & 251 \end{aligned}$ | $\begin{aligned} & * 244 \\ & 250 \end{aligned}$ | $\begin{aligned} & * 244 \\ & 245 \end{aligned}$ | $\begin{aligned} & * 244 \\ & 254 \end{aligned}$ | 252 | *244 |
| 7 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \text { *236 } \\ & 236 \end{aligned}$ | $\begin{aligned} & * 236 \\ & 237 \end{aligned}$ | $\begin{aligned} & * 236 \\ & 236 \end{aligned}$ | $\begin{aligned} & \text { "236 } \\ & 238 \end{aligned}$ | 237 | *236 |
| 8 | $7 \times 5$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 217 \\ & 217 \end{aligned}$ | $\begin{aligned} & 217 \\ & * 216 \\ & 216 \end{aligned}$ | $\begin{aligned} & 219 \\ & 219 \end{aligned}$ | $\begin{aligned} & 219 \\ & 218 \\ & 218 \end{aligned}$ | 217 | 217 |

MDYNA $=1$, partial adjustment of due dates.
$=2$, full adjustment of due dates.

Table 5.35 Comparative evaluation of the heuristics on the dynamic FMS makespan problems (STUDY 2)

| 9 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & \hline 301 \\ & 301 \end{aligned}$ | $\begin{aligned} & \hline 301 \\ & 309 \end{aligned}$ | $\begin{aligned} & 312 \\ & 312 \end{aligned}$ | $\begin{aligned} & 312 \\ & 309 \\ & 319 \end{aligned}$ | 307 | *301 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 10 | $7 \times 6$ | 1 2 | $\begin{aligned} & \hline 296 \\ & * 294 \\ & 294 \end{aligned}$ | $\begin{aligned} & 296 \\ & 297 \end{aligned}$ | $\begin{aligned} & * 294 \\ & 315 \end{aligned}$ | $\begin{aligned} & * 294 \\ & 313 \end{aligned}$ | *294 | 296 |
| 11 | $7 \times 6$ | 0 1 2 | $\begin{aligned} & 301 \\ & 306 \end{aligned}$ | $\begin{aligned} & 301 \\ & 298 \\ & 296 \end{aligned}$ | $\begin{aligned} & 305 \\ & 329 \end{aligned}$ | $\begin{gathered} 305 \\ 305 \end{gathered}$ | *294 | 301 |
| 12 | $7 \times 6$ | 0 1 | $\begin{aligned} & 216 \\ & 216 \end{aligned}$ | $\begin{aligned} & 216 \\ & 216 \end{aligned}$ | $\begin{aligned} & 216 \\ & 216 \end{aligned}$ | $\begin{aligned} & 216 \\ & 216 \end{aligned}$ | *215 | 216 |
| 13 | $10 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \text { *317 } \\ & 322 \end{aligned}$ | $\begin{aligned} & * 317 \\ & 328 \end{aligned}$ | $\begin{aligned} & 324 \\ & 345 \end{aligned}$ | $\begin{gathered} 324 \\ 351 \end{gathered}$ | 324 | *317 |
| 14 | $10 \times 6$ | 1 | $\begin{aligned} & 246 \\ & 246 \end{aligned}$ | $\begin{aligned} & 246 \\ & 250 \end{aligned}$ | $\begin{aligned} & 248 \\ & 248 \end{aligned}$ | $\begin{aligned} & 248 \\ & 249 \end{aligned}$ | *239 | 251 |
| 15 | $10 \times 6$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 235 \\ & 235 \end{aligned}$ | $\begin{aligned} & \text { *235 } \\ & 243 \end{aligned}$ | $\begin{aligned} & \text { *235 } \\ & 235 \end{aligned}$ | $\begin{aligned} & \text { *235 } \\ & 249 \end{aligned}$ | 237 | 239 |
| 16 | $10 \times 6$ | 0 1 | $\begin{aligned} & 236 \\ & 236 \end{aligned}$ | $\begin{aligned} & 236 \\ & 241 \end{aligned}$ | $\begin{aligned} & 237 \\ & 237 \end{aligned}$ | $\begin{aligned} & 237 \\ & 251 \end{aligned}$ | 235 | *234 |

Table 5.35 (continued)

| Example | $n_{p} \times$ NOP | Iteration number | MAKESPAN |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Heuristic H 1 |  | Heuristic H2 |  | FIFO | SIP |
|  |  |  | MDYNA |  | MDYNA |  |  |  |
|  |  |  | 1 | 2 | 1 | 2 |  |  |
| 1 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 205 \\ & 205 \end{aligned}$ | $\begin{aligned} & 205 \\ & { }^{2} 201 \\ & 201 \end{aligned}$ | $\begin{aligned} & 202 \\ & 202 \end{aligned}$ | $\begin{aligned} & 202 \\ & 202 \end{aligned}$ | 203 | 205 |
| 2 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \text { *232 } \\ & 232 \end{aligned}$ | $\begin{aligned} & * 232 \\ & 238 \end{aligned}$ | $\begin{aligned} & 238 \\ & 238 \end{aligned}$ | $\begin{aligned} & 238 \\ & 234 \\ & 234 \end{aligned}$ | 238 | *232 |
| 3 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 229 \\ & 229 \end{aligned}$ | $\begin{aligned} & \text { *229 } \\ & 229 \end{aligned}$ | $\begin{aligned} & \text { *229 } \\ & 229 \end{aligned}$ | $\begin{aligned} & \text { *229 } \\ & 229 \end{aligned}$ | 250 | *229 |
| 4 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \text { *198 } \\ & 198 \end{aligned}$ | $\begin{aligned} & \text { *198 } \\ & 198 \end{aligned}$ | $\begin{aligned} & \text { *198 } \\ & 198 \end{aligned}$ | $\begin{aligned} & \text { *198 } \\ & 198 \end{aligned}$ | 199 | *198 |
| 5 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 234 \\ & 234 \end{aligned}$ | $\begin{aligned} & 234 \\ & \text { "232 } \\ & 232 \end{aligned}$ | $\begin{aligned} & 234 \\ & 234 \end{aligned}$ | $\begin{aligned} & 234 \\ & 241 \end{aligned}$ | 241 | 234 |
| 6 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 224 \\ & 224 \end{aligned}$ | $\begin{aligned} & \text { "224 } \\ & 239 \end{aligned}$ | $\begin{aligned} & 224 \\ & 224 \end{aligned}$ | $\begin{aligned} & \text { *224 } \\ & 239 \end{aligned}$ | 232 | *224 |
| 7 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 216 \\ & 216 \end{aligned}$ | $\begin{aligned} & \text { *216 } \\ & 217 \end{aligned}$ | $\begin{aligned} & * 216 \\ & 216 \end{aligned}$ | $\begin{aligned} & \text { *216 } \\ & 218 \end{aligned}$ | 217 | *216 |
| 8 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 197 \\ & 197 \end{aligned}$ | $\begin{aligned} & 197 \\ & * 196 \\ & 196 \end{aligned}$ | $\begin{aligned} & 199 \\ & 199 \end{aligned}$ | $\begin{aligned} & 199 \\ & 198 \\ & 198 \end{aligned}$ | 197 | 197 |

MDYNA $=1$, partial adjustment of due dates.
$=2$, full adjustment of due dates.

Table 5.36 Comparative evaluation of the heuristics on the dynamic FMS makespan problems (STUDY 3 )

| 9 | $7 \times 6$ | $0$ | $\begin{aligned} & \text { *242 } \\ & 242 \end{aligned}$ | $\begin{aligned} & \hline * 242 \\ & 242 \end{aligned}$ | $\begin{aligned} & \hline * 242 \\ & 242 \end{aligned}$ | $\begin{aligned} & \text { *242 } \\ & 242 \end{aligned}$ | 248 | *242 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 10 | $7 \times 6$ | 0 1 2 3 | $\begin{aligned} & \hline 249 \\ & 249 \\ & { }^{*} 242 \end{aligned}$ | $\begin{aligned} & \hline 249 \\ & 249 \\ & 244 \\ & 254 \end{aligned}$ | $\begin{aligned} & 247 \\ & 247 \end{aligned}$ | $\begin{aligned} & 247 \\ & 272 \end{aligned}$ | 244 | 249 |
| 11 | $7 \times 6$ | 0 1 2 | $\begin{aligned} & 257 \\ & 257 \end{aligned}$ | $\begin{aligned} & 257 \\ & 256 \\ & 256 \end{aligned}$ | $\begin{aligned} & 257 \\ & 257 \end{aligned}$ | $\begin{aligned} & 257 \\ & 257 \end{aligned}$ | *253 | 257 |
| 12 | $7 \times 6$ | 0 1 | $\begin{aligned} & 196 \\ & 196 \end{aligned}$ | $\begin{aligned} & 196 \\ & 196 \end{aligned}$ | $\begin{aligned} & 196 \\ & 196 \end{aligned}$ | $\begin{aligned} & 196 \\ & 196 \end{aligned}$ | *195 | 196 |
| 13 | $10 \times 6$ | 0 1 2 3 | $\begin{aligned} & 259 \\ & 257 \\ & 256 \\ & 264 \end{aligned}$ | $\begin{aligned} & \hline 259 \\ & 273 \end{aligned}$ | $\begin{aligned} & * 253 \\ & 253 \end{aligned}$ | $\begin{aligned} & \text { *253 } \\ & 257 \end{aligned}$ | 256 | 259 |
| 14 | $10 \times 6$ | 0 1 | $\begin{aligned} & 226 \\ & 226 \end{aligned}$ | $\begin{aligned} & 226 \\ & 230 \end{aligned}$ | $\begin{aligned} & 227 \\ & 227 \end{aligned}$ | $\begin{aligned} & 227 \\ & 228 \end{aligned}$ | *219 | 226 |
| 15 | $10 \times 6$ | 0 1 | $\begin{aligned} & * 215 \\ & 215 \end{aligned}$ | $\begin{aligned} & * 215 \\ & 231 \end{aligned}$ | $\begin{aligned} & \text { "215 } \\ & 215 \end{aligned}$ | $\begin{gathered} * 215 \\ 231 \end{gathered}$ | 217 | 219 |
| 16 | $10 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 216 \\ & 216 \end{aligned}$ | $\begin{aligned} & 216 \\ & 221 \end{aligned}$ | $\begin{aligned} & 217 \\ & 217 \end{aligned}$ | $\begin{aligned} & 217 \\ & 237 \end{aligned}$ | 215 | *214 |

Table 5.36 (continued)

| Example | $n_{p} \times$ NOP | Iteration <br> number | MAKESPAN |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Heuristic H1 |  | Heuristic H2 |  | FIFO | SIP |
|  |  |  | MDYNA |  | MDYNA |  |  |  |
|  |  |  | 1 | 2 | 1 | 2 |  |  |
| 1 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 177 \\ & 183 \end{aligned}$ | $\begin{aligned} & * 177 \\ & 183 \end{aligned}$ | $\begin{aligned} & 199 \\ & 201 \end{aligned}$ | $\begin{aligned} & 199 \\ & 207 \end{aligned}$ | 191 | *177 |
| 2 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \hline \text { *382 } \\ & 399 \end{aligned}$ | $\begin{aligned} & * 382 \\ & 405 \end{aligned}$ | $\begin{aligned} & 405 \\ & 384 \\ & 384 \end{aligned}$ | $\begin{aligned} & 405 \\ & 412 \end{aligned}$ | 385 | 406 |
| 3 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \hline 363 \\ & 382 \end{aligned}$ | $\begin{aligned} & 363 \\ & 348 \\ & 357 \end{aligned}$ | $\begin{aligned} & 363 \\ & 388 \end{aligned}$ | $\begin{aligned} & \hline 363 \\ & 356 \\ & 358 \end{aligned}$ | *339 | 363 |
| 4 | $7 \times 4$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & \hline 165 \\ & 171 \end{aligned}$ | $\begin{aligned} & 165 \\ & * 161 \\ & 161 \end{aligned}$ | $\begin{aligned} & 189 \\ & 174 \\ & 174 \end{aligned}$ | $\begin{aligned} & \hline 189 \\ & 183 \\ & 183 \end{aligned}$ | 162 | 173 |
| 5 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 346 \\ & 350 \\ & 337 \\ & 337 \end{aligned}$ | $\begin{aligned} & 346 \\ & 325 \\ & 323 \\ & \text { *322 } \\ & 324 \end{aligned}$ | $\begin{aligned} & 346 \\ & 366 \end{aligned}$ | $\begin{aligned} & 346 \\ & 344 \\ & 344 \end{aligned}$ | 328 | 351 |
| 6 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 298 \\ & 308 \end{aligned}$ | $\begin{aligned} & 298 \\ & 298 \end{aligned}$ | $\begin{aligned} & 286 \\ & 314 \end{aligned}$ | $\begin{aligned} & 286 \\ & 295 \end{aligned}$ | 330 | *282 |
| 7 | $7 \times 5$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 276 \\ & * 261 \\ & 281 \end{aligned}$ | $\begin{aligned} & 276 \\ & 262 \\ & 292 \end{aligned}$ | $\begin{aligned} & 278 \\ & 292 \end{aligned}$ | $\begin{aligned} & 278 \\ & 279 \end{aligned}$ | 273 | 264 |
| 8 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & * 162 \\ & 171 \end{aligned}$ | $\begin{aligned} & \text { "162 } \\ & 165 \end{aligned}$ | $\begin{aligned} & 180 \\ & 180 \end{aligned}$ | $\begin{aligned} & 180 \\ & 189 \end{aligned}$ | 166 | 170 |

MDYNA $=1$, partial adjustment of due dates.
$=2$, full adjustment of due dates.

Table 5.37 Comparative evaluation of the heuristics on the dynamic FMS makespan problems (STUDY 4 )

| 9 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \end{aligned}$ | $\begin{gathered} * 401 \\ 429 \end{gathered}$ | $\begin{aligned} & * 401 \\ & 412 \end{aligned}$ | $\begin{aligned} & 439 \\ & 480 \end{aligned}$ | $\begin{aligned} & 439 \\ & 449 \end{aligned}$ | 420 | *401 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 10 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 395 \\ & 411 \end{aligned}$ | $\begin{aligned} & 395 \\ & 414 \end{aligned}$ | $\begin{aligned} & 404 \\ & 402 \\ & 467 \end{aligned}$ | $\begin{aligned} & 404 \\ & 404 \end{aligned}$ | *392 | 395 |
| 11 | $7 \times 6$ | 0 1 2 | $\begin{aligned} & \hline 457 \\ & 411 \\ & 455 \end{aligned}$ | $\begin{aligned} & 457 \\ & 454 \\ & 489 \end{aligned}$ | $\begin{aligned} & 431 \\ & 478 \end{aligned}$ | $\begin{aligned} & 431 \\ & 436 \end{aligned}$ | *400 | 457 |
| 12 | $7 \times 6$ | 0 1 2 3 | $\begin{aligned} & \hline 162 \\ & 164 \\ & * 160 \\ & 160 \end{aligned}$ | $\begin{aligned} & 162 \\ & 164 \end{aligned}$ | $\begin{aligned} & \hline 160 \\ & 165 \\ & 163 \\ & 172 \end{aligned}$ | $\begin{aligned} & \text { *160 } \\ & 165 \end{aligned}$ | 172 | 174 |
| 13 | $10 \times 6$ | 0 1 2 | $\begin{aligned} & 461 \\ & 489 \\ & * 421 \end{aligned}$ | $\begin{aligned} & 461 \\ & 461 \end{aligned}$ | $\begin{aligned} & 479 \\ & 463 \\ & 485 \end{aligned}$ | $\begin{aligned} & 479 \\ & 480 \end{aligned}$ | 432 | 461 |
| 14 | $10 \times 6$ | 0 1 2 | $\begin{aligned} & 285 \\ & 297 \end{aligned}$ | $\begin{aligned} & 285 \\ & 291 \end{aligned}$ | $\begin{aligned} & 282 \\ & 275 \\ & 282 \end{aligned}$ | $\begin{aligned} & 282 \\ & 290 \end{aligned}$ | *255 | 295 |
| 15 | $10 \times 6$ | 0 1 | $\begin{aligned} & 290 \\ & 307 \end{aligned}$ | $\begin{aligned} & 290 \\ & 300 \end{aligned}$ | $\begin{aligned} & 297 \\ & 313 \end{aligned}$ | $\begin{gathered} 297 \\ 300 \end{gathered}$ | *285 | 286 |
| 16 | $10 \times 6$ | 0 1 2 3 | $\begin{aligned} & 327 \\ & 311 \\ & 332 \end{aligned}$ | $\begin{aligned} & \hline 327 \\ & 312 \\ & 308 \\ & 310 \end{aligned}$ | $\begin{aligned} & 326 \\ & 366 \end{aligned}$ | $\begin{gathered} 326 \\ 355 \end{gathered}$ | *277 | 318 |

Table 5.37 (continued)

| Example | $n_{p} \times N O P$ | Iteration <br> number | AVERAGE LEAD TIME |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Heuristic H 1 |  | Heuristic H2 |  | FIFO | SIP |
|  |  |  | MDYNA |  | MDYNA |  |  |  |
|  |  |  | 1 | 2 | 1 | 2 |  |  |
| 1 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 29.81 \\ & 29.38 \\ & 29.29 \\ & 29.29 \end{aligned}$ | $\begin{aligned} & 29.81 \\ & 30 \end{aligned}$ | $\begin{aligned} & 27.76 \\ & 27.71 \\ & 27.71 \end{aligned}$ | $\begin{aligned} & 27.76 \\ & * 27.67 \\ & 27.67 \end{aligned}$ | 31.62 | 30.24 |
| 2 | $7 \times 4$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 76.33 \\ & 81.38 \end{aligned}$ | $\begin{aligned} & 76.33 \\ & 79.24 \end{aligned}$ | $\begin{aligned} & 71 \\ & 70.71 \\ & 74.05 \end{aligned}$ | $\begin{aligned} & 71 \\ & +68.38 \\ & 72.43 \end{aligned}$ | 89 | 76.33 |
| 3 | $7 \times 4$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 56.86 \\ & 56.86 \end{aligned}$ | $\begin{aligned} & \hline 56.86 \\ & * 55.86 \\ & 55.86 \end{aligned}$ | $\begin{aligned} & 57.38 \\ & 62.19 \end{aligned}$ | $\begin{aligned} & 57.38 \\ & 60.29 \end{aligned}$ | 65.71 | 57.9 |
| 4 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 26.57 \\ & 26.33 \\ & 26.33 \end{aligned}$ | $\begin{aligned} & \begin{array}{l} 26.57 \\ * 25.86 \\ 25.86 \end{array} \end{aligned}$ | $\begin{aligned} & 26.57 \\ & 26.33 \\ & 26.33 \end{aligned}$ | $\begin{aligned} & 2 \times 57 \\ & \text { *25.86 } \\ & 25.86 \end{aligned}$ | 29.71 | 26.57 |
| 5 | $7 \times 5$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \\ & 3 \\ & 4 \\ & 4 \end{aligned}$ | $\begin{aligned} & 69.33 \\ & 68.19 \\ & 70.76 \end{aligned}$ | $\begin{aligned} & 69.33 \\ & 69.24 \\ & 68.57 \\ & 68.29 \\ & 67.9 \\ & 67.9 \end{aligned}$ | $\begin{aligned} & \hline 69.24 \\ & 68.05 \\ & * 66.67 \\ & 66.67 \end{aligned}$ | $\begin{aligned} & 69.24 \\ & 68.29 \\ & 70.14 \end{aligned}$ | 83.48 | 72.33 |
| 6 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 58.19 \\ & 58.19 \end{aligned}$ | $\begin{aligned} & 58.19 \\ & 60.29 \end{aligned}$ | $\begin{aligned} & \hline 56.52 \\ & 56.52 \end{aligned}$ | $\begin{aligned} & * 56.52 \\ & 57.57 \end{aligned}$ | 67.71 | 58.95 |
| 7 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \hline 46.95 \\ & 51.33 \end{aligned}$ | $\begin{aligned} & * 46.95 \\ & 52.33 \end{aligned}$ | $\begin{aligned} & \hline 47.43 \\ & 52.1 \end{aligned}$ | $\begin{aligned} & 47.43 \\ & 51.57 \end{aligned}$ | 57.24 | 53.81 |
| 8 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 31.14 \\ & 30.95 \\ & 30.95 \end{aligned}$ | $\begin{aligned} & 31.14 \\ & \times 30.57 \\ & 30.57 \end{aligned}$ | $\begin{aligned} & 31.14 \\ & 30.95 \\ & 30.95 \end{aligned}$ | $\begin{aligned} & 31.14 \\ & * 30.57 \\ & 30.57 \end{aligned}$ | 31.14 | 31.14 |

MDYNA $=1$, partial adjustment of due dates.
$=2$, full adjustment of due dates.

Table 5.38 Comparative evaluation of the heuristics on the dynamic FMS average lead time problems (STUDY 1)

| 9 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 82.05 \\ & 80.57 \\ & 79.71 \\ & 79.71 \end{aligned}$ | $\begin{aligned} & 82.05 \\ & 74.81 \\ & 77.52 \end{aligned}$ | 84.52 80.81 78.95 78.95 | $\begin{aligned} & \hline 84.52 \\ & 71.52 \\ & 71.19 \\ & 71.48 \end{aligned}$ | 87.43 | 82.05 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 10 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 85.14 \\ & 87.05 \end{aligned}$ | $\begin{aligned} & 85.14 \\ & 80.1 \\ & * 75.81 \\ & 77.71 \end{aligned}$ | $\begin{aligned} & 89.67 \\ & 89.1 \\ & 80.95 \\ & 80.95 \end{aligned}$ | $\begin{aligned} & 89.67 \\ & 77.9 \\ & 81.62 \end{aligned}$ | 88.76 | 85.43 |
| 11 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 87.14 \\ & 86.86 \\ & 89.19 \end{aligned}$ | $\begin{aligned} & \hline 87.14 \\ & 89.81 \end{aligned}$ | $\begin{array}{r} * 86.43 \\ 90.67 \end{array}$ | $\begin{aligned} & \hline \text { *86.43 } \\ & 88.71 \end{aligned}$ | 99.52 | 87.14 |
| 12 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 24.14 \\ & 24.05 \\ & 24.05 \end{aligned}$ | $\begin{array}{r} 24.14 \\ * \\ \text { 23.86 } \\ 23.86 \end{array}$ | $\begin{aligned} & 24.14 \\ & 24.05 \\ & 24.05 \end{aligned}$ | $\begin{aligned} & 24.14 \\ & { }_{2}^{23.86} \\ & 23.86 \end{aligned}$ | 27.43 | 24.14 |
| 13 | $10 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 93.8 \\ & 90.13 \\ & 91.53 \end{aligned}$ | $\begin{aligned} & 93.8 \\ & 88.4 \\ & 89.53 \end{aligned}$ | $\begin{aligned} & 97.2 \\ & 90.87 \\ & 90.87 \end{aligned}$ | $\begin{aligned} & 97.2 \\ & * 87.43 \\ & 91.17 \end{aligned}$ | 111.07 | 94.17 |
| 14 | $10 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & 41.2 \\ & 44.07 \end{aligned}$ | $\begin{aligned} & 41.2 \\ & 42.87 \end{aligned}$ | $\begin{aligned} & 41.87 \\ & 43.47 \end{aligned}$ | $\begin{aligned} & 41.87 \\ & 42.4 \end{aligned}$ | 50.67 | *40.7 |
| 15 | $10 \times 6$ | 0 | $\begin{aligned} & * 47.7 \\ & 53.33 \end{aligned}$ | $\begin{aligned} & * 47.7 \\ & 52.17 \end{aligned}$ | $\begin{aligned} & 48.23 \\ & 54.33 \end{aligned}$ | $\begin{aligned} & 48.23 \\ & 54.77 \end{aligned}$ | 56.53 | 48.93 |
| 16 | $10 \times 6$ | 0 1 2 | $\begin{aligned} & 49.57 \\ & * 48.53 \\ & 48.8 \end{aligned}$ | $\begin{aligned} & 49.57 \\ & 50.03 \end{aligned}$ | $\begin{aligned} & 51.33 \\ & 51.4 \end{aligned}$ | $\begin{aligned} & \hline 51.33 \\ & 55.23 \end{aligned}$ | 55.13 | 48.97 |

Table 5.38 (continued)

## AVERAGE LEAD TIME

| Example | $n_{p} \times$ NOP | Iteration <br> number | AVERAGE LEAD TIME |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Heuristic H1 |  | Heuristic H2 |  | FIFO | SIP |
|  |  |  | MDYNA |  | MDYNA |  |  |  |
|  |  |  | 1 | 2 | 1 | 2 |  |  |
| 1 | $7 \times 4$ | 0 | 30.71 | 30.71 | 27.86 | 27.86 | 30.14 | 30.71 |
|  |  | 1 | 30.39 | 29.43 | 27.82 | *27.71 |  |  |
|  |  | 2 | 30.32 | 29.14 | 27.82 | 27.71 |  |  |
|  |  | 3 | 30.32 | 29.14 |  |  |  |  |
| 2 | $7 \times 4$ | 0 | 59.21 | 59.21 | 59.43 | 59.43 | 73.79 | 57.04 |
|  |  | 1 | 62.04 | 65.64 | *56.04 | 62.82 |  |  |
|  |  | 2 |  |  | 59.54 |  |  |  |
| 3 | $7 \times 4$ | 0 | 48 | 48 | *47.32 | *47.32 | 58.25 | 48 |
|  |  | 1 | 48 | 49.04 | 47.93 | 47.86 |  |  |
| 4 | $7 \times 4$ | 0 | 26.57 | 26.57 | 26.57 | 26.57 | 29.71 | 26.57 |
|  |  | 1 | 26.39 | *25.86 | 26.39 | *25.86 |  |  |
|  |  | 2 | 26.39 | 25.86 | 26.39 | 25.86 |  |  |
| 5 | $7 \times 5$ | 0 | 55.82 | 55.82 | 55.36 | 55.36 | 66.82 | 55.57 |
|  |  | 1 | 54.68 | 55.64 | *53.57 | 53.82 |  |  |
|  |  | 2 | 54.61 | 55.11 | 55.71 | 54.82 |  |  |
|  |  | 3 | 54.61 | 55.57 |  |  |  |  |
| 6 | $7 \times 5$ | 0 | *49.71 | *49.71 | *49.71 | *49.71 | 54.36 | *49.71 |
|  |  | 1 | 54.04 | 54.39 | 50.75 | 54 |  |  |
| 7 | $7 \times 5$ | 0 | *41.71 | *41.71 | *41.71 | *41.71 | 44.29 | 41.86 |
|  |  | 1 | 42.89 | 46.43 | 42.96 | 46.71 |  |  |
| 8 | $7 \times 5$ | 0 | 31.14 | 31.14 | 31.14 | 31.14 | 31.14 | 31.14 |
|  |  | 1 | 31 | *30.57 | 31 | *30.57 |  |  |
|  |  | 2 | 31 | 30.57 | 31 | 30.57 |  |  |

MDYNA $=1$, partial adjustment of due dates.
$=2$, full adjustment of due dates.

Table 5.39 Comparative evaluation of the heuristics on the dynamic FMS average lead time problems (STUDY 2 )

| 9 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 68.54 \\ & 67.54 \\ & 67.54 \end{aligned}$ | $\begin{aligned} & 68.54 \\ & * 66.14 \\ & 66.96 \end{aligned}$ | $\begin{aligned} & 71.57 \\ & 72.79 \end{aligned}$ | $\begin{aligned} & 71.57 \\ & 67 \\ & 67.61 \end{aligned}$ | 76.11 | 68.54 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 10 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 70.11 \\ & 69 \\ & 69 \end{aligned}$ | $\begin{aligned} & 70.11 \\ & \times 64.93 \\ & 67.18 \end{aligned}$ | $\begin{aligned} & 71.64 \\ & 79.96 \end{aligned}$ | $\begin{aligned} & 71.64 \\ & 74.25 \end{aligned}$ | 68.5 | 70.32 |
| 11 | $7 \times 6$ | 0 1 2 3 4 | $\begin{aligned} & 73.79 \\ & 72.79 \\ & 73.07 \end{aligned}$ | $\begin{aligned} & 73.79 \\ & 71.5 \\ & 69.82 \\ & * 69.75 \\ & 69.75 \end{aligned}$ | $\begin{aligned} & 75.64 \\ & 73.96 \\ & 72.54 \\ & 72.54 \end{aligned}$ | $\begin{aligned} & 75.64 \\ & 73.18 \\ & 73.14 \\ & 73.14 \end{aligned}$ | 75.89 | 73.79 |
| 12 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & \hline 24.14 \\ & 24.07 \\ & 24.07 \end{aligned}$ | $\begin{aligned} & 24.14 \\ & { }^{2} 23.86 \\ & 23.86 \end{aligned}$ | $\begin{aligned} & \hline 24.14 \\ & 24.07 \\ & 24.07 \end{aligned}$ | $\begin{aligned} & 24.14 \\ & * 23.86 \\ & 23.86 \end{aligned}$ | 27.43 | 24.14 |
| 13 | $10 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 83.28 \\ & 88.33 \end{aligned}$ | $\begin{aligned} & 83.28 \\ & * 81.8 \\ & 82.65 \end{aligned}$ | $\begin{aligned} & 86.88 \\ & 95 \end{aligned}$ | $\begin{aligned} & 86.88 \\ & 88.48 \end{aligned}$ | 93.58 | 83.3 |
| 14 | $10 \times 6$ | 0 1 | $\begin{aligned} & \hline 37.95 \\ & 38.85 \end{aligned}$ | $\begin{aligned} & 37.95 \\ & 40.9 \end{aligned}$ | $\begin{aligned} & \hline 38.1 \\ & 38.13 \end{aligned}$ | $\begin{aligned} & \hline 38.1 \\ & 38.2 \end{aligned}$ | 45.5 | 38.7 |
| 15 | $10 \times 6$ | 0 1 | $\begin{aligned} & \hline 36.5 \\ & 39.58 \end{aligned}$ | $\begin{aligned} & * 36.5 \\ & 42.7 \end{aligned}$ | $\begin{aligned} & \hline \text { *36.5 } \\ & 39.58 \end{aligned}$ | $\begin{aligned} & \hline \text { "36.5 } \\ & 44.1 \end{aligned}$ | 41.2 | 36.6 |
| 16 | $10 \times 6$ | 0 1 2 3 | $\begin{aligned} & 43.2 \\ & 42.8 \\ & 42.43 \\ & 44.23 \end{aligned}$ | $\begin{aligned} & \hline 43.2 \\ & 41.6 \\ & 44.5 \end{aligned}$ | $\begin{aligned} & 43.2 \\ & 44.85 \end{aligned}$ | $\begin{aligned} & \hline 43.2 \\ & 48.53 \end{aligned}$ | 42.9 | *41.5 |

Table 5.39 (continued)

| Example | $n_{p} \times N O P$ | Iteration <br> number | AVERAGE LEAD TIME |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Heuristic H1 |  | Heuristic H2 |  | FIFO | SIP |
|  |  |  | MDYNA |  | MDYNA |  |  |  |
|  |  |  | 1 | 2 | 1 | 2 |  |  |
| 1 | $7 \times 4$ | 0 | 30.71 | 30.71 | 27.86 | 27.86 | 30.14 | 30.71 |
|  |  | 1 | 30.29 | 29.43 | 27.81 | *27.71 |  |  |
|  |  | 2 | 30.19 | 29.14 | 27.81 | 27.71 |  |  |
|  |  | 3 | 30.19 | 29.14 |  |  |  |  |
| 2 | $7 \times 4$ | 0 | 54.43 | 54.43 | *51.57 | *51.57 | 62.57 | 54.43 |
|  |  | 1 | 56.62 | 61 | 51.81 | 52.29 |  |  |
| 3 | $7 \times 4$ | 0 | *45 | *45 | *45 | *45 | 54.62 | *45 |
|  |  | 1 | 45 | 45 | 45.81 | 47.43 |  |  |
| 4 | $7 \times 4$ | 0 | 26.57 | 26.57 | 26.57 | 26.57 | 29.71 | 26.57 |
|  |  | , | 26.33 | *25.86 | 26.33 | *25.86 |  |  |
|  |  | 2 | 26.33 | 25.86 | 26.33 | 25.86 |  |  |
| 5 | $7 \times 5$ | 0 | 52.71 | 52.71 | 52.71 | 52.71 | 63 | *49 |
|  |  | 1 | 52 | 50.57 | 51.67 | 49.57 |  |  |
|  |  | 2 | 51.9 | 50.29 | 52.29 | 51.1 |  |  |
|  |  | 3 | 51.9 | 50.29 |  |  |  |  |
| 6 | $7 \times 5$ | 0 | *49.71 | *49.71 | *49.71 | *49.71 | 56.43 | *49.71 |
|  |  | 1 | 50.62 | 52.43 | 50.62 | 52.43 |  |  |
| 7 | $7 \times 5$ | 0 | *41.71 | *41.71 | *41.71 | *41.71 | 44.29 | 41.86 |
|  |  | 1 | 43.29 | 46.43 | 43.38 | 46.71 |  |  |
| 8 | $7 \times 5$ | 0 | 31.14 | 31.14 | 31.14 | 31.14 | 31.14 | 31.14 |
|  |  | 1 | 30.95 | *30.57 | 30.95 | *30.57 |  |  |
|  |  | 2 | 30.95 | 30.57 | 30.95 | 30.57 |  |  |

MDYNA $=1$, partial adjustment of due dates.
$=2$, full adjustment of due dates.

Table 5.40 Comparative evaluation of the heuristics on the dynamic FMS average lead time problems (STUDY 3 )

| 9 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 59 \\ & 57.67 \\ & 57.67 \end{aligned}$ | $\begin{aligned} & 59 \\ & 55 \\ & 55 \end{aligned}$ | $\begin{aligned} & \hline 57.57 \\ & 56.67 \\ & 56.57 \\ & 56.52 \\ & 56.52 \end{aligned}$ | $\begin{aligned} & 57.57 \\ & 54.86 \\ & 54.57 \\ & 54.43 \\ & 54.43 \end{aligned}$ | 60.71 | 59 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 10 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 57.76 \\ & 57.71 \\ & 57.76 \end{aligned}$ | $\begin{aligned} & 57.76 \\ & 56.67 \\ & 56.43 \\ & * 55.67 \\ & 55.67 \end{aligned}$ | $\begin{aligned} & \hline 61.1 \\ & 61.19 \end{aligned}$ | $\begin{aligned} & \hline 61.1 \\ & 61.29 \end{aligned}$ | 60.43 | 57.76 |
| 11 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & \hline 63 \\ & 62 \\ & 62.1 \end{aligned}$ | $\begin{aligned} & \hline 63 \\ & * 60 \\ & 60.29 \end{aligned}$ | $\begin{aligned} & \hline 63 \\ & 62 \\ & 62.1 \end{aligned}$ | $\begin{aligned} & \hline 63 \\ & * 60 \\ & 60.29 \end{aligned}$ | 62.71 | 63 |
| 12 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 24.14 \\ & 24.05 \\ & 24.05 \end{aligned}$ | $\begin{aligned} & 24.14 \\ & * 23.86 \\ & 23.86 \end{aligned}$ | $\begin{aligned} & 24.14 \\ & 24.05 \\ & 24.05 \end{aligned}$ | $\begin{aligned} & 24.14 \\ & * 23.86 \\ & 23.86 \end{aligned}$ | 27.43 | 24.14 |
| 13 | $10 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 61.5 \\ & 65.7 \\ & 60.97 \\ & 63.37 \end{aligned}$ | $\begin{aligned} & \hline 61.5 \\ & 66.17 \end{aligned}$ | $\begin{aligned} & * 59.67 \\ & 60.17 \end{aligned}$ | $\begin{aligned} & \hline \text { *59.67 } \\ & 62.43 \end{aligned}$ | 71.7 | 61.5 |
| 14 | $10 \times 6$ | 0 1 | $\begin{aligned} & \hline 37.5 \\ & 37.93 \end{aligned}$ | $\begin{aligned} & 37.5 \\ & 38.8 \end{aligned}$ | $\begin{aligned} & \hline 36.2 \\ & 36.27 \end{aligned}$ | $\begin{aligned} & \text { *36.2 } \\ & 36.4 \end{aligned}$ | 45.5 | 37.5 |
| 15 | $10 \times 6$ | 0 1 | $\begin{aligned} & 36.5 \\ & 38.4 \end{aligned}$ | $\begin{aligned} & * 36.5 \\ & 42.2 \end{aligned}$ | $\begin{aligned} & 36.5 \\ & 38.4 \end{aligned}$ | $\begin{aligned} & * 36.5 \\ & 42.2 \end{aligned}$ | 41.2 | 36.6 |
| 16 | $10 \times 6$ | 0 1 2 | $\begin{aligned} & 43.2 \\ & 43.67 \\ & 43.1 \end{aligned}$ | $\begin{aligned} & \hline 43.2 \\ & 41.6 \\ & 42.9 \end{aligned}$ | $\begin{aligned} & 43.2 \\ & 43.63 \end{aligned}$ | $\begin{aligned} & 43.2 \\ & 44.5 \end{aligned}$ | 42.9 | *41.5 |

Table 5.40 (continued)

| Example | $n_{p} \times N O P$ | Iteration <br> number | AVERAGE LEAD TIME |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Heuristic H 1 |  | Heuristic H2 |  | FIFO | SIP |
|  |  |  | MDYNA |  | MDYNA |  |  |  |
|  |  |  | 1 | 2 | 1 | 2 |  |  |
| 1 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 30.86 \\ & 30.97 \end{aligned}$ | $\begin{aligned} & 30.86 \\ & 31.43 \end{aligned}$ | $\begin{aligned} & 30.06 \\ & { }^{30.03} \\ & 30.03 \end{aligned}$ | $\begin{aligned} & 30.06 \\ & 31.51 \end{aligned}$ | 33.14 | 30.86 |
| 2 | $7 \times 4$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 60.17 \\ & 58.91 \\ & 63.09 \end{aligned}$ | $\begin{aligned} & 60.17 \\ & * 58.17 \\ & 61 \end{aligned}$ | $\begin{aligned} & 58.77 \\ & 59.74 \end{aligned}$ | $\begin{aligned} & 58.77 \\ & 59.86 \end{aligned}$ | 61.06 | 60.11 |
| 3 | $7 \times 4$ | $\begin{aligned} & 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \text { *47.57 } \\ & 48.23 \end{aligned}$ | $\begin{aligned} & * 47.57 \\ & 49.31 \end{aligned}$ | $\begin{aligned} & \hline 47.57 \\ & 48.17 \end{aligned}$ | $\begin{aligned} & * 47.57 \\ & 48.63 \end{aligned}$ | 52.03 | * 47.57 |
| 4 | $7 \times 4$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 29.51 \\ & 28.8 \\ & 28.8 \end{aligned}$ | $\begin{aligned} & 29.51 \\ & 28.74 \\ & 28.74 \end{aligned}$ | $\begin{aligned} & 28.94 \\ & 28.46 \\ & 28.46 \end{aligned}$ | $\begin{aligned} & 28.94 \\ & 28.51 \\ & 29.43 \end{aligned}$ | 30.11 | *27.97 |
| 5 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 53.91 \\ & 53.89 \\ & 52.11 \\ & 52.11 \end{aligned}$ | $\begin{aligned} & 53.91 \\ & 53.29 \\ & 56 \end{aligned}$ | $\begin{aligned} & 53.91 \\ & 55.17 \end{aligned}$ | $\begin{aligned} & 53.91 \\ & 54.49 \end{aligned}$ | 59.51 | ${ }^{*} 51.69$ |
| 6 | $7 \times 5$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 48.11 \\ & 48.43 \end{aligned}$ | $\begin{aligned} & 48.11 \\ & 48.83 \end{aligned}$ | $\begin{aligned} & \hline 48.2 \\ & * 48.06 \\ & 48.06 \end{aligned}$ | $\begin{aligned} & 48.2 \\ & 49.97 \end{aligned}$ | 51.49 | 48.23 |
| 7 | $7 \times 5$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 45.06 \\ & 44.97 \\ & 46.46 \end{aligned}$ | $\begin{aligned} & 45.06 \\ & 47.23 \end{aligned}$ | $\begin{aligned} & * 44.66 \\ & 46.23 \end{aligned}$ | $\begin{aligned} & * 44.66 \\ & 45.94 \end{aligned}$ | 45.4 | 45.51 |
| 8 | $7 \times 5$ | $\begin{aligned} & \hline 0 \\ & 1 \end{aligned}$ | $\begin{aligned} & \text { *28.26 } \\ & 28.69 \end{aligned}$ | $\begin{aligned} & \hline \text { *28.26 } \\ & 28.71 \end{aligned}$ | $\begin{aligned} & 29.17 \\ & 29.17 \end{aligned}$ | $\begin{aligned} & 29.17 \\ & 30.17 \end{aligned}$ | 30.54 | 29.11 |

MDYNA $=1$, partial adjustment of due dates.
$=2$, full adjustment of due dates.

Table 5.41 Comparative evaluation of the heuristics on the dynamic FMS average lead time problems (STUDY 4 )

| 9 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 57.51 \\ & 58.26 \end{aligned}$ | 57.51 56.83 59.23 | 55.8 *54.4 56.14 | $\begin{aligned} & 55.8 \\ & 56.57 \end{aligned}$ | 59.46 | 57.51 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 10 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 56.37 \\ & 55.37 \\ & 56.83 \end{aligned}$ | 56.37 <br> 56.29 <br> 56.89 | $\begin{aligned} & 57.4 \\ & 56.89 \\ & * 54.11 \\ & 54.11 \end{aligned}$ | $\begin{aligned} & 57.4 \\ & 56.74 \\ & 57.14 \end{aligned}$ | 60.09 | 56.37 |
| 11 | $7 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 61.69 \\ & 59.71 \\ & 60.8 \end{aligned}$ | $\begin{aligned} & 61.69 \\ & 62.17 \end{aligned}$ | $\begin{aligned} & * 59.29 \\ & 61.23 \end{aligned}$ | $\begin{aligned} & \text { *59.29 } \\ & 60.23 \end{aligned}$ | 65.17 | 61.66 |
| 12 | $7 \times 6$ | $\begin{aligned} & \hline 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 24.97 \\ & 24.4 \\ & 23.63 \\ & 23.63 \end{aligned}$ | $\begin{aligned} & 24.97 \\ & 25.14 \end{aligned}$ | $\begin{aligned} & 24.49 \\ & 24.06 \\ & { }^{2} 23.31 \\ & 23.97 \end{aligned}$ | $\begin{aligned} & 24.49 \\ & 24.77 \end{aligned}$ | 26.31 | 26.43 |
| 13 | $10 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 61.74 \\ & 60.86 \\ & 62.24 \end{aligned}$ | $\begin{aligned} & \hline 61.74 \\ & 62.9 \end{aligned}$ | 61.36 *59.74 60.56 | $\begin{aligned} & 61.36 \\ & 62.7 \end{aligned}$ | 68.68 | 61.74 |
| 14 | $10 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & 37.02 \\ & 37.94 \end{aligned}$ | $\begin{aligned} & 37.02 \\ & 38.26 \end{aligned}$ |  | $\begin{aligned} & * 36.68 \\ & 37.74 \end{aligned}$ | 40.62 | 37.84 |
| 15 | $10 \times 6$ | $\begin{aligned} & 0 \\ & 1 \\ & 2 \\ & 3 \end{aligned}$ | $\begin{aligned} & 40.32 \\ & 39.84 \\ & 39.24 \\ & 39.24 \end{aligned}$ | $\begin{aligned} & 40.32 \\ & 40.26 \\ & 39.78 \\ & 40.24 \end{aligned}$ | $\begin{aligned} & 40.1 \\ & 38.96 \\ & \text { *38.64 } \\ & 38.7 \end{aligned}$ | $\begin{aligned} & 40.1 \\ & 40.74 \end{aligned}$ | 45.3 | 39.6 |
| 16 | $10 \times 6$ | 0 1 2 | 40.7 *39.02 39.96 | 40.7 <br> 40.22 <br> 41.68 | $\begin{aligned} & 39.92 \\ & 41.44 \end{aligned}$ | $\begin{aligned} & 39.92 \\ & 41.5 \end{aligned}$ | 44.14 | 41.94 |

Table 5.41 (continued)

Total no. of tests $=16$

|  |  | Heuristic H1 |  | Heuristic H 2 |  | FIFO | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | partially adjusted | fully adjusted | partially adjusted | fully adjusted |  |  |
| No. of best performance of | m.s. | 9 | 8 | 1 | 2 | 4 | 6 |
|  | 1 | 3 | 7 | 3 | 9 | 0 | 1 |
| Ranking | m.s. | **2.688 | 2.875 | 4.25 | 4.25 | 3.469 | 3.469 |
|  | 1 | 2.875 | **2.313 | 3.188 | **2.313 | 5.969 | 4.563 |

Table 5.42 Ranking for the heuristics on the dynamic FMS makespan/average lead time problems (STUDY 1)

Total no. of tests $=16$

|  |  | Heuristic H 1 |  | Heuristic H2 |  | FIFO | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | partially adjusted | fully adjusted | partially adjusted | fully adjusted |  |  |
| No. of best performance of | m.s. | 8 | 9 | 7 | 7 | 4 | 8 |
|  | I | 4 | 11 | 6 | 8 | 0 | 2 |
| Ranking | m.s. | 3.188 | **2.844 | 3.906 | 3.844 | 3.813 | 3.406 |
|  | 1 | 3.063 | **2.125 | 3.094 | 3.063 | 5.469 | 4.188 |

Table 5.43 Ranking for the heuristics on the dynamic FMS makespan/average lead time problems (STUDY 2)

Total no. of tests $=16$

|  |  | Heuristic H 1 |  | Heuristic H2 |  | FIFO | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | partially adjusted | fully adjusted | partially adjusted | fully adjusted |  |  |
| $\overline{\text { No. of best }}$ performance of | m.s. | 8 | 10 | 7 | 7 | 3 | 7 |
|  | 1 | 4 | 9 | 7 | 13 | 0 | 4 |
| Ranking | m.s. | 3.125 | *2.625 | 3.719 | 3.563 | 4.031 | 3.625 |
|  | 1 | 3.438 | 2.531 | 3.094 | **2.281 | 5.531 | 4.125 |

Table 5.44 Ranking for the heuristics on the dynamic FMS makespan/average lead time problems (STUDY 3 )

Total no. of tests $=16$

|  |  | Heuristic $\mathrm{H}_{1}$ |  | Heuristic H2 |  | FIFO | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | partially adjusted | fully adjusted | partially adjusted | fully adjusted |  |  |
| $\bar{N}$ o. of best performance of | m.s. | 7 | 6 | 1 | 1 | 6 | 3 |
|  | 1 | 3 | 3 | 11 | 4 | 0 | 3 |
| Ranking | m.s. | **2.594 | 2.75 | 4.438 | 4.625 | 2.625 | 3.969 |
|  | 1 | 2.813 | 3.375 | **1.906 | 3.031 | 5.875 | 4 |

Table 5.45 Ranking for the heuristics on the dynamic FMS makespan/average lead time problems (STUDY 4 )

Total no. of tests $=48$

|  |  | Heuristic H1 |  | Heuristic H 2 |  | FIFO | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | partially adjusted | $\begin{aligned} & \text { fully } \\ & \text { adjusted } \end{aligned}$ | partially adjusted | fully adjusted |  |  |
| No. of best performance of | m.s. | 25 | 27 | 15 | 16 | 11 | 21 |
|  | 1 | 11 | 27 | 16 | 30 | 0 | 7 |
| Ranking | m.s. | 3 | **2.781 | 3.958 | 3.886 | 3.771 | 3.5 |
|  | 1 | 3.125 | **2.323 | 3.146 | 2.552 | 5.656 | 4.25 |

Table 5.46 Summary of performance of the heuristics ( STUDY 1, STUDY 2, STUDY 3)

Total no. of tests $=64$

|  |  | Heuristics (H1 + H2 ) | FIFO | SIP |
| :--- | :---: | :---: | :---: | :---: |
| Number of occurance <br> of minimum | m.s. | 43 | 17 | 24 |
| Percentage of best <br> performance in 64 problems | m.s. | 58 | 0 | 10 |

Table 5.47 Summary of the heuristics on the measurement of makespan and average lead time

| Scheduling Method |  | Average execution time required for the dynamic FMS makespan/average lead time problems (cp second) |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | STUDY 1 | STUDY 2 | STUDY 3 | STUDY 4 |
| Heuristic H1 | partial adjustment | 4.893 | 6.739 | 5.27 | 10.03 |
|  | full adjustment | 4.903 | 6.746 | 5.36 | 10.54 |
| Heuristic H 2 | partial adjustment | 5.13 | 7.082 | 5.489 | 10.72 |
|  | full adjustment | 5.367 | 7.098 | 5.607 | 10.85 |
| FIFO |  | 2.187 | 2.298 | 2.371 | 3.97 |
| SIP |  | 2.256 | 2.361 | 2.404 | 4.23 |

Table 5.48 Summary of computational effort on the dynamic FMS makespan or average lead time problems

|  | Best scheduling technique to obtain the optimal value of |  |  |
| :--- | :---: | :---: | :---: | :---: |
|  | Cost of tardiness | Makespan | Average lead time |
| STATIC SYSTEM | H 2 | H 1 | H 2 |
| DYNAMIC SYSTEM | H 2 | H 1 | H 1 , or H 2 |

Table 5.49 Best scheduling method for each performance measure

## CHAPTER 6 : DEVELOPMENT OF THE SIMULATION PACKAGE

6.1 Production Scheduling Models for FMS
6.2 Description of Control Rules
6.3 FMS Simulation Program
6.3.1 Model builder
6.3.2 Activity cycle generator
6.3.3 Controller simulator
6.4 Evaluation of control rules
6.4.1 Control rules for alternative routes
6.4.2 Control rules for using transport facility
6.4.3 Control rules for machines breakdown
6.5 On-line Control Application
6.5.1 FMS control system
6.5.2 Practical implementation

## 6 DEVELOPMENT OF THE SIMULATION PACKAGE

The heuristics have been applied successfully in solving scheduling problems via the developed simulation package( chapters 4 \& 5 ). Most of the existing simulation packages( e.g. ECSL, SIMAN and etc.) require the associated simulation language processor, and a huge amount of effort in modification whenever a complicated scheduling technique has to be considered. However, the developed simulation package does not rely on the availability of any simulation language processor. It is a self-contained package which only requires a FORTRAN compiler, and it is highly flexible to be modified such that advanced scheduling algorithms( e.g. heuristics H 1 and H 2 ) can be taken into account.

FMSs offer great potential for solving the problems of traditional batch production. The complexity of these systems and the random processing of parts require extreme care in selecting the different building blocks of the system, their location and the production policies. Although FMSs are capable of producing a wide variety of parts, optimal results can only be achieved with careful selection of workpieces and operations. In the dynamic environment of random processing, all parts must utilise the limited available resources effectively. Discrete simulation has proved to be a useful tool ( EIMaraghy and Ho 1982 ), both in the design stage and during the operation of such system. It can also be used to evaluate design alternatives, to assist in selecting hardware components and their layout, and to test system control strategies ( Ireland 1983 ). Simulation can also provide on-going support for the user in planning changes in part design or part-mix, as well as evaluating different
production strategies and operational changes before implementation.

As previously suggested, in conceptual terms there are no reasons to debar the application of FMS techniques to all aspects of manufacture, but in order to do so several technical problems require solving. Marshall (1982) has mentioned that the computerised loading and scheduling is one of the major problems. Real-time scheduling is not necessary simply to be able to make frequent changes by the hour or minute, but rather to have the ability to change a manufacturing schedule quickly at a particular point in time, and take full account of such a change throughout the factory as a whole. This enables at least two of the likely benefits of FMS - namely reduced work-inprogress and better response to customer demands. However, currently, the development of a multi-purpose software module for FMS is lagging behind the development of hardware.

EIMaraghy and Ho (1982) has pointed out that most of the simulation programs developed so far apply to specific system configurations and are not suitable for use as general purpose design aid. Many of these programs use canned simulation packages which take up considerable computer memory. Data input and initialization of such programs require a fairly thorough knowledge of the simulation language used. Only standard, simple dispatching rules are employed for solving scheduling problem, but it has been proved that they provide unsatisfactory results as shown in chapter 4 and chapter 5.

This chapter describes a discrete event dynamic scheduling simulator of FMS. It is a general purpose, user-oriented program capable of simulating the most common configurations of FMS. The topology (
straight line, loop or network ), actual location of stations, and material handling systems ( conveyor, carts or A.G.V.) are specified by the user as part of the input data. Standard dispatching rules as well as complicated heuristics are developed inside the simulator for the control of scheduling. The purpose of developing this simulator was to provide an easily understood, rapid access analysis tool useful in studying large complex production networks ( e.g. FMS ) in which both the steady state and transient state performance are required. In addition, the simulator can also be organised as an on-line controller used to monitor the behaviour of a production system.

### 6.1 Production scheduling models for FMS

In contrast to a transfer line where all parts follow the same sequence of operations, the material handling system in an FMS should permit the parts to follow a variety of different routings. In a model of FMS, flexible routings ( Buzacott and Shanthikumar 1980) can be achieved by :
(1) providing separate paths between each pair of machines where part movement might occur, or
(2) using a common material handling device through which all parts pass and which connects all machines. (For example, a loop conveyor passing all machines or an automated guided vehicle.)

Within an FMS it is necessary to plan for the storage space. Two basic alternatives can be used for this; interstage buffers at each machine or a common storage which is accessible by all machines. There are a number of ways of providing the common storage. One
method of achieving flexible routing is to install a loop conveyor which is used to move parts between machines, where the parts in the loop can be considered as being in the common storage, that is, the size of the common storage is the number of spaces for parts in the loop conveyor ( figure 6.1). Some systems use both common and local storage. For example, in loop conveyor systems a small number of storage spaces may be provided as an interstage buffer for each machine (figure 6.2 ). On the other hand, some systems use only local storage and railed cart will be installed for the transportation purpose ( figure 6.3 ). The purpose of the interstage buffer is to reduce the machine idling time caused by the delay of the job coming from the transport facility.

However, the above mentioned transport facilities ( conveyor and railed cart ) have certain disadvantages, for example, they require large shop floor space for installation, and every job will be forced to travel around the loop hence there may be some unnecessary delay. The most common FMS currently constructed employs automated guided vehicles (A.G.V.) as the main transport facility ( figure 4.1). They can be programmed to travel from station to station by following the electric/magnetic paths which are installed under the shop floor, hence much more complex transport paths can be achieved.


Figure 6.1 FMS with loop conveyor as a common storage


Figure 6.2 FNS with local input buffer and loop conveyor
as a common storage

Where $B_{1}, B_{2}, B_{3}$ are local input buffers.


Figure 6.3 FNS with railed cart and local input buffer Where $B_{1}, B_{2}, B_{3}$ are local input buffers.

### 6.2 Description of Control Rules

Because of the complexity of FMS, the potential diversity of part routing and the variability in operation times, it is necessary to give careful consideration to the control of the system at five levels:
(1) pre-release planning, (2) release or input control, (3) operational control, (4) loading control and (5) transportation control.

## (1) Pre-release planning

At the pre-release phase, the parts which are to be manufactured by the system are decided, constraints on the operation sequence identified, and operation durations estimated.
(2) Release or input control

The purpose of input control is to determine the sequence and timing of the release of jobs to the system. Here three different rules are considered as follows :
(a) input rate $=$ output rate,
(b) a certain number of parts are dispatched to the loading station periodically and
(c) a part is periodically dispatched providing that there is an empty space at the loading station. ( where the part type is randomly selected.)
(3) Operational control

At the operational control level, the movement of parts between machines must be ensured. If a number of alternatives exist, different rules may be chosen for dispatch of components to :
(a) the machine having an interstage buffer with the shortest queue length. This rule minimises the blockage of interstage buffer.
(b) the machine with highest priority. Precedence would be given to
the machine which is operated at lowest manufacturing cost.
(c) the machine having an interstage buffer with the shortest waiting time. This provides a balanced workload.
(4) Loading control

At the loading control level different rules for loading a part on a machine are considered :
(a) simple dispatching rules can be applied to the interstage buffer, such as First In First Out ( FIFO ) rule, Shortest Imminent Processing time (SIP) rule, Minimum Slack Time (SLACK ) rule etc..
(b) the developed heuristics H 1 and H 2 can also be implemented locally on each station for the scheduling calculation.
(c) A pre-emptive priority scheme which assigns a loading priority factor to each part type, so that the part type with the highest priority factor is always loaded on the machine first. This rule provides a mechanism for the fast response of certain part types.
(d) For the case of non-universal buffers only. A machine $M_{1}$ may be blocked due to unavailability of space in the interstage buffer of the next operation machine $M_{2}$, where the finished part type produced from $M_{1}$ will be delivered for its next operation. A signal which represents this particular part type will be sent to machine $M_{2}$ so that a higher loading priority factor will be assigned to it. After $\mathrm{M}_{2}$ has completed its present operation, this part will be loaded on the machine $M_{2}$ in order to provide an empty space in the interstage buffer, and eventually free the blockage of $M_{1}$.
(5) Transportation Control

In the case of a system having limited transport facilities, sharing is necessary. Priority is given to the component which :
(a) goes to the next operation station where the shortest queue length exists. This minimises the blockage of interstage buffer.
(b) goes to the next operation station which offers the shortest waiting time. This may help reduce some unnecessary machine idle time.
(c) goes to the next operation station which offers the shortest processing time. This may reduce the lead times for some part types.
(d) goes to the station which has been assigned the highest priority factor. This may apply to an expensive machine, whose idle time is required to be kept at a minimum.
(e) First Come First Serve ( FCFS ), this is easy to implement.

### 6.3 FMS Simulation program

In this section only one category of FMS simulators will be considered: the detailed discrete simulator (Kay 1984 ), which performs step-by-step computation of the system behaviour. Since every possible event is considered and known in advance, it is possible to build into a model all the decision-making logic that the final system will use. This enables much more realistic predictions to be made about a system's performance.

Although the developed simulator provides the user with a wide range of options in selecting priorities, it is impossible to include all alternatives. A simple user-defined subroutine can be added to the simulator which allows the user to define his own priority rules. This special feature increases the flexibility of the simulator. It is particularly useful for testing management policies before implementation.

The discrete event simulator has been developed at Imperial College, and is written in Fortran for execution on a Cyber 855 computer system. The developed simulator consists of three main sections ( figure 6.4 ) :
(1) the model builder,
(2) the activity cycle generator,
$(3)$ the controller simulator,

### 6.3.1 Model builder

The input data to the model builder will describe the entire system,

## Basic manufacturing data



Figure 6.4 Simplified flow chart for the developed simulator
for example, the number of machines, number of transporters, number of buffers, capacity of buffers, number of part types, number of operations, routings, control rules, machining time, machine failure rate, machine repair rate etc..

In a model construction of FMSs, it is necessary to include the following capabilities in a model to make it more realistic ( Iwata 1982) :

- capability to handle various FMS configurations and/or different material handling systems.
- capability to handle many kinds of station such as machine tools, loading/unloading station, inspection facility, and buffer storages.
- capability to select an appropriate machine tool among candidate machine tools which can perform a predetermined operation for each processing stage of parts.
- capability to schedule part movements between stations via the material transportation system.
- capability to consider capacity constraints on buffer storages.
- capability to consider various loading rules ( or heuristics ) on each station.


### 6.3.2 Activity cycle generator

The basis of this simulation is that the finishing time of each task currently active is compared to the value on a time counter. One unit on the counter corresponds to one simulated time step, say one second or one minute, the time scale involved being a function of the system complexity and the level of detail involved. If the appropriate finishing times agree with the counter's value, the activities are
stopped. The next stage is probably the most complex. It has to be decided which activities may be started. It is in the next section that the proposed system controller's decision-making must be incorporated. Once the new activities, if any, have been allocated the appropriate times, these, together with those already active, are considered, and the cycle is repeated. As the performance of the system is simulated step-by-step, pseudo function-generators can be used for machine breakdown simulation and analysis of the transient response of a system is also possible.

### 6.3.3 Controller simulator

Computer simulation techniques can be applied to all aspects of manufacturing planning, particularly in the area of on-line control software development. Because of the complexity of FMS, the choice of applicable control strategies depends on many particular system variables. This controller model( Chan and Pak 1986) will be used to evaluate the performance of the planned FMS under a variety of operating strategies and external influences ( machine breakdown, for example ). Results from these experiments are assessed to decide which control rule is best suited to the planned FMS, and also to meet the manufacturers' requirements.

Major functions performed by an FMS controller ( Knight 1984 ), operating as a "real time" system include the following :
(a) Alternative route control

In an FMS, alternative operation for some jobs is available. The controller issues appropriate commands to load workpieces to the station through the use of stored control algorithms.
(b) Material transport facility control

The controller has stored in its data base the current location of all transport devices and their status (e.g. idle, carrying workpiece, going to get workpiece, etc. ). Through the use of stored control algorithms, the controller monitors status changes in the transport system, receives and arbitrates on control system requests which it then processes and finally issues appropriate commands to move workpieces along transport pathways between stations, in a manner consistent with optimal FMS operation.
(c) Machine failure control

The control system issues appropriate instructions for dealing with the problem of machine failure. Basically, two control rules have been considered. The first rule is simply to stop delivering any component to a failed machine. This may help prevent the blockage of the interstage buffer at this machine. However, the upstream machine may be blocked and its production lost. Therefore, a second rule is introduced to maintain the continuity of delivering components to the machine even when it has already failed. This may help provide a smooth production.
(d) Workpiece loading control

The controller monitors the loading of jobs on machines according to stored control heuristics.
(e) Output information

The following useful information can be obtained :

1. production rate,
2. throughput time for each component,
3. queue length statistics,
4. machine utilisation,
5. transport device utilisation,
6. current buffer status,
7. current machine and transport device working status,
8. machine failure statistics,
9. possible cost of tardiness.

One important area of software often missed is traceability. It deals with recording which operations were completed by which machines and/or operations to enable back tracking, especially of faulty manufacture, to the machine station where the operation was done.

Such a facility is important :

1. to stop further manufacture of faulty parts,
2. to identify and correct the fault on the machine, and
3. to identify the actual machine tool if there are several similar ones in the system.

The key to event-oriented simulation is the ability to organise and execute events in the same chronological order as in the real system. The operation of an FMS is fully simulated as shown in figure 6.5. It can be seen how the different controllers ( e.g. workpiece loading controller ) function within the simulation package.

The simulation process can be initiated by introducing the starting events such as part arrival, start of machining, operation of the transporter, etc. The basic mode of operation of the package is shown in figure 6.6.


Figure 6.5 Simplified cycle of the discrete event simulation of an FMS


Figure 6.6 Basic mode of operation of the simulator

### 6.4 Evaluation of control rules

The role of a supervisory computer in a Flexible Manufacturing System (FMS) is to control the interaction between the system constituents which include machines, parts and material handling systems characterised by their high capital cost. It is, therefore, generally accepted that a great deal of detailed analysis should be carried out during the system design stage for the selection of machinery and computer hardware and software. In order to carry out this task the simulation package has been developed to help provide an insight into the operation of the system.

In this section, emphasis is placed on the analysis of different control rules which apply to the supervisory controller for the effective operation of FMS.

It has already been shown that the performance of a system is greatly affected by employing different loading rules, such that the developed heuristics out perform the other rules. In order to show how the system behaviour may be affected by applying other control rules, and also how the simulation package can be used as a design tool, simulation of three simple systems are performed, and some of their results will be discussed.

### 6.4.1 Control rules for alternative routes

The manufacturing system can be described as follows :

Number of part type $=3$
Number of machine $=4$
Number of A.G.V. $=1$
Transportation time between each station $=1$ time unit
Condition for component enters to the system : input rate=output rate Loading rule on machine $=$ First In First Out (FIFO)

Simulated time cycle $=450$ time units
Buffer capacity ( universal ) : interstage buffer = 10
loading/unloading station $=$ infinite
Initial condition : 5 components of each part type have been loaded at the loading station.

The objective of this example is to investigate the effect of different control rules for the selection of alternative routes (see table 6.1) on the machine and transporter utilisation, as well as the lead times of different part types. The basic manufacturing data for each part is presented in table 6.2. Since the goal for this study is to analyse the control rules of alternative routes, jobs will be loaded onto machines according to the simple First In First Out (FIFO) rule, and the rule for using the transporter is a First Come First Serve (FCFS).

The resulting system utilisation, number of finished products and the average lead time of each part are presented in table 6.3. • In addition, the minimum buffer size required in each simulation is presented in table 6.4, and the dynamic behaviour of the system is plotted in figure 6.7 and figure 6.8.

From figure 6.7, it can be observed that the mean utilisation of machines is increased from zero and then gradually saturated at about

| Control rule parameter <br> IMPRI | Selection of alternative routes <br> which offers | Purpose |
| :---: | :--- | :--- |
| 1 | The shortest queue length | Minimise the blockage <br> of interstage buffer |
| 2 | The shortest processing <br> time | Lower the manufacturing <br> cost |
| 3 | The shortest waiting time | To provide a balanced <br> workload in the system |

Table 6.1 Control rules for the selection of alternative routes

| Part type | Sequence of operation |  | Duration of operation |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $M_{1}$ | $M_{2}$ | $M_{4}$ | 6. | 14. |
|  |  | $M_{3}$ |  | 1. |  |
| 2 | $M_{3}$ | $M_{1}$ | $M_{4}$ | 8. | 15. |
|  |  | $M_{2}$ |  | 1. |  |
| 3 | $M_{2}$ | $M_{1}$ | $M_{4}$ | 4. | 6. |

Table 6.2 Basic data for a three-part type, four-machine FMS scheduling problem
Note: When there is more than one machine under the column of sequence of operation, it means that an alternative operation exists. For example, part type 1 can be loaded or either $\mathrm{M}_{2}$ or $\mathrm{M}_{3}$ for its second operation.

| IMPRI | $\begin{gathered} U \\ (M / C) \end{gathered}$ | U (A.G.V.) | No. of finished products |  |  |  | Average lead time |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | part 1 | part 2 | part 3 | Total | part 1 | part 2 | part 3 |
| 1 | 64.611 | 97.333 | 21 | 21 | 14 | 56 | 94.2 | 95.3 | 142. |
| 2 | 52.444 | 92.889 | 19 | 15 | 17 | 51 | 104.3 | 124. | 112.3 |
| 3 | 60.389 | 99.778 | 19 | 18 | 19 | 56 | 100.6 | 110.4 | 105.2 |

Table 6.3 Simulation results for different control rules of alternative routes selection

| IMPRI | Record of maximum number of components <br> found in each interstage buffer |  | Total space required for <br> interstage buffers |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: |
|  | $\mathrm{B}_{1}$ | $\mathrm{~B}_{2}$ | $\mathrm{~B}_{3}$ | $\mathrm{~B}_{4}$ |  |
| 1 | 7 | 7 | 5 | 1 |  |
| 2 | 4 | 2 | $\# 10$ | 1 | 20 |
| 3 | 5 | 5 | 5 | 2 | 17 |

Table 6.4 Queue length statistics for each interstage buffer

Note :
Where $\mathrm{U}=$ mean utilization.
The asterisk (\#) denotes the buffer $\mathrm{B}_{3}$ is blocked when $\operatorname{IMPRI}=2$.
For the meaning of parameter IMPRI, please refer to table 6.1.


Figure 6.7 Mean utilisation of machines and transporter ( with different alternative routes control )



Figure 6.8 Lead times for each part type (with different

150 time units. The initial starvation of machines is due to the awaiting of jobs which are being delivered from the loading station to the first operation machine by an A.G.V. . The utilisation of the transporter is decreased from $100 \%$ and then gradually saturated at about 200 time units. The initial full utilisation of the transporter is in the main due to the high demand from the stock which has been stored at the loading station. From table 6.3, it is found that the shortest queue length rule ( $\operatorname{IMPRI}=1$ ) produces the highest mean machine utilisation and shortest average lead time of part type 1 and part type 2. Highest utilisation of the transporter, as well as the shortest average lead time of part type 3, can be achieved by applying the shortest waiting time rule ( IMPRI = 3). However, the shortest processing time rule ( IMPRI = 2 ) offers the worst mean machine and transporter utilisation, and also gives the lowest production rate.

The reason for the poor performance of the shortest processing time rule is that the workload has not been balanced in the system. From the basic manufacturing data, as shown in table 6.2, it can be seen that $M_{3}$ offers the shortest processing time in the second operation for both part type 1 and part type 3 . Hence there will be an unbalanced workload between $M_{2}$ and $M_{3}$ when part type 1 is being produced, and similarly the workload is not balanced between $M_{1}$ and $M_{3}$ when machining part type 3 . In fact, $M_{2}$ will be used to process part type 1 if, and only if, the interstage buffer of $M_{3}$ is full. Similarly, part type 3 will not be loaded onto $M_{1}$ unless there is an absence of empty space in $B_{3}$. This is vertified by the blockage of buffer $\mathrm{B}_{3}$ as shown in table 6.4 .

Considering the production rate, the shortest queue length rule and the shortest waiting time rule produce the same number of finished products, i.e. 56. However, when considering the average lead time of these finished components, the latter rule produces the minimum value of 105.31 time units. This can be calculated as follows :

1. Shortest queue length rule, average lead time (including all parts )
$=(21 \times 94.2+21 \times 95.3+14 \times 42) / 56$
$=106.56$
2. Shortest processing time rule, average lead time (including all parts)
$=(19 \times 104.3+15 \times 124+17 \times 112.3) / 51$
$=112.76$
3. Shortest waiting time rule, average lead time (including all parts )
$=(19 \times 100.6+18 \times 110.4+19 \times 105.2) / 56$
$=105.31$

Besides the best performance measure of lead time which has been predicted by the shortest waiting time rule, the total space required for the interstage buffers is also small compared to that produced using the shortest queue length rule ( table 6.4). From figure 6.8, the lead time curve of each part type predicted by the shortest waiting time rule fluctuates less than that determined by other rules. The overall merit obtained from the shortest waiting time rule is
achieved by its improved workload distribution in the system. From table 6.4, it can be observed that whilst the shortest queue length rule offers the highest mean utilisation of machines it does so at the expense of comparatively large interstage buffers.

### 6.4.2 Control rules for using transport facility

The manufacturing system is described as follows :

Number of part type $=3$
Number of machine $=4$
Number of A.G.V. $=1$
Transportation time between each station $=1$ time unit
Condition for component enters to the system : input rate=output rate Loading rule on machine $=$ First In First Out (FIFO)

Simulated time cycle $=450$ time units
Buffer capacity ( universal) : interstage buffer $=10$
loading/unloading station $=$ infinite
Initial condition : 5 components of each part type have been loaded at the loading station.

The main goal of this study is to examine the importance of using different transport rules for cell or system operation ( table 6.5 ). For simplicity, the manufacturing system to be analysed is a flexible flow shop. For a conventional flow shop, each job must pass through each machine. Here jobs may by-pass some of the machines. The basic production data for this flexible flow shop is presented in table 6.6 . Jobs are simply loaded onto machines with the First In First Out (FIFO) rule.

| Control rule parameter <br> IDEPRI | Priority of using transporter | Purpose |
| :---: | :--- | :--- |
| 1 | Gives the highest priority to deliver <br> the component which is going to its <br> next operation station where the <br> shortest queue length exists | Minimise the <br> blockage of <br> interstage buffer |
| 2 | First Come First Serve (FCFS) <br> Gives the highest priority to deliver <br> the component which is going to its <br> next operation station which offers <br> the shortest processing time | Reduce the lead times <br> for some part types |
| 4 | Gives the highest priority to deliver <br> the component which is going to its <br> next operation station which offers <br> the shortest waiting time | Reduce unnecessary <br> idle time on some <br> machines |

Table 6.5 Control rules for using transport facilities

| Part type | Sequence of operation |  |  |  | Duration of operation |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $M_{1}$ | $\mathrm{M}_{2}$ | $\mathrm{M}_{3}$ | $\mathrm{M}_{4}$ | 2. | 10. | 7. | 5. |
| 2 | $\mathrm{M}_{1}$ | $\mathrm{M}_{3}$ | $\mathrm{M}_{4}$ |  | 2. | 7. | 5. |  |
| 3 | $\mathrm{M}_{2}$ | $\mathrm{M}_{4}$ |  |  | 10. | 5. |  |  |

Table 6.6 Basic data for a three-part type, four-machine flexible flow-shop scheduling problem

The simulation results are presented in table 6.7 and table 6.8, the dynamic behaviour of the system is plotted in figure 6.9 and figure 6.10.

According to table 6.7, the maximum number of finished products as well as the highest mean machine utilisation can be obtained by employing the First Come First Serve (FCFS) transport rule ( IDEPRI = 2 ). On the other hand, the shortest processing time transport rule ( IDEPRI $=3$ ) produces the worst results in terms of mean machine utilisation and production rate. In this simulation, either the shortest processing time ( IDEPRI = 3) or the shortest waiting time ( IDEPRI $=4$ ) rule produces a dramatically long lead time for part type 3. This is because the first operation machine for part type 3 has been allocated to $M_{2}$ which offers a longer machining time ( 10 time units ) than another first operation machine $M_{1}$ ( 2 time units ), hence part type 3 will receive a relatively low priority to be transported from the loading station to $M_{2}$. From figure 6.9 , it can be observed that the lead time for part type 3 is still in the transient state if the shortest processing time or shortest waiting time rule is employed. Another important system parameter to be considered here is the size of the interstage buffer. According to table 6.8, the total space required for the interstage buffers is 17 if the FCFS rule is used, but maximum production rate and best mean machine utilisation can be achieved. Although the shortest queue length rule ( $\operatorname{IDEPRI}=1$ ) offers the second highest mean machine utilisation, the smallest total space required for the interstage buffers makes an attractive feature.

| IDEPRI | U <br> (M/C) | U (A.G.V.) | No. of finished products |  |  |  | Average lead time |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | part 1 | part 2 | part 3 | Total | part 1 | part 2 | part 3 |
| 1 | 56.444 | 100. | 19 | 25 | 11 | 55 | 102.4 | 82.6 | 160.3 |
| 2 | 58.5 | 100. | 15 | 25 | 17 | 57 | 125.5 | 82. | 114.6 |
| 3 | 53.556 | 100. | 20 | 25 | 4 | 49 | 99.2 | 81.7 | 246.7 |
| 4 | 54.5 | 100. | 20 | 25 | 5 | 50 | 98.8 | 80.9 | 266.6 |

Table 6.7 Simulation results for different control rules of using transporter

| IDEPRI | Record of maximum number of components <br> found in each interstage buffer |  | Total space required for <br> interstage buffers |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- |
|  | $\mathrm{B}_{1}$ | $\mathrm{~B}_{2}$ | $\mathrm{~B}_{3}$ | $\mathrm{~B}_{4}$ |  |
|  |  |  |  |  |  |
|  | 1 | 3 | 6 | 1 |  |
| 2 | 1 | 6 | 5 | 5 | 11 |
| 3 | 1 | 3 | 7 | 1 | 17 |
| 4 | 1 | 3 | 7 | 1 | 12 |

Table 6.8 Queue length statistics for each interstage buffer
Note :
Where $\mathrm{U}=$ mean utilization.
For the meaning of parameter IDEPRI, please refer to table 6.5.




Figure 6.9 Lead times for each part type (with different
transport facility control)



Figure 6.10 Queue length statistics for interstage buffers (with different transport facility control)

From figure 6.10, the queue inside the interstage buffer $B_{2}$ is longest when the FCFS rule ( IDEPRI = 2) is applied. In this case, each part type has equal opportunity to be transported from the loading station to its first operation machine. For part type 1, the processing time of its first operation ( 2 time units ) is much shorter than its second operation ( 10 time units ). Therefore, a queue is expected inside the interstage buffer $B_{2}$. Furthermore, for part type 3 , the first operation machine is again $M_{2}$ which offers a long machining time on this part, i.e. 10 time units. This increases the workload on $M_{2}$ and hence an even longer queue appears inside the buffer $B_{2}$. On the other hand, the shortest processing time ( IDEPRI $=3$ ) and the shortest waiting time ( IDEPRI $=4$ ) transport rules have a stopping effect to restrict the part type 3 to be transported from the loading station to $M_{2}$. Hence the congestion inside the buffer is not as serious as before. The application of the shortest queue length transport rule ( $\mid D E P R I=1$ ) will initially attempt to balance the workload between machines $M_{1}$ and $M_{2}$. However, a small queue is developed in $B_{2}$ due to the long processing time required for the first operation on part type 3 and the second operation on part type 1. Because a queue in $B_{1}$ is less likely, due to the fast machining time offered by $M_{1}$, the transporter will select part 1 or part 2 in preference to part 3 if the shortest queue length rule is applied. Therefore, the effective number of parts going to machine 2 is reduced.

According to figure 6.10, the queue length statistics in the interstage buffer $B_{3}$ are very different from that in the buffer $B_{2}$. In this case,
both the shortest processing time ( IDEPRI = 3) and the shortest waiting time ( $\operatorname{IDEPRI}=4$ ) rule produce a long queue inside the buffer $B_{3}$. As it has been mentioned before, part type 1 and part type 2 have relatively higher priority to be processed first when the above two transport rules ( $\operatorname{IDEPRI}=3,4$ ) are applied. For part type 2, there is a significant difference in processing time between its first and second operation ( i.e. 2 time units on $M_{1}$, and 7 time units on $M_{3}$ ). Hence, a queue is expected inside buffer $B_{3}$. On the other hand, the other two transport rules (i.e. FCFS and the shortest queue length rule ) have the effect of trying to balance the workload between the first operation machines, i.e. $\mathrm{M}_{1}$ and $\mathrm{M}_{2}$. Hence this will reduce the workload on $M_{1}$. Consequently, the workload on $M_{3}$ is also decreased and so is the congestion inside the buffer $B_{3}$.

For interstage buffer $B_{4}$, the dynamic behaviour of the buffer status is similar to that occurs in the buffer $\mathrm{B}_{2}$. This can be explained as before. For the FCFS rule, it distributes the jobs with equal opportunity to the first operation machines, i.e. part 1 and part 2 go to $M_{1}$, and part 3 goes to $M_{2}$. Consequently, the last machine $M_{4}$ is in high demand to produce all these three part types. This is reflected by the highest production rate and mean machine utilisation achieved over the other rules applied ( table 6.7). On the other hand, the other three transport rules have a stopping effect to allow part type 3 to be transported from the loading station to $M_{2}$. Consequently, this reduces the workload on $M_{4}$ and hence there is no serious congestion inside this buffer.

It should be stressed here that the value of the maximum number of components found in each interstage buffer may occur only during the transient state, or within a very short period ( figure 6.10). If this is the case, a lot of the buffer spaces will be wasted most of the time. By reducing the buffer capacity, the mean machine utilisation may be decreased due to the creation of bottlenecks at some stations. One can reduce the amount of space allocated to each buffer and run the simulation again until there is a compromised solution. This highlights the simulation package as a design tool before the actual implementation.

### 6.4.3 Control rules for machines breakdown

The system is described as follow :
Number of part type $=2$
Number of machine $=4$
Number of A.G.V. $=1$
Transportation time between each station $=1$ time unit
Loading rule on machine $=$ First In First Out (FIFO)
Condition for component entering to the system : launch one component of each part type to the loading station in every 15 time units.

Simulated time cycle $=450$ time units
Buffer capacity ( universal) : interstage buffer $=10$
loading/unloading station $=$ infinite
Initial condition : 2 components of each part type have been loaded at the loading station.

Machine failure information : $\mathrm{M}_{2}$ fails randomly, repairs time $=50$ time units

In order to show how a system will respond to an external disturbance, simulation of a system with an unreliable machine is performed. For simplicity, the production system to be examined is a simple job shop. The FIFO loading rule and FCFS transport rule are assumed. In case of machine failure, two different control rules are proposed in table 6.9. The basic manufacturing data is presented in table 6.10 .

The results of this simulation are presented in table 6.11 and table 6.12 , and the dynamic behaviour of the system has been plotted in figure 6.11, figure 6.12 and figure 6.13. From figure 6.11, if the control action is to stop further delivery of components to the failed machine $M_{2}(\operatorname{MBRKDEL}=1)$, the mean machine utilisation will be decreased dramatically for each breakdown of $M_{2}$. This is because $M_{1}$ and $M_{2}$ have been forced to stop their production while $M_{2}$ has failed. For the same reason, the interstage buffers $B_{1}$ and $B_{3}$ are eventually blocked ( figure 6.13) due to periodical supply of jobs coming from the loading station. On the other hand, if it can keep delivering jobs to a failed machine ( MBRKDEL $=2$ ), the mean machine utilisation will not be decreased when breakdown occurs. However, there is still a sudden dropping of mean machine utilisation at about 300 time units ( figure 6.11 ). This is caused by the saturation of interstage buffer $B_{2}$ as shown in figure 6.13, and consequently machines $M_{1}$ and $M_{3}$ are blocked. From figure 6.13, a queue built up in buffer $B_{2}$ for each failure of $M_{2}$, as was expected. After the first failure of $M_{2}$, the work-in-progress in $B_{2}$ was cleared at about 120 time units.

| Control rule parameter <br> MBRKDEL | Control action dealing with machine <br> failure | Purpose |
| :---: | :--- | :--- |
| 1 | Stop to deliver any component to a <br> failed machine | Prevent the blockage <br> of interstage buffer <br> at this station |
| 2 | continue to deliver component to <br> the machine even when it has <br> already failed | Try to maintain a <br> smooth production |
| 3 | All the machines are reliable |  |

Table 6.9 Control rules dealing with machine failure

| Part type | Sequence of operation |  | Duration of operation |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $M_{1}$ | $M_{2}$ | $M_{4}$ | 8. | 2. | 1. |
| 2 | $M_{3}$ | $M_{2}$ | $M_{4}$ | 7. | 2. | 1. |

Table 6.10 Basic data for a two-part type, four-machine job-shop scheduling problem

| MBRKDEL | $\begin{gathered} U \\ (M / C) \end{gathered}$ | $\begin{gathered} U \\ \text { (A.G.V.) } \end{gathered}$ | No. of finished products |  |  | Average lead time |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | part 1 | part 2 | Total | part 1 | part 2 |
| 1 | 22.833 | 66.667 | 19 | 18 | 37 | 93.6 | 104.5 |
| 2 | 30.5 | 80.444 | 22 | 21 | 43 | 77 | 82.5 |
| 3 | 36.111 | 97.333 | 30 | 30 | 60 | 31.8 | 38.5 |

Table 6.11 Simulation results for machine failure condition

| MBRKDEL | Record of maximum number of components found in each interstage buffer |  |  |  | Total space required for interstage buffers |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\mathrm{B}_{1}$ | $\mathrm{B}_{2}$ | $\mathrm{B}_{3}$ | $\mathrm{B}_{4}$ |  |
| 1 | \#\#10 | 1 | \#\#10 | 1 | 22 |
| 2 | 4 | \#\#10 | 4 | 1 | 19 |
| 3 | 4 | 1 | 2 | 1 | 5 |

Table 6.12 Queue length statistics for each interstage buffer
Note: The asterisk (\#\#) denotes the corresponding buffer is blocked.
Where $U=$ mean utilization
For the meaning of parameter MBRKDEL , please refer to table 6.9


Figure 6.11 Mean utilisation of machines (with different machines breakdown control)


Fisure $6.12 \quad \mathrm{M}_{2}$ operation statistics



Figure 6.13 Queue length statistics for interstage buffers ( with different machines breakdown control)

However, it can be observed that the buffer $B_{2}$ is eventually blocked due to the high frequency of machine failure.

As a result, the control rule with non-stop production of $M_{1}$ and $M_{3}$, i.e. MBRKDEL $=2$, out performs another rule $(\operatorname{MBRKDEL}=1)$ provided that the interstage buffer $\mathrm{B}_{2}$ is large enough to absorb the disturbance.

The results of these examples can be summarised as follows :
(1) For the control of alternative routes, the shortest waiting time rule out performs the others in obtaining optimal results of production rate, average lead time, utilisation of transporter and buffer size.
(2) For the control of transport facility, the First Come First Serve (FCFS) rule has been used to obtain optimal results of production rate as well as mean machine utilisation. However, the size of interstage buffers is larger than the other transport rules. Therefore, if the cost of installing a large buffer is considerable, the shortest queue length rule is preferred.
(3) For the control of machine failure in a job shop, the best rule is the one which continues to deliver jobs to the machine even when it has already failed. The merit of this rule is achieved by installing an interstage buffer with considerable size at the failed station in order to maintain a smooth production.

This study provided an insight into the modelling of an FMS controller, and the significance of employing different control rules has been reflected by the results. In order to operate an FMS efficiently, a
suitable system controller software is required. However, because of the complexity involved it is necessary to simulate the FMS controller before actually implementing the control software which could be a very expensive method of finding some design errors.

### 6.5 On-line Control Application

### 6.5.1 FMS control system

The components of FMS control are presented in table 6.13. Functional realization of the control components involves the tasks presented in table 6.14. To implement these tasks a division of control responsibilities is made in a hierarchical network.

As is shown in figure 6.14 and table 6.15 , there are generally three levels of control ( Sadowski et al. 1979, Hitomi 1979, Young 1981, Caputo 1983 and Jones and McLean 1984 ). The first level communicates directly with the process and involves most of the process control tasks, for instance, control of loading a job onto the machine. The second level supervises the first level, makes tactical decisions, communicates with the first level, manages system data using local database, determines system status and makes and implements decisions. The third level of control is indirect control, making strategic decisions and maintaining a complete database.

The third level is usually a central computer not directly involved in the control of the FMS. The level one computer is usually a process control computer with enhanced communications and control capabilities. The level two controller is usually a general purpose minicomputer with specialised software that enables it to effectively implement the information flow and control requirements. Each processor at each level has its own executive programs at a given level are functionally equivalent.

## FMS Control Component Functions

| 1 | Controls the CNC equipment. |
| :--- | :--- |
| 2 | Controls the material handling equipment. |
| 3 | Controls part movement within the system. |
| 4 | Controls information on system performance. |

Table 6.13 FMS control component functions

Tasks of the software control system

System data acquisition.
System data storage and retrieval.
System data interpretation.
System status determination and interpretation.
Decision making.
Decision implementation.

Table 6.14 Tasks of the software control system


Figure 6.14 Hierarchical structure of a typical FMS

## LEVEL 3 (Makes strategic decisions)

|  | Exercise indirect control over the FMS system. |
| :---: | :---: |
|  | Maintains a complete data base. |
|  | Handles management/FMS system interface. |
|  | Downloads software changes to the level 2 controller. |

## LEVEL 2 (Makes tactical decisions)

## ---------- Exercises direct control over the FMS.

---------- Supervises level 1 controllers.
--------- Communicates directly with level 1 and level 3 controllers.
---------- Acquires and manages the system data.
--------- Determines the system status.
---------- Maintains an NC program library.
--------- Maintains system performance data.
LEVEL 1 (Makes process specific decisions)
Communicates directly with the process.
---------- Involves most of the process control tasks.
---------- Communicates directly with the level 2 controller.

Table 6.15 Division of control responsibilities for an FMS.

The level one executive program must be capable of the following :

- Communicating with the level two controller.
- Executing numerical control ( NC ) programs transferred from the level two controller.
- Monitoring machine loading operation.
- Monitoring machine operations during NC program execution.

The normal communication would consist of the following types of activities :

- Acknowledgement of a communication.
- Transfer of programs from the level two controller.
- Transfer of requested information between the two controllers.
- Notification of an activity's completion.

Communication acknowledgement is required to allow the level two controller to determine when the level one controller is ready to accept communication and when message reception is completed. Without this activity the level two controller could attempt a message transfer when the level one processor was not prepared to receive it . This would result in the level one processor's missing either part or all of the message. The acknowledgement of reception allows the level two controller to immediately turn its attention away from the message transfer task.

Besides the NC programs being transferred to the level one processor, additional information which may be transferred upon request includes items such as machine status, tool status, current operation
status, NC program sequence number, etc. Once an activity is completed, the level two controller is notified that the machine status has changed.

The level two controller supervises the FMS and is referred as the supervisory computer. The level two executive program must be more sophisticated than the level one executive. The level two controller performs more diverse activities and carries a heavier processing load than a level one controller. This executive directs the performance of the tasks listed in table 6.14 . For instance, the program applies the developed heuristics ( $\mathrm{H}_{1}$ or $\mathrm{H}_{2}$ ) for the scheduling calculation. Additional responsibilities are directed toward communication with the level three processor, including program transfer, and queries about current system status and system historical data.

The data structure, presented in table 6.16, includes information which is both static and dynamic. Static information will not change once the system is initialized in a particular configuration. Dynamic information changes with each event occurrence within the system, for example, the current operation for the part.

### 6.5.2 Practical implementation

It has already been mentioned that the FMS control system operates at three different levels, as figure 6.14 shows. The main duty of the central supervisory controller is to ensure the optimal control of the whole system as well as the registration of a great number of data, the calculation of statistics, the printing of reports.

| Part Identifier | --- Part type <br> --- Part location <br> --- Pallet type requirement <br> -- Current operation for the part <br> --- Next operation for the part <br> --- Operation start time <br> --- Expected operation duration |
| :---: | :---: |
| Machine Identifier | --- Machine type <br> -- Machine location <br> --- Machine status: Busy/idle Part transfer Operative/inoperative <br> --- Identification of the NC program in the machine <br> --- Part identifier for part on the machine <br> -- Pallet identifier for pallet on the machine |
| Material Handling Component Identifier | --- Component status : Moving/idle <br> Transferring part to/from machine <br> Operative/inoperative <br> --- Current location <br> --- Part identifier for the part on the material handling component <br> -- Pallet identifier for the pallet on the material handling component <br> --- Location of the component at the start of the move <br> --- Destination <br> --- Start time <br> --- Expected move duration |
| Pallet Identifier | --- Pallet type <br> --- Pallet location <br> --- Pallet status: Busy/idle <br> Operative/inoperative <br> -- Part identifier for the part loaded on the pallet |

[^1]This section shows how the developed simulation package and the heuristics can be practically implemented.

The developed simulation package can be organized as the control software in the supervisory computer. This can be done because of the simulation program has been constructed in a step-by-step nature. From figure 6.6, the basic mode of operation of the simulator, the system state, will be changed whenever the time counter value equals to any of the event finishing times. In practice, the event finishing time will be replaced by an actual signal produced from a machine ( or A.G.V. etc.) via the process controller at the level one control. Once the supervisory computer receives the signal, then the system state will be changed and an appropriate control action may be carried out. This means that the change of system data is no longer governed by the relation such that Time counter value $=$ Event finished time, but rather by an actual signal.

The implementation of the system requires firstly that the factory data (e.g. transportation time between machines ) be interpreted and set up into the files of information. Secondly, the developed simulation program must be organized into the main frame computer ( figure 6.14). Thirdly, the controller simulator with the developed heuristic procedures have to be built into the central supervisory computer as a software control module. Fourthly, all the necessary interfacing mechanisms must be ensured so that the communication between different levels is efficient.

In this context, the work has concentrated on the optimisation of the cost of tardiness, makespan and average lead time. In order to obtain
the optimal solution of an objective measure of performance, the data files for production have been prepared in a period of "scheduled time" ( e.g. each day or each week ). Within this "scheduled time", data files should remain unchanged, e.g. the speed of robots, input rate of new jobs, routing, due dates of jobs ( if they are given ), etc.. According to the given information within this "scheduled time", the best heuristic procedure corresponding to the objective measure of performance can then be determined by the simulation carried out on the mainframe computer system. A set of data values representing this selected heuristic will be transmitted from the mainframe computer system to the supervisory controller. Moreover, if the objective measure is either the makespan or the average lead time, a set of "optimal due dates" will need to be transferred as well . During the stage of actual manufacturing, the supervisory controller monitors the scheduling of jobs to the machines according to the selected heuristic procedure which has been determined by the simulation program. However, if some disturbance occur ( e.g. machine breakdown, a new production design, change of speed of robot and etc. ), rescheduling is required (Torii T. et al. 1983 and Gideon H. et al. 1984 ). This can be achieved by simulating the system within the mainframe computer with all the up-dated information, and consequently determining another best heuristic approach with optimal due dates. Therefore, the system should have an efficient up-dating scheme so that the preparation time of new data is reduced and the best heuristic can quickly be redetermined as disturbances occur. The computation time for the developed simulation program on a reasonably large schedule is small, and it therefore offers an economic proposition to small, as well as large, manufacturing systems. In addition, the scheduling calculation time is very small
for the developed heuristics, hence the heuristics could be practically implemented to the central supervisory computer.

## CHAPTER 7: CONCLUSIONS AND FURTHER RESEARCH

7.1 Discussion Of The Context And Summary Of The Thesis
7.2 Suggestions For Further Research

## 7 CONCLUSIONS AND FURTHER RESEARCH

### 7.1 Discussion Of The Context And Summary Of The Thesis

FMS is the most common sense in the automation industry (Chapter 2 ). They have filled the gap between high-production transfer lines and low production NC machines. The survey in Chapter 1 show how FMSs have developed, and this progress has chiefly been due to their attractive advantages. However, the development of an efficient scheduling technique for the FMS is still behind the development of hardware. The complicated configuration of an FMS (e.g. alternative routings ) and the uncertainty and instability inherent in the real life systems do not allow an overall optimisation of the system. Thus, it is believed, that sub-optimal solutions have to be accepted.

Although, in practice, the meaning of optimality in industry is rather vague, owing to the instability and variety of objectives, in theory it is not. Theoretically optimal flow shop and job shop scheduling are possible if certain simplifying assumptions are made. However, the potential of exact methods is limited to very small real life problems by the complexity of the problem. In fact, many of these methods lack considerations of the characteristics of an FMS such as system structure, complexity, and flexibility, with the result that it is impossible to apply these methods directly to the production scheduling of FMS in practice. The approximate techniques and methodology developed in this thesis can be used to optimise certain objective measures in both dedicated and flexible manufacturing environments. The objective measures which have been considered are the makespan, the average lead time and the possible cost of
tardiness.

Within the context defined above, a study of scheduling techniques has been carried out ( Chapter 3 ). A review of the exact (optimal) methods and of the computational complexity in scheduling has recommended that there is a change of direction of research in scheduling. The determination of an optimal schedule is not considered to be a very fruitful direction any longer. The aim of the present work is to develop efficient heuristic algorithms for scheduling FMS in a near real time manner. The heuristics have been evaluated by simulating different FMSs with the developed dynamic scheduling simulation package.

Two heuristic algorithms ( H 1 and H 2 ) have been developed for solving the scheduling problem in a statically loaded FMS. For due date problems, the heuristics have been used to obtain a schedule such that the respective due dates are met, or failing this, the cost of tardiness is minimised. Simulation results suggested that the heuristic H 2 is the best performer in determining the minimum cost of tardiness, as compared to some of the well accepted rules ( e.g. SLACK and SIP ). When the heuristics are applied to solve the due date problems, improved results of makespan and average lead time have been obtained by tightening the due dates (Chapter 4 ). This leads to the development of an approximate method for solving the makespan and average lead time problems ( Chapter 5 ).

Applying the same heuristics, a method is proposed to determine the optimal makespan and the optimal average lead time. The heuristics find an optimal due date, $d_{j}{ }^{*}$, for each job iteratively. Using these
values of $d_{j}{ }^{*}$, the algorithms can be applied locally at each station to decide which job should be scheduled next. In the static case, heuristic H 1 and heuristic H 2 are the best performers in obtaining the schedules associated with the optimal makespan and the optimal average lead time respectively, as compared to the well accepted rules (e.g. FIFO and SIP ). For the due date problem of dynamically loaded FMSs, heuristic H2 again out performs other simple dispatching rules in determining the optimal cost of tardiness. Two different techniques of due dates assumption have been proposed to solve the makespan and average lead time problems in the dynamic case. The best method of obtaining the minimum makespan again involves the use of heuristic H 1 . Both heuristic H 1 and heuristic H 2 produce excellent results for the average lead time. The small computational effort for executing both heuristics offers the possibility of the actual implementation of the on-line real-time scheduling ( Chapter 5 ).

Simulation techniques, which have been neglected in the past in helping decision-making policy during the day-to-day life of production management problems, are now increasingly being used in the development of FMSs as design evaluation tool. Discrete event simulation has also proved to be useful (ElMaraghy and Ho 1982), both in the design stage and during the operation of a real manufacturing system. However, most of the existing simulation packages require a huge amount of effort in modification whenever a complicated scheduling technique has to be considered, and sometimes their use is impossible due to the complexity of the structure. The heuristics have been built into the simulation package in order to achieve an effective operation of a manufacturing system
in a real time manner.

The developed simulation package is an effective test tool for studying both the transient and steady state behaviour of a proposed dedicated or flexible manufacturing system. It can model a wide variety of FMSs with straight line, loop or network topology, different part types, complicated alternative operations and a large selection of decision rules. The three most commonly used material handling systems (i.e. conveyors, carts and automated guided vehicles ) can also be simulated, as are random machine breakdown, repair and part arrival patterns ( Chapter 6 ).

Unlike other models, the simulation package does not rely on the availability of any simulation language processor. It is a portable, stand-alone, self-contained package which only requires a FORTRAN compiler. The size of the FMS which can be simulated by the developed simulator is limited only by the available computer memory, but with advances in technology towards high speed, large memory mini- and microcomputers, size is not a limitation. Also simulation time varies with the complexity of the manufacturing system as well as the level of decision making.

This simulator is a useful tool for both designing and operating a flexible manufacturing system. It can be used in the design stage to obtain qualitative and quantitative information about a proposed configuration. It predicts production capacity, utilisation of various components, lead times of individual parts, possible cost of tardiness, and sensitivity of the system performance to changes in various design parameters. It can also be used to test specific
system control strategies and identify the best one associated with the optimum performance.

The developed simulator allows the designer to evaluate various alternatives, and gain insight into the complex interaction between different system components before purchasing and installing expensive equipment. It can also evaluate changes in part mix or part design, and plan future operational changes or expansions without interrupting the actual production. Furthermore, the simulator can be arranged as an on-line, real-time controller to monitor the behaviour of an FMS.

Simulation results show that the developed heuristics appear to out perform the other published techniques used in obtaining the schedules associated with minimum makespan, minimum average lead time and minimum cost of tardiness. Finally, the simulation of the dynamic cases indicates that the heuristics could also be implemented locally on each station for the scheduling calculation.

### 7.2 Suggestions for Further Research

It is believed that no exact technique can be constructed for the optimisation of FMS scheduling problem and that the practical benefits are insignificant. Thus, it is argued that future research should concentrate on the area of sub-optimal or approximate methods, with a view to establishing guarantees of performance, and their practical implementation to on-line scheduling. The latter point is of great importance, as it would fill the existing gap between the theory of scheduling and the scheduling practices in FMS. Although the general FMS scheduling problem cannot be solved with exact methods, the theory of scheduling ( heuristic algorithms, approximate methods ), is relatively advanced compared with current practice. Work is required in this area in order to bridge this gap, taking into account the potential of the theory and the current computer techriology.

Some ideas which occurred to the author during this research are listed below. They are not, however pursued due to lack of time and computational expense.

## (i) Heuristic H3 - INSERT

Actually, this is an extension of heuristic H2. Once a "look back" job has been scheduled there is a period of idle time on the machine, starting at the "present" time. If there is a job in the queue whose next operation can be completed by the time the look back job is due to arrive at this machine, then the operation should be scheduled. In the event of more than one job possessing this characteristic, the job with the longest operation which can be fitted into the idle time gap
should be scheduled. It is obvious that the INSERT heuristic is helpful but it is debateable as to whether this situation would occur often enough to warrant its inclusion in the program.
(ii) Control of alternative routes

The "shortest waiting time" rule works successfully in the scheduling of FMSs. It can be classified as a local optimisation technique. The author feels that better results could be obtained by further investigation of this control rule. Here one method is suggested where the 'waiting time' for the job to be scheduled is not only calculated locally, but rather takes into account the overall queue length existing at all the downstream stations which the scheduled job will visit in the near future. Dynamic programming methods can be employed to solve this kind of problem.
(iii) Stopping decision

It has already been mentioned that improved makespan and average lead time can be obtained by relaxing the stopping criterion during the process of iteration. This can be achieved by terminating the simulation if there is no further improvement in the desired objective measure within a pre-determined number of iterations.
(iv) Simulation of unreliability of production units

The effects of maintenance/breakdown of the transportation system or machines should be examined.
(v) Simulation of tool availability constraints

There are some complications to these constraints stemming from the facts that tools come in various sizes, and measured in the
number of slots it blocks in a tool magazine, and that some of the same tools may be used for different operations. Also, the space occupied by the tools in the magazine depends upon their arrangement, which is constrained by a requirement that the weight on each side be approximately balanced.
(vi) Implementation of multiple objective criteria

The criteria of performance used in industry are more complex than 'minimum makespan, average lead time, cost of tardiness' etc. They can be 'minimum production cost', 'maximum return' and more generally, 'maximum profit'. Heuristics which take into account these objectives should be developed.
(vii) Practical implementation

A physical miniature FMS-like production cell should be built, based on the findings of this research to facilitate the technological requirements of future FMS.
(viii) Application in industry

At present, only simple dispatching rules are practically applied for FMS scheduling. It is believed that more sophisticated scheduling routines, like heuristics H 1 and H 2 , can be of value in improving scheduling procedures. These routines, with relatively small core requirement and fast execution time, could be practically implemented at the shop floor level with an on-line real-time controller. The development and implementation of these types of routines ( heuristics ) are strongly recommended to the manufacturing industry.

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## APPENDICES

## APPENDIX A

Data for $N$ jobs and single machine due date problems

APPENDIXA : Data for $N$ jobs and single machine due date problems
(1) Elmaghraby (1968)

| Job number | j | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| :--- | :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Due date | $\mathrm{d}_{\mathrm{j}}$ | 2 | 5 | 6 | 8 | 10 | 15 | 17 |
| Processing time | $\mathrm{P}_{\mathrm{j}}$ | 3 | 3 | 2 | 1 | 5 | 4 | 4 |
| Penalty for lateness | $(\mathrm{CF})_{\mathrm{j}}$ | 1 | 3 | 4 | 1 | 2 | 3 | 1.5 |

(2) Moore (1968)

| Job number | j | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| :--- | :---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
| Due date | $\mathrm{d}_{\mathrm{j}}$ | 35 | 20 | 11 | 8 | 6 | 25 | 28 | 9 |
| Processing time | $\mathrm{P}_{\mathrm{j}}$ | 10 | 6 | 3 | 1 | 4 | 8 | 7 | 6 |
| Penalty for lateness | $(\mathrm{CF})_{\mathrm{j}}$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

(3) Shwimer (1972)

| Job number | $j$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Due date | $d_{j}$ | 3 | 4 | 7 | 8 | 11 | 15 | 16 | 20 | 20 | 25 |
| Processing time | $P_{j}$ | 4 | 1 | 2 | 4 | 1 | 4 | 2 | 2 | 3 | 2 |
| Penalty for lateness | $(\mathrm{CF})_{\mathrm{j}}$ | 3 | 1 | 4 | 2 | 3 | 5 | 1 | 5 | 3 | 10 |

## APPENDIX B

Data for FMS with 7 jobs - 4 operations

APPENDIX B : Data for FMS with 7 jobs - 4 operations.
Four different sets of processing time are presented as follows :-
(1) DATA B1

| $\begin{gathered} \overline{\text { Job }} \\ \text { j } \end{gathered}$ | Sequence of operations ( machine number) |  |  |  | Duration of operations |  |  |  | Total mean processing time 4 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 4 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 5 | 6 | 3 | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | 5 | 1 | 13.5 |
| 2 | 3 | 1 | 2 | 6 | 9 | 7 | 3 | 1 | 20 |
| 3 | 5 | 4 1 | 2 3 | 6 | 8 | $\begin{aligned} & 11 \\ & 15 \end{aligned}$ | $\begin{aligned} & 4 \\ & 7 \end{aligned}$ | 1 | 27.5 |
| 4 | 2 | 4 | 1 3 | 6 | 5 | 16 | $\begin{aligned} & \hline 5 \\ & 5 \end{aligned}$ | 1 | 27 |
| 5 | $\begin{aligned} & 3 \\ & 4 \end{aligned}$ | 1 2 | 5 | 6 | $\begin{aligned} & 4 \\ & 2 \end{aligned}$ | $\begin{aligned} & 7 \\ & 8 \end{aligned}$ | 6 | 1 | 17.5 |
| 6 | $\begin{aligned} & 2 \\ & 5 \end{aligned}$ | 1 | 4 | 6 | $\begin{aligned} & 5 \\ & 2 \end{aligned}$ | 5 | 7 | 1 | 16.5 |
| 7 | $\begin{aligned} & \hline 3 \\ & 1 \end{aligned}$ | 4 5 | 2 | 6 | $\begin{aligned} & 6 \\ & 9 \end{aligned}$ | $\begin{aligned} & \hline 6 \\ & 8 \end{aligned}$ |  | 1 | 23.5 |

(2) DATA B2

| $\begin{gathered} \overline{\text { Job }} \\ \text { j } \end{gathered}$ | Sequence of operations ( machine number) |  |  |  | Duration of operations |  |  |  | Total mean processing time 4 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 4 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 5 | 6 | 14 | $\begin{aligned} & 14 \\ & 11 \end{aligned}$ | 9 | 1 | 36.5 |
| 2 | 3 | 1 | 2 | 6 | 21 | 7 | 9 | 1 | 38 |
| 3 | 5 | $\begin{aligned} & \hline 4 \\ & 1 \end{aligned}$ | $\begin{aligned} & 2 \\ & 3 \end{aligned}$ | 6 | 13 | $\begin{aligned} & 26 \\ & 31 \end{aligned}$ | $\begin{aligned} & 9 \\ & 4 \end{aligned}$ | 1 | 49 |
| 4 | 2 | 4 | $\begin{aligned} & \hline 1 \\ & 3 \end{aligned}$ | 6 | 6 | 25 | $\begin{aligned} & 17 \\ & 28 \end{aligned}$ | 1 | 54.5 |
| 5 | $\begin{aligned} & \hline 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 5 | 6 | $\begin{aligned} & 5 \\ & 5 \end{aligned}$ | $\begin{gathered} 4 \\ 17 \end{gathered}$ | 14 | 1 | 30.5 |
| 6 | $\begin{aligned} & \hline 2 \\ & 5 \end{aligned}$ | 1 | 4 | 6 | $\begin{aligned} & 3 \\ & 1 \end{aligned}$ | 17 | 11 | 1 | 31 |
| 7 | $\begin{aligned} & 3 \\ & 1 \end{aligned}$ | $\begin{aligned} & \hline 4 \\ & 5 \end{aligned}$ | 2 | 6 | $\begin{aligned} & 15 \\ & 26 \end{aligned}$ | $\begin{gathered} 15 \\ 6 \end{gathered}$ | 12 | 1 | 44 |

(3) DATA B3

| $\overline{\mathrm{Job}}$ | Sequence of operations ( machine number) |  |  |  | Duration of operations |  |  |  | Total mean processing time 4 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 4 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ |  | 6 |  | $\begin{aligned} & 12 \\ & 12 \end{aligned}$ | 21 | 1 | 35 |
| 2 | 3 | 1 | 2 | 6 | 12 | 27 | 14 | 1 | 54 |
| 3 | 5 | $\begin{aligned} & \hline 4 \\ & 1 \end{aligned}$ | $\begin{aligned} & 2 \\ & 3 \end{aligned}$ | 6 | 12 | $\begin{aligned} & 11 \\ & 11 \end{aligned}$ | $\begin{aligned} & \hline 5 \\ & 6 \end{aligned}$ | 1 | 29.5 |
| 4 | 2 |  | $\begin{aligned} & \hline 1 \\ & 3 \end{aligned}$ | 6 | 9 | 7 | $\begin{aligned} & \hline 3 \\ & 1 \end{aligned}$ | 1 | 19 |
| 5 | $\begin{aligned} & \hline 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 5 | 6 | $\begin{aligned} & 15 \\ & 11 \end{aligned}$ | $\begin{gathered} 16 \\ 9 \end{gathered}$ | 5 | 1 | 31.5 |
| 6 | $\begin{aligned} & 2 \\ & 5 \end{aligned}$ |  | 4 | 6 | $\begin{aligned} & 9 \\ & 7 \end{aligned}$ |  | 8 | 1 | 31 |
| 7 | $\begin{aligned} & 3 \\ & 1 \\ & 1 \end{aligned}$ | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | 2 | 6 | $\begin{aligned} & 14 \\ & 13 \end{aligned}$ | $\begin{aligned} & 9 \\ & 9 \end{aligned}$ |  | 1 | 36.5 |
| (4) DATA B4 |  |  |  |  |  |  |  |  |  |
| Job | Sequence of operations ( machine number) |  |  |  | Duration of operations |  |  |  | ```Total mean processing time 4 \(\sum_{k=1} \mathrm{p}_{\mathrm{j}, \mathrm{k}}\)``` |
| 1 | 4 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 5 | 6 | 3 | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | 5 | 1 | 13.5 |
| 2 | 1 | 3 | 2 | 6 | 7 | 9 | 3 | 1 | 20 |
| 3 | 5 | $\begin{aligned} & 3 \\ & 2 \end{aligned}$ | $\begin{aligned} & 1 \\ & 4 \end{aligned}$ | 6 | 8 | $\begin{aligned} & 7 \\ & 4 \end{aligned}$ | $\begin{aligned} & 15 \\ & 11 \end{aligned}$ | 1 | 27.5 |
| 4 | 4 | 2 | $\begin{aligned} & \hline 1 \\ & 3 \end{aligned}$ | 6 | 16 | 5 | $\begin{aligned} & 5 \\ & 5 \end{aligned}$ | 1 | 27 |
| 5 | $\begin{aligned} & 2 \\ & 4 \end{aligned}$ | $\begin{aligned} & 1 \\ & 3 \end{aligned}$ | 5 | 6 | $\begin{aligned} & \hline 8 \\ & 2 \end{aligned}$ | $\begin{aligned} & 7 \\ & 4 \end{aligned}$ | 6 | 1 | 17.5 |
| 6 | $\begin{aligned} & 4 \\ & 1 \end{aligned}$ | 5 | 2 | 6 | $\begin{aligned} & \hline 7 \\ & 5 \end{aligned}$ | 2 | 5 | 1 | 14 |
| 7 | $\begin{aligned} & 3 \\ & 1 \end{aligned}$ | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ |  | 6 | $\begin{aligned} & 6 \\ & 9 \end{aligned}$ | $\begin{aligned} & \hline 6 \\ & 8 \end{aligned}$ |  | 1 | 23.5 |

## APPENDIX C

Data for FMS with 7 jobs - 5 operations

APPENDIX C : Data for FMS with 7 jobs -5 operations.
Four different sets of processing time are presented as follows:-
(1) DATA C1

| $\begin{gathered} \text { Job } \\ \text { j } \end{gathered}$ | Sequence of operations ( machine number) |  |  |  |  | Duration of operations |  |  |  |  | Total mean processing time 5 $\sum_{k=1}^{\Sigma} p_{j, k}$ <br> 41 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 4 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 4 | 1 | 6 | 9 | $\begin{aligned} & 11 \\ & 13 \end{aligned}$ | 11 | 8 | 1 |  |
| 2 | 3 | 1 | 2 | 3 | 6 | 9 | 14 | 18 | 8 | 1 | 50 |
| 3 | 5 | $\begin{aligned} & \hline 4 \\ & 1 \end{aligned}$ | $\begin{aligned} & 5 \\ & 2 \end{aligned}$ | 4 | 6 | 4 | $\begin{aligned} & 11 \\ & 11 \end{aligned}$ | $\begin{array}{r} 13 \\ 7 \end{array}$ | 11 | 1 | 37 |
| 4 | 2 | $\begin{aligned} & 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 2 \\ & 1 \end{aligned}$ | 5 | 6 | 11 | $\begin{aligned} & 21 \\ & 10 \end{aligned}$ | $\begin{gathered} 11 \\ 9 \end{gathered}$ | 2 | 1 | 39.5 |
| 5 | $\begin{aligned} & 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & \hline 3 \\ & 4 \end{aligned}$ | 2 | 6 | $\begin{array}{r} 13 \\ 1 \end{array}$ | $\begin{gathered} 7 \\ 17 \end{gathered}$ | $\begin{array}{r} 13 \\ 1 \end{array}$ | 7 | 1 | 34 |
| 6 | $\begin{aligned} & 2 \\ & 5 \end{aligned}$ | $\begin{aligned} & 1 \\ & 3 \end{aligned}$ | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ |  | 6 | $\begin{gathered} \hline 8 \\ 14 \end{gathered}$ | $\begin{gathered} 5 \\ 10 \end{gathered}$ | $\begin{gathered} \hline 7 \\ 14 \end{gathered}$ | 8 | 1 | 38 |
| 7 | $\begin{aligned} & \hline 3 \\ & 1 \end{aligned}$ | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | $\begin{aligned} & \hline 3 \\ & 1 \end{aligned}$ | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | 6 | $\begin{aligned} & \hline 6 \\ & 9 \end{aligned}$ | $\begin{aligned} & \hline 6 \\ & 8 \end{aligned}$ | $\begin{aligned} & \hline 6 \\ & 9 \end{aligned}$ | $\begin{gathered} 6 \\ 18 \end{gathered}$ | 1 | 30 |

(2) DATA C2

| $\begin{gathered} \mathrm{Job} \\ \text { j } \end{gathered}$ | Sequence of operations ( machine number) |  |  |  |  | Duration of operations |  |  |  |  | Total mean processing time 5 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 4 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 4 | 1 | 6 | 3 | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | 11 | 3 | 1 | 22.5 |
| 2 | 3 | 1 | 2 | 3 | 6 | 9 | 7 | 12 | 4 | 1 | 33 |
| 3 | 5 | $\begin{aligned} & \hline 4 \\ & 1 \end{aligned}$ | $\begin{aligned} & 5 \\ & 2 \end{aligned}$ | 4 | 6 | 8 | $\begin{aligned} & 11 \\ & 15 \end{aligned}$ | $\begin{aligned} & 13 \\ & 14 \end{aligned}$ | 5 | 1 | 40.5 |
| 4 | 2 | $\begin{aligned} & 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 2 \\ & 1 \end{aligned}$ | 5 | 6 | 5 | $\begin{aligned} & 21 \\ & 16 \end{aligned}$ | $\begin{gathered} 11 \\ 7 \end{gathered}$ | 6 | 1 | 39.5 |
| 5 | 3 | 1 | 4 | 2 | 6 | 4 | 7 | 2 | 7 | 1 | 21 |
| 6 | $\begin{aligned} & \hline 2 \\ & 5 \end{aligned}$ | $\begin{aligned} & 1 \\ & 3 \end{aligned}$ | $\begin{aligned} & \hline 4 \\ & 5 \end{aligned}$ | 2 | 6 | 5 2 | $\begin{gathered} \hline 5 \\ 10 \end{gathered}$ | $\begin{aligned} & 24 \\ & 25 \end{aligned}$ | 8 | 1 | 44.5 |
| 7 | $\begin{aligned} & \hline 3 \\ & 1 \end{aligned}$ | $\begin{aligned} & \hline 4 \\ & 5 \end{aligned}$ | $\begin{aligned} & \hline 3 \\ & 1 \end{aligned}$ | $\begin{aligned} & \hline 4 \\ & 5 \end{aligned}$ | $6$ | 6 9 | $\begin{aligned} & \hline 6 \\ & 8 \end{aligned}$ | $\begin{aligned} & 7 \\ & 5 \end{aligned}$ | $\begin{gathered} 9 \\ 10 \end{gathered}$ | 1 | 31 |


| $\begin{gathered} \overline{\text { Job }} \\ j \end{gathered}$ | Sequence of operations ( machine number) |  |  |  |  | Duration of operations |  |  |  |  | Total mean processing time 5 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 4 | 1 2 | 4 | 1 | 6 | 1 | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | 11 | 3 | 1 | 20.5 |
| 2 | 3 | 1 | 2 | 3 | 6 | 1 | 7 | 12 | 4 | 1 | 25 |
| 3 | 5 | 4 1 | $\begin{aligned} & 5 \\ & 2 \end{aligned}$ | 4 | 6 | 1 | $\begin{aligned} & 11 \\ & 15 \end{aligned}$ | $\begin{aligned} & 13 \\ & 14 \end{aligned}$ | 5 | 1 | 33.5 |
| 4 | 2 | 3 4 | $\begin{aligned} & 2 \\ & 1 \end{aligned}$ | 5 | 6 | 5 | $\begin{aligned} & 21 \\ & 16 \end{aligned}$ | $\begin{gathered} 11 \\ 7 \end{gathered}$ | 6 | 1 | 39.5 |
| 5 | $\begin{aligned} & \hline 3 \\ & 4 \end{aligned}$ | 1 2 | $\begin{aligned} & \hline 3 \\ & 4 \end{aligned}$ | 2 | 6 | $\begin{aligned} & 1 \\ & 1 \end{aligned}$ | $\begin{aligned} & 7 \\ & 8 \end{aligned}$ | $\begin{aligned} & 15 \\ & 21 \end{aligned}$ | 7 | 1 | 34.5 |
| 6 | $\begin{aligned} & 2 \\ & 5 \end{aligned}$ | 1 3 | $\begin{aligned} & 4 \\ & \hline 5 \end{aligned}$ |  | 6 | 1 | $\begin{gathered} 5 \\ 10 \end{gathered}$ | $\begin{aligned} & 24 \\ & 25 \end{aligned}$ | 8 | 1 | 42 |
| 7 | $\begin{aligned} & 3 \\ & 1 \end{aligned}$ | 4 5 | 3 1 | 4 5 |  | 1 | $\begin{aligned} & \hline 6 \\ & 8 \end{aligned}$ | $\begin{aligned} & 7 \\ & 5 \end{aligned}$ | $\begin{gathered} 9 \\ 10 \end{gathered}$ | 1 | 24.5 |

(4) DATA C4

| $\begin{gathered} \hline \text { Job } \\ \text { j } \end{gathered}$ | Sequence of operations ( machine number) |  |  |  |  | Duration of operations |  |  |  |  | Total mean processing time 5 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 4 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 4 | 1 | 6 | 1 | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | 4 |  | 1 | 13.5 |
| 2 | 3 | 1 | 2 | 3 | 6 | 1 | 7 | 4 | 4 | 1 | 17 |
| 3 | 5 | $\begin{aligned} & \hline 4 \\ & 1 \end{aligned}$ | $\begin{aligned} & 5 \\ & 2 \end{aligned}$ | 4 | 6 | 8 | $\begin{aligned} & \hline 6 \\ & 3 \end{aligned}$ | $\begin{aligned} & 7 \\ & 5 \end{aligned}$ | 5 | 1 | 24.5 |
| 4 | 2 | $\begin{aligned} & \hline 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 2 \\ & 1 \end{aligned}$ | 5 | 6 | 5 | $\begin{aligned} & \hline 8 \\ & 6 \end{aligned}$ | $\begin{aligned} & 6 \\ & 7 \end{aligned}$ | 6 | 1 | 25.5 |
| 5 | $\begin{aligned} & \hline 3 \\ & 4 \end{aligned}$ | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | $\begin{aligned} & \hline 3 \\ & 4 \end{aligned}$ | 2 | 6 | $\begin{aligned} & 1 \\ & 1 \end{aligned}$ | $\begin{aligned} & 7 \\ & 8 \end{aligned}$ | 1 4 |  | 1 | 19 |
| 6 | $\begin{aligned} & 2 \\ & 5 \end{aligned}$ | $\begin{aligned} & 1 \\ & 3 \end{aligned}$ | $\begin{aligned} & \hline 4 \\ & 5 \end{aligned}$ | 2 | 6 | $\begin{aligned} & 1 \\ & 1 \end{aligned}$ | $\begin{aligned} & 5 \\ & 4 \end{aligned}$ | 2 |  | 1 | 14.5 |
| 7 | $\begin{aligned} & 3 \\ & 1 \end{aligned}$ | $\begin{aligned} & \hline 4 \\ & 5 \end{aligned}$ | $\begin{aligned} & 3 \\ & 1 \end{aligned}$ | $\begin{aligned} & \hline 4 \\ & 5 \end{aligned}$ | $6$ | $\begin{aligned} & 1 \\ & 1 \end{aligned}$ | $\begin{aligned} & \hline 6 \\ & 8 \end{aligned}$ | 7 5 | $\begin{gathered} 9 \\ 10 \end{gathered}$ | 1 | 24.5 |

## APPENDIX D

Data for FMS with 7 jobs - 6 operations

APPENDIXD : Data for FMS with 7 jobs -6 operations. Four different sets of processing time are presented as follows :-
(1) DATA D1

| $\overline{\mathrm{Job}}$ | Sequence of operations ( machine number) |  |  |  |  | Duration of operations |  |  |  |  |  | Total mean processing time $n_{j}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 1 | 2 | 3 | 4 | 56 | 8 | 7 | 6 | 5 | 4 | 1 | 31 |
| 2 | 1 | 5 | 3 | 2 | 46 | 2 | 4 | 6 | 8 | 10 | 1 | 31 |
| 3 |  | $\begin{aligned} & 5 \\ & 2 \end{aligned}$ |  | 3 | 6 |  | $\begin{aligned} & 5 \\ & 5 \end{aligned}$ |  | 15 | 1 |  | 32 |
| 4 |  | $\begin{aligned} & \hline 2 \\ & 1 \end{aligned}$ | $3$ | $\begin{aligned} & \hline 4 \\ & 5 \end{aligned}$ | 6 |  | $\begin{aligned} & \hline 6 \\ & 6 \end{aligned}$ |  | $\begin{aligned} & 10 \\ & 10 \end{aligned}$ | 1 |  | 42 |
| 5 | 1 | 5 | 6 |  |  | 14 | 9 | 1 |  |  |  | 24 |
| 6 |  |  | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 3 | 6 |  |  |  |  | 1 |  | 56 |
| 7 |  | $\begin{aligned} & 1 \\ & 5 \end{aligned}$ | $\begin{aligned} & \hline 2 \\ & 3 \end{aligned}$ | 6 |  | 15 | $\begin{aligned} & 13 \\ & 13 \end{aligned}$ | $\begin{aligned} & \hline 6 \\ & 6 \end{aligned}$ |  |  |  | 35 |
| (2) DATA D2 |  |  |  |  |  |  |  |  |  |  |  |  |
| $\begin{aligned} & \hline \text { Job } \\ & \text { j } \end{aligned}$ | Sequence of operations ( machine number) |  |  |  |  | Duration of operations |  |  |  |  |  | ```Total mean processing time nj \sum [ pj,k``` |
| 1 | 1 | 2 | 3 | 4 | 56 | 5 | 8 | 6 | 10 | 4 | 1 | 34 |
| 2 | 1 | 5 | 3 | 2 | 46 | 2 | 7 | 6 | 8 | 10 | 1 | 34 |
| 3 | 1 | $\begin{aligned} & \hline 5 \\ & 2 \end{aligned}$ | 4 | 3 | 6 | 7 | $\begin{aligned} & 5 \\ & 5 \end{aligned}$ |  | 15 | 1 |  | 32 |
| 4 | 4 | $\begin{aligned} & 2 \\ & 1 \end{aligned}$ |  | $\begin{aligned} & 4 \\ & 5 \\ & 5 \end{aligned}$ | $6$ | 8 | $\begin{aligned} & \hline 6 \\ & 6 \end{aligned}$ | $17$ | $\begin{gathered} \hline 8 \\ 10 \end{gathered}$ | 1 |  | 41 |
| 5 | 1 | 5 | 6 |  |  | 11 | 4 | 1 |  |  |  | 16 |
| 6 | 4 | 3 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 3 | 6 | 14 | 9 | $\begin{aligned} & 10 \\ & 12 \end{aligned}$ | 17 | 1 |  | 52 |
| 7 |  | $\begin{aligned} & 1 \\ & 5 \end{aligned}$ | $\begin{aligned} & \hline 2 \\ & 3 \end{aligned}$ | 6 |  | 15 | $\begin{aligned} & 21 \\ & 21 \end{aligned}$ | $\begin{aligned} & \hline 6 \\ & 6 \end{aligned}$ |  |  |  | 43 |

(3) DATA D3

| Job | Sequence of operations ( machine number) |  |  |  |  | Duration of operations |  |  |  |  |  | Total mean processing time $\mathrm{n}_{\mathrm{j}}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 1 | 2 | 3 | 4 | 56 |  | 9 | 3 | 10 | 4 | 1 | 32 |
| 2 | 1 | 5 | 3 | 2 | 46 |  | 13 | 9 | 11 | 10 | 1 | 49 |
| 3 |  | $\begin{aligned} & 5 \\ & 2 \end{aligned}$ |  |  | 6 |  | $\begin{gathered} 7 \\ 15 \end{gathered}$ |  | 15 | 1 |  | 43 |
| 4 |  | $\begin{aligned} & 2 \\ & 1 \end{aligned}$ | 3 | $\begin{aligned} & \hline 4 \\ & 5 \end{aligned}$ | 6 |  | $\begin{gathered} \hline 6 \\ 11 \end{gathered}$ |  | $\begin{aligned} & \hline 8 \\ & 6 \end{aligned}$ | 1 |  | 27.5 |
| 5 |  | 5 | 6 |  |  | 11 | 13 | 1 |  |  |  | 25 |
| 6 |  |  | $\begin{aligned} & \hline 1 \\ & 2 \end{aligned}$ | 3 | 6 |  |  |  |  | 1 |  | 69.5 |
| 7 |  |  | $\begin{aligned} & 2 \\ & 3 \end{aligned}$ | 6 |  |  |  | $\begin{array}{r} 15 \\ 6 \end{array}$ |  |  |  | 46.5 |
| (4) DATA D4 |  |  |  |  |  |  |  |  |  |  |  |  |
| $\begin{gathered} \hline \text { Job } \\ \text { j } \end{gathered}$ | Sequence of operations ( machine number) |  |  |  |  | Duration of operations |  |  |  |  |  | $\begin{aligned} & \text { Total mean processing time } \\ & \sum_{\mathrm{j}=1}^{\mathrm{n}_{\mathrm{j}}} \mathrm{p}_{\mathrm{j}, \mathrm{k}} \end{aligned}$ |
| 1 | 1 | 2 | 3 | 4 | 56 | 3 | 4 | 2 | 7 | 4 | 1 | 21 |
| 2 | 1 | 5 | 3 | 2 | 46 | 5 | 1 | 5 | 3 | 3 | 1 | 18 |
| 3 | 1 | $\begin{aligned} & 5 \\ & 2 \end{aligned}$ | 4 | 3 |  |  | $\begin{aligned} & \hline 2 \\ & 6 \end{aligned}$ |  |  | 1 |  | 20 |
| 4 | 4 | $\begin{aligned} & 2 \\ & 1 \end{aligned}$ | $3$ | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | $6$ |  | $\begin{aligned} & \hline 6 \\ & 5 \end{aligned}$ | $1$ | $\begin{aligned} & 4 \\ & 6 \end{aligned}$ | 1 |  | 14.5 |
| 5 | 1 | 5 | 6 |  |  | 2 | 3 | 1 |  |  |  | 6 |
| 6 | 4 | 3 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 3 | 6 |  | 7 | $\begin{aligned} & \hline 4 \\ & 2 \end{aligned}$ | $6$ | 1 |  | 21 |
| 7 |  | $\begin{aligned} & 1 \\ & 5 \end{aligned}$ | $\begin{aligned} & 2 \\ & 3 \end{aligned}$ | 6 |  |  | $\begin{aligned} & 7 \\ & 6 \end{aligned}$ | $\begin{aligned} & \hline 5 \\ & 6 \end{aligned}$ | $1$ |  |  | 16 |

## APPENDIX E

Data for FMS with 10 jobs -6 operations

APPENDIXE : Data for FMS with 10 jobs -6 operations.
Four different sets of processing time are presented as follows :-
(1) DATA E1

| Job | Sequence of operations ( machine number) |  |  |  |  |  | Duration of operations |  |  |  |  |  |  | Total mean processing time $n_{j}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 1 | 2 | 3 | 4 | 5 | 6 | 8 | 7 |  | 6 | 5 | 4 | 1 | 31 |
| 2 | 1 | 5 | 3 | 2 | 4 | 6 | 2 | 4 |  | 6 | 8 | 10 | 1 | 31 |
| 3 |  | $\begin{aligned} & 5 \\ & 2 \end{aligned}$ | 4 | 3 | 6 |  |  | 5 5 |  |  | 15 | 1 |  | 32 |
| 4 | 4 | $\begin{aligned} & 2 \\ & 1 \end{aligned}$ | 3 | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | 6 |  |  | 6 6 |  |  | $\begin{aligned} & 10 \\ & 10 \end{aligned}$ | 1 |  | 43 |
| 5 | 1 | 5 | 6 |  |  |  | 14 | 9 |  | 1 |  |  |  | 24 |
| 6 | 4 | 3 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 3 | 6 |  | 14 | 9 |  | $\begin{aligned} & 12 \\ & 12 \end{aligned}$ | $20$ | 1 |  | 56 |
| 7 |  | $\begin{aligned} & 1 \\ & 5 \end{aligned}$ | $\begin{aligned} & \hline 2 \\ & 3 \end{aligned}$ | 6 |  |  | 15 | 13 13 |  | $\begin{aligned} & \hline 6 \\ & 6 \end{aligned}$ |  |  |  | 35 |
| 8 | 1 | 2 | 4 | 5 | 6 |  | 18 | 4 |  | 15 | 12 | 1 |  | 50 |
| 9 | 1 | 5 | 6 |  |  |  | 5 |  |  | 1 |  |  |  | 11 |
| 10 | 4 | 1 | 3 2 | $\begin{aligned} & \hline 5 \\ & 1 \end{aligned}$ | 6 |  | 4 | 7 |  | 7 | $\begin{aligned} & 5 \\ & 5 \end{aligned}$ |  |  | 24 |

(2) DATA E2
$\left.\begin{array}{llllllllllllll}\begin{array}{c}\text { Job } \\ j\end{array} & \begin{array}{c}\text { Sequence of operations } \\ \text { (machine number ) }\end{array} & \text { Duration of operations } & \begin{array}{c}\text { Total mean processing time } \\ n_{j} \\ \sum p_{j, k}\end{array} \\ \hline 1 & 1 & 2 & 3 & 4 & 5 & 6 & 8 & 7 & 6 & 5 & 4 & 1 & 31 \\ k=1\end{array}\right]$

## (3) DATA E3

| Job | Sequence of operations ( machine number) |  |  |  |  | Duration of operations |  |  |  |  |  | Total mean processing time $n_{j}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 1 | 2 | 3 | 4 | 56 | 2 | 4 | 6 | 8 | 10 | 1 | 31 |
| 2 | 1 | 5 | 3 | 2 | 46 | 2 | 10 | 6 | 4 | 8 | 1 | 31 |
| 3 | 1 | 5 2 | 4 | 3 | 6 |  | $\begin{gathered} 10 \\ 4 \end{gathered}$ |  | 6 | 1 |  | 24 |
| 4 | 4 | 2 | 3 | $\begin{aligned} & 4 \\ & 5 \end{aligned}$ | 6 |  | $\begin{aligned} & \hline 4 \\ & 2 \end{aligned}$ | $6$ | $\begin{gathered} 10 \\ 2 \end{gathered}$ |  |  | 24 |
| 5 | 1 | 5 | 6 |  |  |  | 6 | 1 |  |  |  | 11 |
| 6 | 4 | 3 | $\begin{aligned} & \hline 1 \\ & 2 \end{aligned}$ |  | 6 |  |  | $\begin{gathered} 8 \\ 10 \end{gathered}$ | 4 | 1 |  | 22 |
| 7 | 4 | 1 5 | $\begin{aligned} & 2 \\ & 3 \end{aligned}$ | 6 |  |  | $\begin{aligned} & \hline 8 \\ & 6 \end{aligned}$ | $\begin{gathered} 10 \\ 2 \end{gathered}$ | 1 |  |  | 18 |
| 8 | 1 | 2 | 4 | 5 | 6 | 8 | 10 | 2 | 4 | 1 |  | 25 |
| 9 | 1 | 5 | 6 |  |  | 6 | 8 | 1 |  |  |  | 15 |
| 10 | 4 | 1 |  | $\begin{aligned} & 5 \\ & 1 \end{aligned}$ | 6 | 8 |  | $\begin{aligned} & 6 \\ & 4 \end{aligned}$ | $\begin{gathered} 10 \\ 2 \end{gathered}$ |  |  | 30 |

(4) DATA E4

| Job | Sequence of operations ( machine number) |  |  |  |  |  | Duration of operations |  |  |  |  |  | Total mean processing time $n_{j}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 1 | 2 | 3 | 4 | 5 | 6 | 3 | 4 | 7 | 8 | 9 | 1 | 32 |
| 2 | 1 | 5 | 3 | 2 | 4 | 6 | 2 | 11 | 6 | 5 | 9 | 1 | 34 |
| 3 | 1 | $\begin{aligned} & \hline 5 \\ & 2 \end{aligned}$ | 4 | 3 | 6 |  | 3 | $\begin{aligned} & \hline 9 \\ & 4 \end{aligned}$ | 8 | 7 | 1 |  | 25.5 |
| 4 | 4 | $\begin{aligned} & 2 \\ & 1 \end{aligned}$ | 3 | $\begin{aligned} & \hline 4 \\ & 5 \end{aligned}$ | 6 |  | 8 | $\begin{aligned} & 4 \\ & 3 \end{aligned}$ | 7 | $\begin{gathered} 11 \\ 3 \end{gathered}$ | 1 |  | 26.5 |
| 5 | 1 | 5 | 6 |  |  |  | 3 | 7 | 1 |  |  |  | 11 |
| 6 | 4 | 3 | $\begin{aligned} & 1 \\ & 2 \end{aligned}$ | 3 | 6 |  | 5 | 3 | 7 | 4 | 1 |  | 21 |
| 7 | 4 | $\begin{aligned} & \hline 1 \\ & 5 \end{aligned}$ | $\begin{aligned} & 2 \\ & 3 \end{aligned}$ | 6 |  |  | 5 | $\begin{aligned} & 9 \\ & 7 \end{aligned}$ | $\begin{array}{r} 11 \\ 3 \end{array}$ | $\begin{aligned} & 1 \\ & 1 \end{aligned}$ |  |  | 21 |
| 8 | 1 | 2 | 4 | 5 | 6 |  | 9 | 12 | 1 | 3 | 1 |  | 26 |
| 9 | 1 | 5 | 6 |  |  |  | 5 | 7 | 1 |  |  |  | 13 |
| 10 | 4 | 1 | 3 2 | 5 1 | 6 |  | 6 | 9 | 7 5 | $\begin{gathered} 11 \\ 4 \end{gathered}$ | 1 |  | 29.5 |

## PUBLICATIONS

(1) Chan T.S. and Pak H.A. (1986) Heuristical job allocation in a flexible manufacturing system, The International Journal of Advanced Manufacturing Technology, 1(2), pp. 69-90.
(2) Chan T.S. and Pak H.A. (1986) Modelling of a controller for a flexible manufacturing cell, Proceedings of The Institution of Mechanical Engineers, Part B, Vol. 200, B3. ( will be published in August 1986 )

# The Institution of <br> Mechanical Engineers 

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# Heuristical Job Allocation in a Flexible Manufacturing System 

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#### Abstract

Two heuristic algorithms are presented for solving the scheduling problem in a statically loaded Flextble Manufacturing System (FMS). The heuristics goal is to minimise the total cost resulting from the tardiness of Jobs. Using the same heuristics, an iterative method is proposed to find an optumal makespan and the average lead time. Modifications required to handle the case of a dynamically loaded FMS are then presented Simulation results show that the developed heuristics appear to out perform the other published techniques used in obtaining the schedules associated with minimum makespan, minimum average lead time and minimum cost of tardiness. Finally, the simulation of the dynamic case shows that the algorithms could be implemented locally on each station for the scheduling calculation.


## 1. INTRODUCTION

It has been estımated ${ }^{[1]}$ that $75 \%$ of all machined parts are manufactured in batches of less than 50 . Component cost is about 10 to 30 tımes greater than if mass production methods were used. Within the past 10 years, a new mode of batch manufacturing has emerged in industry. Numerically controlled machines, having large magazines containing cuttıng tools and automatic tool changers, have been linked together by automatic material-handling devices (e.g. robots, automated guided vehicle, etc.) to become integrated systems capable of performing the operations required to produce parts with minimum human intervention. The system can simultaneously machine several parts of different types, and it may provide alternative routes for some operations. The movement of workpieces between stations and the scheduling of operations are controlled by one or more computers. The workstations are equipped with stored program controllers which direct local operations. Such a production system is commonly called a Flexible Manufacturing System (FMS). The basic objectıve of the flexible manufacturing concept is to achieve the efficiency and utilisation levels of mass production, whilst retaining the flexibility of manually operated job shops. The advantages of FMS may be summarised as follows:
(1) The production of familes of workparts
(11) The random launching of workparts
(ii1) Reduced lead times
(1v) Reduced in-progress inventory
(v) Increased machine utilisation
(vi) Reduced direct and indirect labour cost, and
(vii) Improved management control

In recent years many operational researchers have suggested different methods of solving part routing problems in FMS. Buzacott ${ }^{[4]}$ has suggested that the manufacturing paths can either be found in advance, or a set of dispatching rules can be established which may be used to schedule the jobs in real time. Reviews of relevant research on real time control policies have been given by Olsder and Suri ${ }^{[16]}$, Hıldebrant ${ }^{[10]}$ and Kımemia and Gershwin. ${ }^{[13]}$

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Coffman ${ }^{[6]}$ has applied the combinatorial techniques to solve the job-shop scheduling problem, but the computational effort for solving job-shop problems increased rapidly with the number of jobs and machines. Hitz ${ }^{[12]}$ described a periodic scheduling algorithm which is a heuristic combinatorial technique for obtainıng schedules that maxımise the production rate of an FMS. However, the routes for all the parts must be established before the computation of the periodic schedule is possible. Solberg, ${ }^{[21]}$ Secco Svardo, ${ }^{[19]}$ Buzacott and Shanthikumar ${ }^{[3]}$ and Stecke and Solberg ${ }^{[22]}$ have applied analytical techniques which are based on queuing theory to examine the effects of routing policies on the lead time and in progress inventory of an FMS. A survey of analytical methods for solving the scheduling problems in some larger production systems appears in Buzacott and Yao. ${ }^{[4]}$

In common industrial practice, jobs are scheduled in such a way that the workloads at the workstations are equal. ${ }^{[15,}{ }^{20]}$ This idea can be applied to solve the problem of alternative routing in an FMS such that jobs will be scheduled to the station where the workload is mınımum, i.e. shortest waiting time. For this reason, the solution technıques of this paper are not intended to determine the optimal part routing in advance, but rather concentrate the work on scheduling locally at each workstation. It is therefore unnecessary to enumerate all of the possible routes for each part type in advance.

In this paper, the original work of Gere ${ }^{[8]}$ is extended and two heuristic algortthms for FMS applications are developed. The algorithms are built into a simulation program which is written in Fortran and runs on a Cyber 855 computer system. For the due date problem, the heuristics are used to obtain a schedule such that the respective due dates are met, or failing this, the cost of tardiness is mınımised. For the makespan and average lead tıme problems, the algorithms find an optımal due date, $d_{J}{ }^{*}$, for each job. Usıng these values of $d_{J}{ }^{*}$, the algorithms are applied locally on each station to decide which job should be allocated next. This approach renders the algorithms suitable for use with on-line scheduling of tasks in an FMS.

## 2. THE HEURISTICS

The following assumptions are made for the development of the heuristic scheduling algorithms:

1. No machine may process more than one operation at a time
2. No job may be processed by more than one machine at a tıme
3. A finite process tıme is assumed which includes the set up time
4. The time intervals for processing are independent of the order in which the operations are performed
5. Machines do not breakdown
6. The job routing is given and alternative routings are permitted. When there is an alternative route for a job to take for its next operation, the station which offers the shortest waiting time will be selected, i.e. balanced workload
7. Transportation times between machines are either fixed or negligible
8. Due dates are known and fixed when the objective measure of performance is the cost of tardiness
9. There is a local storage buffer at each station (Figure 1)

A summary of necessary notation is presented below to formulate the heuristics The notation is as follows:
$K_{J} \quad=$ total number of operations for job $J$
$k \quad=$ operation number $\left(\right.$ on $\left.\mathrm{job}_{J}\right), k=1,2, \ldots, K_{J}$
$J=$ total number of jobs
$J \quad=$ job number, $J=1,2, \quad, J$
$n, \quad=$ number of next operation to be scheduled (on job $J$ )
$t=$ present tıme


Figure 1 Model of a flexible manufacturing system.

| d | $=$ due date of job ${ }_{J}$ |
| :---: | :---: |
| $p_{\text {J, }, k}$ | $=$ mean processing time for the $k$ th operation of the $j$ th job |
| $S_{J}$ | = slack time, job ${ }_{\text {, }}$ |
| $J^{*}$ | $=$ job selected to be scheduled |
| $\psi_{m}{ }^{*}$ | $=$ the set of jobs waiting to be processed on the given machine $m$ at time $t$ |
| $P^{*}$ | $=$ priority rating for job $J^{*}$ |
| (CF), | $=$ cost per unit lateness of job $J$ |
| $C_{1}$ | $=$ cost of lateness if job $J$ is scheduled |
| $C_{1,}$ | = cost of lateness obtained from the scheduled job $j$ which was already late |
| $C_{2, ~}$ | $=$ cost of lateness obtained from those jobs which have been queued inside the buffer $m$ if job $J$ has been scheduled (1.e. jobs in the set $\gamma_{J}$ ) |
| $C_{3,}$ | $=$ cost of lateness for those jobs which will be queued inside the buffer $m$ in future time if $j$ ob $J$ has been scheduled |
| $t_{\text {, }, ~}$ | $=$ the tıme of job $j$ arrives at buffer $m$ |
| $T_{J s, m}$ | $=$ the completion time for the scheduled job Js on machine $m$ |
| $A_{m}$ | $=$ the set of jobs which have been scheduled to machine $m$ for therr next operation, they are being processed on some other machines or being transported at time $t$ |
| ${ }^{1} \Omega_{J S, m}$ | $=$ a subset of $A_{m}$ with the condition such that jobs satisfy $t_{\text {d,m }}<T_{J s, m}$ |
| ${ }^{2} \Omega_{J S, m}$ | $=$ a set of critical jobs due to reach the machine $m$ at some future time, yet before the scheduled operation on $J s$ is completed |
| $\gamma_{J}$ | $=$ a set of critical jobs queued inside the buffer if job $J$ has been scheduled |
| $r_{j k}$ | $=$ number of alternative routes for job $j$ in the $k$ th operation |
| $q_{\text {kl }}$ | $=$ machine number for processing job $J$ in the $k$ th operation, $l=1,2, \ldots, r_{j k}$ |
| $\left(t_{p}\right)_{1, m}$ | $=$ processing tıme for the job $j$ on machine $m$. |

### 2.1 Alternate Operation Heuristic ( $H_{l}$ )

1 Select a dynamic job dispatching rule which takes into account the due date, the present tıme and the remaining processing tıme. e.g. job slack rule,


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2. Schedule the operation according to the selected rule.
3. Check to see if this will make another job 'critical' (that is, see if the slack of any other job has just become negative). If so, revoke the last operation, and schedule the next operation on the critical job. Suppose the original selected job is $J^{*}$, and the set of critical jobs is $J_{l}{ }^{*}$, compute and record the cost of lateness $C_{J}{ }^{*}$ due to job $J^{*}$ being scheduled on the machine $m$ (Table 1) 1.e. to obtain

Table 1. An example to show the relationship between ${ }_{J}, \gamma_{J}$ and $C_{J}$ for $\psi_{m}=\{1,2,3,4,5\}$

| Scheduled job $J$ | Critical jobs set $\gamma_{J}$ |  | $\underset{C}{\text { Cost of lateness }}$ |
| :---: | :---: | :---: | :---: |
| $J^{*} \longrightarrow 1$ | 2,3 \} | $J_{1}^{*}$ | $C_{1} \longleftarrow C^{*}$ |
| $J_{1}{ }^{*}\left\{\begin{array}{l}2 \\ 3\end{array}\right.$ | $\left.{ }_{2}^{1,5}\right\}$ | $J_{2}$ | $\mathrm{C}_{2}$ |
| $J_{2}{ }^{*}\{5$ | $2\}$ | $J_{3}$ | $C_{5}$ |

$$
S_{J}= \begin{cases}d_{J}-\sum_{k=n_{J}}^{K_{J}} p_{J, k^{-t-}-p_{J}^{*}, n_{J}^{*}} & , \text { for } j \varepsilon \psi_{m} \& J \neq J^{*} \\ d_{J}-\sum_{k=n_{J}}^{K_{J}} p_{J, k^{-t}} & , \text { for } J=J^{*}\end{cases}
$$

Hence obtain the set of critical jobs $J_{1}{ }^{*}$ which satisfy $S,<0$, such that for those jobs with $S_{j}<0, j \varepsilon J_{1}{ }^{*}$. If $J_{1}{ }^{*}=\{\phi\}$, STOP and retain the orıginal schedule $J^{*}$. Otherwise, compute $C_{,}{ }^{*}$ and go to step (4).
where

$$
\begin{aligned}
& C_{J}^{*}=C_{1, J}{ }^{*}+C_{2, J}{ }^{*} \\
& C_{1, J}{ }^{*}=\max \left\{0,-\left(S_{J}^{*}\right) \cdot(C F)_{J}^{*}\right\} \\
& C_{2, J}^{*}=\sum_{j \varepsilon J_{1}^{*}}(C F)_{j} \cdot\left|S_{J}\right|
\end{aligned}
$$

4. Check to see if the set of critical jobs $J_{1}{ }^{*}$ makes another set of critical jobs $J_{2}$. If so, compute the cost of lateness $C_{t}$, where $t_{1} \varepsilon J_{1}{ }^{*}$ and go to step (5). Otherwise, STOP and retain the original schedule $J^{*}$.
where

$$
C_{l 1}=C_{l, 11}+C_{2, t 1}
$$

$$
C_{2,11}=\sum_{,(1)}(C F)_{j} \cdot\left|S_{j}\right|
$$

and

$$
S_{J}= \begin{cases}d_{J}-\sum_{k=n_{j}}^{K_{J}} p_{j, k^{-t}-p} p l 1, n_{t 1} & , \text { for } \jmath \varepsilon \gamma_{l 1} \text { and } J \neq l_{1} \\ d_{J}-\sum_{k=n_{J}}^{K_{J}} p_{J, k^{-t}} & , \text { for } J=l_{1}\end{cases}
$$

5 If all the jobs found in the set $J_{2}$ have been considered before, go to step (8) Otherwise,
obtain a set of unscheduled critical jobs $J_{2}{ }^{*}$.
6. Check to see if this set of critical jobs $J_{2}{ }^{*}$ makes another set of critical jobs $J_{3}$. If so, compute the cost of lateness $C_{12}$, where $t_{2} \varepsilon J_{2}{ }^{*}$ and go to step (7). Otherwise, go to step (8).
7. Repeat step (5), but replace $J_{m}$ by $J_{(m+1)}, J_{m}{ }^{*}$ by $J^{*}{ }_{(m+1)}$ and $l_{m}$ by $l_{(m+1)}$.
8. Schedule the job $J_{s}$ which gives the minimum value of the cost of lateness
i.e. $C_{J_{s}}=\min \left\{\mathrm{C}_{\mathrm{J}}\right\}$
where $j \varepsilon\left\{{ }^{*} U J_{1}{ }^{*} U J_{2}{ }^{*} U \quad U J_{1}{ }^{*}\right\}$
and $J_{s}=$ the final selected job.
Note If more than one minımum exists, select the job which makes the least number of critical jobs. However, if a tie happens again, select the one which has been waiting for a longer time.

### 2.2 Alternate Operation + Look Back Heuristic ( $H_{2}$ )

This heuristıc is actually a contınuation from the Alternate Operation heuristic. Step (1)-(8) are exactly the same as in the previous heuristic $H_{1}$.
9. Check to see if there are critical jobs due to reach this machine in some future tıme, before the selected operation is completed. In an FMS, those critical jobs which have alternative routes in their next operation will not be considered. If there are such critical jobs, check for the effects of these on other jobs. Depending on the resulting analysis of lateness, elther select a new schedule or keep the previously selected operation.
1.e to obtain $t_{, m}$ where $J \varepsilon A_{m}$

If $\left(t_{, m} \geqslant T_{J s, m}\right)$ for all $J$, then STOP and retain the original schedule,
i.e. job $J_{s}$ is actually scheduled on machine $m$.

However, for those jobs satisfying $\left(t_{J, m}<T_{J s, m}\right)$, put $j \varepsilon^{1} \Omega_{J s, m}$. Hence a set of jobs ${ }^{1} \Omega_{J s, m}$ is obtained such that ${ }^{1} \Omega_{J s, m} \subset A_{m}$.
10. Obtain the values of $\left\{d_{J} t_{J, m}-\left(T_{J, m^{-t}, m}\right)-\sum_{k=n_{J}}^{K_{J}} p_{J, k}\right\}$ where $\left(T_{J s, m^{-t}, m}\right)=$ mınımum waitıng tıme for the future arrival job $j$ in buffer $m$ if the job $J_{s}$ is now being processed.

$$
\text { and } J \varepsilon^{1} \Omega_{J S, m}
$$

After simplification, the values of $\left\{d_{J}-T_{J s, m}-\sum_{k=n_{J}}^{K_{J}} p_{J, k}\right\}$ are obtained,
ut $T_{J S, m}=t+p_{J S, n_{J S}}$

$$
\text { obtain }\left\{d_{J}-t-p_{J s, n_{J S}}-\sum_{k=n_{j}}^{K_{J}} p_{J, k}\right\}
$$

If $\left\{d_{J}-t-p_{J s, n_{J s}}-\sum_{k=n_{J}}^{K_{J}} p_{J, k}\right\} \geqslant 0$, for all $j \varepsilon^{1} \Omega_{J_{S, m},}$, then STOP and retain the original schedule, i.e. $J_{S}$ is actually scheduled on machine $m$. However, for those jobs satisfy $\left\{d_{j}-\right.$ $\left.t-p_{J_{S, n} n_{S}}-\sum_{h=n_{J}}^{K_{J}} p_{J, k}\right\}<0$, then put $\varepsilon^{2} \Omega_{J_{s, m}}$. Hence a set of future critical jobs ${ }^{2} \Omega_{J_{S, m}}$ is
obtained, where ${ }^{2} \Omega_{J s, m} \subset{ }^{1} \Omega_{J s, m}$.
11. Compute the cost of lateness due to selection of the original job $J s$ on machine $m$ by taking into account the cost of future lateness of some other jobs.
1.e. $C_{J s}=C_{1, J s}+C_{2, J s}+C_{3, J s}$
where $C_{1, J s}$ and $C_{2, J s}$ can be obtaıned as before,


$$
\therefore C_{J s}=C_{1, J_{s}}+C_{2, J s}+\sum_{J \varepsilon^{2} \Omega_{J s, m}}\left|d_{j}-t-p_{J, n_{J S}}-\sum_{k=n_{J}}^{K_{J}} p_{J, k}\right|(C F)_{J}
$$

Let $\beta_{1}{ }^{*}=\gamma_{J s} U^{2} \Omega_{J s, m}($ see Table 2$)$
Table 2. An example to show the relationship between $J_{,} \gamma_{\rho}{ }^{2} \Omega_{J, m}$ and $c_{J}$ for $\psi_{m}=\{1,2,3,4,5\}$ and $A_{m}=\{6,7\}$. Assuming the original scheduled job $J_{s}$ is job 5

| Scheduled job $J$ | Critical jobs set |  | Cost of lateness$C_{J}$ |
| :---: | :---: | :---: | :---: |
|  | Inside buffer $\gamma$ | Future arrival ${ }^{2} \Omega_{\mathrm{J}, \mathrm{m}}$ |  |
| $J_{s} \longrightarrow 5$ | 2 | 6,7 | $C_{5}$ |
| $\beta_{1}{ }^{*}\left\{\begin{array}{l}2 \\ 6 \\ 7\end{array}\right.$ | 1,5 2 4 | $\left.\begin{array}{l}6 \\ 7 \\ 6\end{array}\right\} \quad \beta_{2}$ | $C_{2}$ $C_{6}$ $C_{7}$ |
| $\beta_{2}{ }^{*} \quad\left\{\begin{array}{l}1 \\ 4\end{array}\right.$ | 2,3 5 | $\left.\begin{array}{l}7 \\ 6\end{array}\right\} \quad \beta_{3}$ | $\mathrm{C}_{1}$ |
| $\beta_{3}{ }^{*}$ \{ 3 | 2 |  | $C_{3}$ |

12. Compute the cost of lateness due to consider each job in the set $\beta_{1}{ }^{*}$ by taking into account the cost of future lateness of some other jobs. This can be done in two parts:
(a) For those jobs $1 \varepsilon \gamma_{J s}$
where $C_{1, t}$ and $C_{2, t}$ can be determıned as before.
computation of $C_{3, t}$
Repeat step (9) and step (10), but replace $J s$ by job $l$, hence obtain ${ }^{1} \Omega_{i, m}$ and ${ }^{2} \Omega_{l, m}$

$$
C_{3, l}=\sum_{J \varepsilon^{2} \Omega_{l, m}}\left|d_{-}-\sum_{k=n_{J}}^{K_{J}} p_{J, k}-t-p l, n_{l}\right|(C F)_{J}
$$

(b) For those jobs $t \varepsilon^{2} \Omega_{J s m}$ ( 1 e . consider those critical jobs which will arrive in some future tıme)
again $C_{l}=C_{1, t}+C_{2, t}+C_{3, l}$
but now $C_{1, t}=\max \left\{0,-\left[d_{l}-t-\sum_{k=n_{t}}^{K_{l}} p_{l, k}-\left(t_{l, m}-t\right)\right] \cdot(C F)_{t}\right\}$
the term $\left(t_{l, m}-t\right)$ is the machıne idlıng time due to awaiting of job $t$
After simplification,
$C_{1, l}=\max .\left\{0,-\left[d_{t}-\sum_{k=n_{l}}^{K_{l}} p_{t k}-t_{l, m}\right] \cdot(C F)_{l}\right\}$
and $C_{2, l}=\sum_{j \varepsilon \psi_{m}} \max .\left\{0,-\left[d_{J}-t-\sum_{k=n_{j}}^{K_{J}} p_{J, k}-\left(t_{l, m}-t\right)-p_{\left.l, n_{t}\right]} \cdot(C F)_{J}\right\}\right.$
After simplification,

$$
C_{2, l}=\sum_{J \varepsilon \psi_{m}} \max .\left\{0,-\left[d_{j}-\sum_{k=n_{J}}^{K_{J}} p_{j, k}-t_{l, m^{-}} p l, n_{l}\right](C F)_{j}\right\}
$$

Assume $D_{J}=d_{J} \sum_{k=n_{J}}^{K_{J}} p_{J, k}-t_{l, m^{-}} p l, n_{t}$
Hence we may obtain a set of critical jobs $\gamma_{t}$ which satisfy the following conditions:

1) $J \varepsilon \psi_{m}$ and
2) $D_{J}<0$

Now, compute $C_{3, f}$ for those jobs satisfying the following conditions:

1) $J \varepsilon A_{m}$
2) $j \neq l$
3) $t_{l, m}<T_{i m}$

$$
\begin{aligned}
& C_{3, F}=\sum \quad \max \left\{0,-\left[d_{j}-t-\sum_{k=n_{J}}^{K_{J}} p_{J, k}-\left(T_{l, m}-t_{\jmath, m}\right) \cdot(C F)\right\}\right. \\
& J \varepsilon A_{m} \\
& j \neq l \\
& \mathrm{t}_{\mathrm{t}, \mathrm{~m}}<T_{l, m}
\end{aligned}
$$

where the term $\left(T_{l, m}-t_{l, m}\right)=$ waiting time of the future job $j$ in buffer $m$ if another future $\mathrm{ob} l$ has been scheduled on machine $m$.

Assume $E_{j}=d_{j}-t-\sum_{k=n_{j}}^{K_{J}} p_{J, k}-\left(T_{l m}-t_{J, m}\right)$
Hence a set of critical jobs may be obtained ${ }^{2} \Omega_{t, m}$ which satisfy the following conditions:

1) $J \varepsilon A_{m}$
2) $J \neq l$
3) $t_{J, m}<T_{l, m}$
4) $E_{J}<0$

Note: In case (b) where $i \varepsilon^{2} \Omega_{J, m}$, if the term $C_{1, t} \neq 0$, job $\iota$ will be an element in the critical jobs set ${ }^{2} \Omega_{l, m}$ as well.
13. Check to see if this creates another critical job set $\beta_{2}{ }^{*}$ which had not been considered before. If so, schedule the next operation on the critical job and obtain the resulting job lateness. Otherwise, schedule the job which offers the minımum cost of lateness.
The heuristic algorithms can best be illustrated by a small example which is taken from Nicholson and Pullen. ${ }^{[14]}$ This is a five-job, three-machine job-shop problem. Detaled calculations will not be shown in this paper, but they are available if required. ${ }^{[5]} \mathrm{As}$ a result, the completion tımes for these five jobs calculated from our heuristics are the same as those presented in Nicholson's paper.

## 3. EXPERIENCE WITH STATIC FMS DUE DATE PROBLEMS

In the previous section, it has been mentioned that the heuristics were validated against Nicholson's example. Here it is desirable to see its application on some static FMS. The resulting cost of tardiness is compared with solutions which are obtained by some general dispatching rules. The minımum slack tıme rule (SLACK) and the shortest imminent process time rule (SIP) are employed for comparison with the developed heuristics. It is generally believed that the first rule is the simplest rule for the due date problems, and the second rule will provide a good estımate of the makespan. There are two assumptions which have been made for this study:
(1) Due date of a job is proportional to its mean total processing time in the system. In this analysis, $d_{J}=1.5 \times \sum_{k=1}^{K_{J}} p_{j, k}$
where $\sum_{k=1}^{K_{J}} p_{J, k}=$ mean total processing tıme of $\mathrm{job} J$.
(2) The cost per unit tardiness for each job is equal to unity.

Since the optımal solutions for these examples are unknown, the performance of these heuristics and dispatching rules have been evaluated by means of a relative ranking index as shown in Table 5. With this method, when a heuristic or dispatching rule gives the best solution value, it is ranked with index 1 . For the second best value, it is ranked with 2 . In the case of two or more techniques giving the same value, they are all ranked with the same index, equal to the average (e.g. 15). With this method, the sum of ranks is the same for all test problems
Nine different examples are considered here, the number of operations varied from four to six, the number of jobs varied from seven to ten and the number of machines was six in all cases, but re-visiting of machine is permitted for some of the jobs Only one set of data is presented in Table 3 due to the limited space in this paper, but other data is avalable if required.
Results of these examples are presented in Table 4 and Table 5. From Table 5 it can be seen that heuristic $H_{2}$ ranks highest in the analysis of the cost of tardiness. In addition, it provides eight tımes the mınimum cost of tardiness in nıne tests. In the analysis of makespan, the SIP rule ranks highest as was expected. Heuristic $H_{1}$ offers the second best result of the cost of tardiness. However, the SLACK rule gives the worst results for all the three objectıve measures of performance

Table 3. Data for FMS example 6

| Job $1$ | Sequence of operations (machine number) | Duration of operations | $\sum_{k=1} p_{1}$ | $d_{1}=15 \times \sum_{h=1} p_{, h}$ |
| :---: | :---: | :---: | :---: | :---: |
| 1 | $\begin{array}{lllll} 4 & 1 & 4 & 1 & 6 \end{array}$ | $\begin{array}{lllll} 3 & 4 & 11 & 3 & 1 \end{array}$ | 225 | 3375 |
| 2 | 31236 | $9712+1$ | 33 | 495 |
| 3 | $\begin{array}{lllll}5 & 4 & 5 & 4 & 6 \\ & 1 & 2 & & \end{array}$ | $\begin{array}{lllll} 8 & 11 & 13 & 5 & 1 \\ & 15 & 14 & & \\ \hline \end{array}$ | 405 | 6075 |
| 4 | 2 3 2 5 6 <br> 4 1    | $\begin{array}{lllll} 5 & 21 & 11 & 6 & 1 \\ & 16 & 7 & & \end{array}$ | 395 | 5925 |
| 5 | 31426 | 4721 | 21 | 315 |
| 6 | $\begin{array}{lllll} 2 & 1 & 4 & 2 & 6 \\ 5 & 3 & 5 & & \\ \hline \end{array}$ | $\begin{array}{rrrrr} 5 & 5 & 24 & 8 & 1 \\ 2 & 10 & 25 & & \end{array}$ | 445 | 6675 |
| 7 | $\begin{array}{lllll}3 & 4 & 3 & 4 & 6 \\ 1 & 5 & 1 & 5 & \end{array}$ | $\begin{array}{rrrrr} 6 & 6 & 7 & 9 & 1 \\ 9 & 8 & 5 & 10 & \end{array}$ | 31 | 465 |

Table 4. Comparative evaluation of the heuristics on the static FMS due date problems

| Example | $n \times$ NOP |  | Heuristic $H_{1}$ | Heuristic $\mathrm{H}_{2}$ | SLACK | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $7 \times 4$ | $\begin{gathered} m s \\ l \\ c \end{gathered}$ | $\begin{gathered} 42 \\ 28.43 \\ 7.8 \end{gathered}$ | $\begin{aligned} & \hline 42 \\ & 27.71 \\ & * 3.5 \end{aligned}$ | $\begin{aligned} & \hline 41 \\ & 28.71 \\ & 8 \end{aligned}$ | $\begin{aligned} & 45 \\ & 30.71 \\ & 26 \end{aligned}$ |
| 2 | $7 \times 4$ | $\begin{gathered} m s \\ l \\ c \end{gathered}$ | $\begin{aligned} & 78 \\ & 60.71 \\ & 37.3 \end{aligned}$ | $\begin{gathered} 77 \\ 5514 \\ * 16.3 \end{gathered}$ | $\begin{aligned} & 78 \\ & 60.71 \\ & 37.3 \end{aligned}$ | $\begin{aligned} & \hline 72 \\ & 54.43 \\ & 23.8 \end{aligned}$ |
| 3 | $7 \times 4$ | $\begin{gathered} \hline m s \\ l \\ c \end{gathered}$ | $\begin{aligned} & 92 \\ & 47.14 \\ & 23.5 \end{aligned}$ | $\begin{aligned} & 92 \\ & 47.14 \\ & 23.5 \end{aligned}$ | $\begin{aligned} & 92 \\ & 47.43 \\ & 24.3 \end{aligned}$ | $\begin{aligned} & \hline 69 \\ & 45 \\ & * 9.5 \end{aligned}$ |
| 4 | $7 \times 4$ | $\begin{gathered} m s \\ l \\ c \end{gathered}$ | $\begin{aligned} & 38 \\ & 26 \\ & * 2.8 \end{aligned}$ | $\begin{aligned} & 38 \\ & 26 \\ & * 2.8 \end{aligned}$ | 43 27.57 6.3 | $\begin{aligned} & \hline 38 \\ & 26.57 \\ & * 2.8 \end{aligned}$ |
| 5 | $7 \times 5$ | $\begin{gathered} m s \\ l \\ c \end{gathered}$ | 80 50.57 $* 5$ | $\begin{aligned} & 80 \\ & 50.57 \\ & * 5 \end{aligned}$ | $\begin{aligned} & 80 \\ & 50.57 \\ & * 5 \end{aligned}$ | $\begin{aligned} & \hline 74 \\ & 49 \\ & 11.5 \end{aligned}$ |
| 6 | $7 \times 5$ | $\begin{gathered} m s \\ l \\ c \end{gathered}$ | $\begin{aligned} & 74 \\ & 53.57 \\ & 35 \end{aligned}$ | $\begin{aligned} & \hline 63 \\ & 46.57 \\ & { }^{2} 1.8 \end{aligned}$ | $\begin{aligned} & 74 \\ & 55 \\ & 46 \end{aligned}$ | $\begin{aligned} & \hline 64 \\ & 49.71 \\ & 36.8 \end{aligned}$ |
| 7 | $7 \times 5$ | $\begin{gathered} m s \\ l \\ c \end{gathered}$ | $\begin{aligned} & \hline 61 \\ & 42.86 \\ & * 13 \end{aligned}$ | $\begin{aligned} & \hline 61 \\ & 42.86 \\ & { }^{2} 1.3 \end{aligned}$ | 65 45.86 14.3 | $\begin{aligned} & \hline 56 \\ & 4186 \\ & 13.8 \end{aligned}$ |
| 8 | $7 \times 5$ | $\begin{gathered} \hline m s \\ l \\ c \end{gathered}$ | $\begin{aligned} & \hline 37 \\ & 3114 \\ & 20.3 \end{aligned}$ | $\begin{gathered} 44 \\ 3114 \\ * 14 \end{gathered}$ | $\begin{aligned} & \hline 42 \\ & 30.71 \\ & 145 \end{aligned}$ | $\begin{aligned} & \hline 37 \\ & 31.14 \\ & 19.3 \end{aligned}$ |
| 9 | $10 \times 6$ | $\begin{gathered} m s \\ l \\ c \end{gathered}$ | $\begin{array}{r} 101 \\ 60.7 \\ * 112.5 \end{array}$ | $\begin{gathered} 101 \\ 60.7 \\ * 112.5 \end{gathered}$ | $\begin{gathered} 120 \\ 66.3 \\ 170 \end{gathered}$ | $\begin{gathered} 93 \\ 59.7 \\ 116 \end{gathered}$ |
| $\begin{aligned} & \text { NOP }=\text { number of operations } \\ & n \quad=\text { number of jobs } \\ & m s=\text { makespan } \end{aligned}$ |  |  | $l$ =average lead tıme <br> $c \quad=$ cost of tardmess <br> Note the asterisk $\left(^{*}\right)$ denotes the best method in each examp |  |  |  |

Table 5. Ranking for the heuristics on the static FMS due date problems
Total number of tests $=9$

|  |  | Heuristic $H_{1}$ | Heurıstıc $H_{2}$ | SLACK | SIP |
| :--- | :--- | :---: | :---: | :---: | :---: |
| Number of best | $m s$ | 2 | 2 | 1 | 7 |
| performance of | $l$ | 1 | 3 | 1 | 5 |
|  | $c$ | 4 | 8 | 1 | 2 |
| Rankıng | $m s$ | 2.67 | 2.5 | 3.22 | ${ }^{* *} 161$ |
|  | $l$ | 2.61 | 2.06 | 3.39 | ${ }^{* *} 1.89$ |
|  | $c$ | 2.333 | $* * 1.5$ | 3.389 | 2.778 |

Note the asterısk (**) denotes the best method for each measure of performance

## 4. DEVELOPMENT OF $d_{j}$ VALUES FOR OBTAINING OPTIMUM MAKESPAN AND AVERAGE LEAD TIME

The static FMS due date problem has been considered in the previous section. The minimisation of work in progress and the maximisation of resource utilisation in an FMS is now considered. In general, the fulfilment of one factor does not automatically imply the fulfilment of the other. It has been shown previously that heuristic $H_{2}$ provides good schedules for obtainıng minımum cost of tardiness, but poor values of makespan. It has been pointed out by Nicholson and Pullen ${ }^{[14]}$ that the meeting of due dates may imply full use of resources if due dates are set tightly, but for static situations, reducing makespan may also imply higher utılisation of resources. Hence a short makespan mıght be expected to be obtained by meeting the due dates which are set tightly. On the other hand, minımising the work in progress may imply mınımısing the lead times of jobs. However, how tight the due dates should be is not known. Therefore, 1 is proposed to set the due dates equal to the mean total processing times (for flow-shop or job-shop, the mean total processing times are equivalent to the earliest completion times), then determine the values of makespan and lead times by applying the heuristics. This can best be illustrated by the following six-job, threemachine flow-shop problem (Table 6) taken from Stinson and Smith. ${ }^{[23]}$ The detarled procedures of obtaining the schedules will not be presented, but the Gantt chart representation of the results are shown in Figure 2 and Figure 3, and the results are summarised in Table 7.
' In this example, the makespan is lowest if heuristic $H_{1}$ is employed. This method results in the job sequence of $4,5,6,1,2,3$, which is the same for all three machines. The makespan is 65 and compares well with the optımal makespan for this problem of 64 (with the sequence of $4,1,2,3,6,5$ ). The sequence obtained from Stinson and Smith ${ }^{[23]}$ which is $1,2,3,6,4,5$ had a makespan equal to 66 (but there was a typing error in the original paper such that the


Figure 2 Gantt chart of Stınson's example with heuristıc $\mathrm{H}_{1}$


Figure3 Gantt chart of Stınson's example with heuristıc $\mathrm{H}_{2}$
Table 6. Operation time in a 6-job, 3-machine Stinson's example

| Job | Machıne |  | Earlest completion |  |
| :---: | ---: | ---: | ---: | :---: |
|  | 1 | 2 | 3 | time |
| 1 | 5 | 6 | 20 | 31 |
| 2 | 6 | 30 | 6 | 42 |
| 3 | 30 | 4 | 5 | 39 |
| 4 | 2 | 5 | 5 | 12 |
| 5 | 3 | 1 | 4 | 17 |
| 6 | 4 | 1 | 4 | 9 |

Table 7. Results of Stinson's example

|  | Heuristic <br> $H_{1}$ | Heurıstıc <br> $H_{2}$ | Stınson and <br> Smith |
| :---: | :---: | :---: | :---: |
| Makespan | 65 | 67 | 66 |
| Average lead time | 38 | 37.8 | 52.2 |

makespan was printed as 67). Heuristic $H_{2}$ gives the lowest value of average lead time (the average lead time from the optimal makespan sequence $4,1,2,3,6,5$ is 45 ). This is mainly due to the machine $M_{2}$ which has been forced to watt for the job 6 at $t=7$ (Figure 3), hence job 6 has left the system with a very short lead tıme. Because of the machining process which has been delayed by 2 units at $M_{2}$, the makespan obtained by heuristic $H_{2}$ is 67. This is the main disadvantage of applying heuristıc $H_{2}$, since there may be several queue jobs delayed by the look-back-job for several hours in excess of the processing time alone. In order to solve this problem, rescheduling may be required, so that unnecessary machine idling tıme will be kept to a mınımum. For this example, this can be done by sequencing job 6 before job 5 in its first operation on $M_{1}$. The improvement is shown in Figure 4. The modified schedule improves the makespan as well as the average lead time, and is equivalent to increasing the utilisation of machines and decreasing the work in progress inventory (improved results: makespan = 66 , average lead time $=37.2$ ).
The above modification is easy and obvious because of the simplicity of the system. For complicated systems such as job-shop with revisit of machines or FMS, it requires a considerable amount of computation to find out the affect on the performance of a system if a job has changed its position in the sequence. An alternative solution for this problem is to re-adjust the due dates, then apply the heuristic algorithms to find another schedule. It is


Figure 4 Gantt chart of Stınson's example with heuristıc $\mathrm{H}_{2}$ and due date adjustment
believed that optımal or near optimal solutions may be obtained by a special choice of due dates. ${ }^{[8]}$ Since the optimal values of these due dates are not known, it is proposed to select due dates equal to the corresponding completion tımes which are calculated from the first schedule. If there is no improvement from the second schedule, then the original schedule will be retained. Otherwise, the due dates equal to the completion tımes which have been given from the second schedule will be re-adjusted. This iteratıve procedure is repeated untıl there is no further improvement of the objective measure of performance of the system. Consequently, the final proposed due dates which will produce the mınımum makespan are defined as 'the optımal due dates for makespan' and the due dates which give the shortest average lead tıme are defined as 'the optımal due dates for average lead tıme' As mentioned before, the optımal due dates for makespan are not necessarily the same as the optımal due dates for average lead times.

## 5. EXPERIENCE WITH STATIC SYSTEM OF MAKESPAN/ AVERAGE LEAD TIME PROBLEMS

In the previous section, determınation of optımal makespan and optimal average lead tıme is equivalent to defining their corresponding optımal due dates. In this section, some of the published technıques are used to evaluate this method. Results are shown in Table 8 where the optımal values of makespan and average lead time obtained from the literature and the developed heuristics are given. Table 9 presents a comparison between the heuristics and other published methods according to two measures of performance. The first measure is the number of best performances produced by each technique, and the second measure is a sımple ranking An examination of the performances which have been shown in Table 9 suggests that the heuristic $H_{1}$ and heuristic $H_{2}$ are the best performers in obtaining the makespan and the average lead time respectıvely. Upon this examınation, it would appear that our heuristics out perform the others. However, most of the examples that have been tested are flow-shop problems, some complicated systems such as FMS are now considered. Here 12 different examples are considered, the number of operations varied from four to six, the number of jobs varied from seven to ten, the number of machines was six for all examples. Since the optimal solutions for these examples are unknown, the results are compared with those obtained from two dispatching rules. The First-In- First-Out (FIFO) rule and the SIP rule are employed for comparison, it is generally accepted that the FIFO rule is the simplest rule for scheduling, and SIP rule always provides a short makespan. The results of these examples are presented in Table 10

Table 8. Comparison of performance of the developed heuristics with other published methods

| Type of system $\mathrm{n} \times \mathrm{m}$ | Method | Makespan | Average lead time | Job sequence on each machıne |
| :---: | :---: | :---: | :---: | :---: |
| $\begin{gathered} 5 \times 3 \\ \text { (Flow-shop) } \end{gathered}$ | $\text { Page }{ }^{[17]}$ | *51 | $34.8$ | $\begin{aligned} & \mathrm{M}_{1}: \\ & \mathrm{M}_{2}: 3,2,1,4,5 \\ & \mathrm{M}_{3}: \end{aligned}$ |
|  | $\begin{aligned} & H_{1} \\ & H_{2} \end{aligned}$ | $\begin{aligned} & * 51 \\ & * 51 \end{aligned}$ | $\begin{aligned} & * 33 \\ & * 33 \end{aligned}$ | $\begin{aligned} & \mathrm{M}_{1}: \\ & \mathrm{M}_{2}: 3,4,1,2,5 \\ & \mathrm{M}_{3}: \end{aligned}$ |
| $\begin{gathered} 6 \times 3 \\ \text { (Flow-shop) } \end{gathered}$ | Gupta ${ }^{[9]}$ <br> $H_{1}$ <br> $H_{2}$ | 68 *67 $68$ | *37.5 <br> 38.5 <br> *37.5 | $\begin{aligned} & \mathbf{M}_{1}: \\ & \mathbf{M}_{2}: 4,6,5,1,2,3 \\ & M_{3}: \\ & M_{1}: \\ & M_{2}: 4,5,6,1,2,3 \\ & M_{3}: \\ & M_{1}: \\ & M_{2}: 4,6,5,1,2,3 \\ & M_{3}: \end{aligned}$ |
| $3 \times 4$ <br> (Flow-shop) | Brooks \& White ${ }^{[2]}$ $\begin{aligned} & H_{1} \\ & H_{2} \end{aligned}$ | $\begin{aligned} & * 32 \\ & * 32 \\ & * 32 \end{aligned}$ | $\begin{aligned} & * 253 \\ & * 25.3 \\ & * 25.3 \end{aligned}$ | $\begin{aligned} & \mathrm{M}_{1}: \\ & \mathrm{M}_{2}: \\ & \mathrm{M}_{3}: 2,3,1 \\ & \mathrm{M}_{4}: \end{aligned}$ |
| $\begin{gathered} 4 \times 5 \\ \text { (Flow-shop) } \end{gathered}$ | Hitomi ${ }^{[1]]}$ $H_{1}$ $\mathrm{H}_{2}$ | 94 <br> 94 *88 | $\text { *63 } 25$ *63.25 $63.5$ | $\mathrm{M}_{1}$ : <br> $\mathrm{M}_{2}$ : <br> $\mathrm{M}_{3}: 2,1,4,3$ <br> $\mathrm{M}_{4}$. <br> $\mathrm{M}_{5}$ : <br> $\mathrm{M}_{1}: 2,1,4,3$ <br> $\mathrm{M}_{2}: 2,1,4,3$ <br> $\mathrm{M}_{3}: 2,1,4,3$ <br> $\mathbf{M}_{4}: 2,1,3,4$ <br> $\mathrm{M}_{5}: 2,1,3,4$ |
| $3 \times 3$ <br> (Job-shop with revisit of machıne) | Bestwick \& Lockyer ${ }^{[7]}$ $\begin{aligned} & H_{1} \\ & H_{2} \end{aligned}$ | $\begin{aligned} & * 10 \\ & * 10 \\ & *_{10} \end{aligned}$ | 9.33 $* 9$ $* 9$ | $\begin{aligned} & \mathrm{M}_{1}: 1,2 \\ & \mathrm{M}_{2}: 2,1,3,2 \\ & \mathrm{M}_{3}: 3,2,1,3 \\ & \mathrm{M}_{1}: 1,2 \\ & \mathrm{M}_{2}: 2,1,3,2 \\ & \mathrm{M}_{3}: 3,1,2,3 \end{aligned}$ |

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Table 8. Continued
$\mathrm{m}=$ number of machine

| Type of system | Method | Makespan | Average lead tıme | Job sequence on each machine |
| :---: | :---: | :---: | :---: | :---: |
| $7 \times 3$ <br> (Flow-shop) | Palmer ${ }^{[18]}$ | 75 | 55.14 | $\begin{aligned} & \mathrm{M}_{1} \cdot \\ & \mathrm{M}_{2}: 1,4,5,2,6,7,3 \\ & \mathrm{M}_{3} . \end{aligned}$ |
|  | $H_{1}$ | * 72 | 43 | $\mathrm{M}_{1}$ : ${ }_{\text {M }}$ |
|  |  |  |  | $\mathrm{M}_{3}{ }^{\text {. }}$. ${ }^{\text {a }}$ |
|  | $\mathrm{H}_{2}$ | 75 | *39 14 | $\mathrm{M}_{1}$. |
|  |  |  |  | $\begin{aligned} & \mathrm{M}_{2} \cdot 4,6,5,7,1,2,3 \\ & \mathrm{M}_{3} \end{aligned}$ |
| $8 \times 3$ <br> (Flow-shop) | Palmer ${ }^{[18]}$ | 85 | 635 | M |
|  |  |  |  | $\mathrm{M}_{2}$ 2,6,8,3,4,7,1,5 |
|  |  |  |  | $\mathrm{M}_{3}$. |
|  | $H_{1}$ | *81 | *52.13 | $\begin{aligned} & \mathrm{M}_{1} . \\ & \mathrm{M}_{2} \\ & 8,3,2,7,4,1,6,5 \end{aligned}$ |
|  | $\mathrm{H}_{2}$ | *81 | *52.13 |  |
| $6 \times 3$ <br> (Flow-shop) | Palmer ${ }^{[18]}$ | *59 | 46.33 | $\begin{aligned} & \mathrm{M}_{1}: \\ & \mathrm{M}_{2} \cdot 6,3,5,4,1,2 \end{aligned}$ |
|  |  |  |  | $\mathrm{M}_{3}{ }^{\text {. }}$ |
|  | $H_{1}$ | *59 | 42.67 | $\mathrm{M}_{1}: 6,4,3,1,5,2$ |
|  |  |  |  | $\mathrm{M}_{2}$ $\mathrm{M}_{3}, 6,3,1,5,2,4,4$ |
|  | $\mathrm{H}_{2}$ | *59 | *41.83 | $\mathrm{M}_{1}{ }^{3}$ |
|  |  |  |  | $\mathrm{M}_{2} \cdot 6,1,3,2,5,4$ |
| $9 \times 3$ <br> (Flow-shop) |  |  |  |  |
|  | Palmer ${ }^{[18]}$ | *84 | 53.33 | $\mathrm{M}_{1}$. |
|  |  |  |  | $\mathrm{M}_{2}$ $\mathrm{M}_{3}$ , |
|  | $\mathrm{H}_{1}$ | 88 | 47.44 | $\mathrm{M}_{1}$. 7,2,3,8,1,5,9,6,4 |
|  |  |  |  | $\mathrm{M}_{2} \cdot 7,8,1,3,9,6,5,4,2$ |
|  |  |  |  | $\mathrm{M}_{3}$. $7,8,1,3,9,6,5,4,2$ |
|  | $\mathrm{H}_{2}$ | 88 | *4722 | $\mathrm{M}_{1}$ 7, ${ }^{\text {l }}$ |
|  |  |  |  | $\mathrm{M}_{2} .7,8,1,3,9,6,4,5,2$ |
|  |  |  |  |  |
| $\begin{gathered} 4 \times 3 \\ \text { (Flow-shop) } \end{gathered}$ | Palmer ${ }^{[88]}$ | *54 | 4275 | $\mathrm{M}_{1}{ }^{\text {- }}$ |
|  |  |  |  | $\mathrm{M}_{2}$ 2,4,3,1 |
|  |  |  |  | $\mathrm{M}_{3}$. |
|  | $H_{1}$ | 60 | *385 | M |
|  |  |  |  | $\mathrm{M}_{2}$ 3,1,4,2 |
|  | $\mathrm{H}_{2}$ | 60 | *38.5 |  |
| $5 \times 3$ <br> (Flow-shop) | Palmer ${ }^{[18]}$ | *80 | 492 | $\mathrm{M}_{1}{ }^{\text {- }}$ |
|  |  |  |  | $\mathrm{M}_{2}$ 3,5,1,2,4 |
|  |  |  |  | $\mathrm{M}_{3}$. |
|  | $\mathrm{H}_{1}$ | *80 | *436 |  |
|  |  |  |  | $\mathrm{M}_{2}$. 5,2,3,1,4 |
|  | $\mathrm{H}_{2}$ | *80 | *43 6 | $\mathrm{M}_{3}$. |

Table 9. Ranking of performance for the heuristics and other published methods
Total number of tests=11

|  |  | Heur1stıc <br> $H_{1}$ | Heurıstıc <br> $H_{2}$ | Other <br> methods |
| :--- | :--- | :---: | :---: | :---: |
| Number of best | $m s$ | ${ }^{* * 8}$ | 7 | 7 |
| performance of | $l$ | 7 | ${ }^{* * 10}$ | 3 |
| Ranking | $m s$ | ${ }^{* *} 1.909$ | 2.045 | 2.045 |
|  | $l$ | 1.818 | ${ }^{* * 1.545}$ | 2.636 |

Table 10. Ranking for the heuristics on the static FMS makespan/average lead time problems

Total number of tests $=12$

|  |  | Heuristic <br> $H_{1}$ | Heuristic <br> $H_{2}$ | FIFO | SIP |
| :--- | :--- | :---: | :---: | :--- | :--- |
| Number of best | $m s$ | ${ }^{* *} 10$ | 6 | 1 | 7 |
| performance of | $l$ | 6 | ${ }^{* * 11}$ | 0 | 3 |
| Rankıng | $m s$ | ${ }^{* *} 1.833$ | 2.583 | 3.25 | 2.333 |
|  | $l$ | 2.125 | ${ }^{* *} 1.417$ | 3.875 | 2.583 |

## 6. DYNAMIC FMS WITH DUE DATE, MAKESPAN / AVERAGE LEAD TIME PROBLEMS

Statıc FMS with due date, makespan and average lead tıme problems has already been considered. The heuristics appear to out perform some of the single dispatching rules and published methods. In practice, the behaviour of FMS is not static due to the rapid change of demands or breakdown of machınes. In this paper, the breakdown of machines has not been considered, but the developed simulation program has taken into account machine failure. A dynamic FMS is a system in which there is some work in progress initially and where new jobs will arrive at a later time. The problem is separated into two parts which is similar to the static case. The first part is the due date problem, and the second part is the makespan and average lead time problems.

### 6.1 Dynamic FMS with due date problems

In the static case, the due date of each job is assumed to be proportional to its mean total processing time inside the system,
i.e. $d_{J}=F, \times \sum_{k=1}^{K_{j}} p_{J, k}$
where $F_{J}=$ a safety factor for job $J$ to account for the congestion in the system.
In the dynamic system, it is assumed $d_{J}=t_{a j}+F_{J} \times \sum_{k=1}^{K_{J}} p_{j, k}$, where $t_{a j}=$ arrival tıme of job $J$. In order to compare the performance of the heuristics with some other methods, the
computation will be terminated if a pre-determined production has been met. The assumptions made are summarised as follows:
(a) Due date $d_{j}=t_{a j}+F_{J} \times \sum_{k=1}^{K_{J}} p_{j, k}$,
(b) Input a batch of job perrodically, and
(c) Decide a production demand.

Several simulations have been done for evaluating the performance of the heuristics. The assumptions that made for these simulations are as follows.

## TEST A

1. Due date $d_{J}=t_{a j}+15 \times \sum_{k=1}^{K_{J}} p_{j, k}$,
2. Input a batch of jobs in every 30 time units, where the batch consists of one job of each part-mix, and
3 Desired production: five jobs of each part-mix.

## TEST B

1. Due date $d_{J}=t_{a j}+2 \times \sum_{k=1}^{K_{J}} p_{j, k}$,
2. Input a batch of jobs in every 20 time units, where the batch consists of one job of each part-mix, and
3. Desired production: three jobs of each part-mix

Table 11. Comparative evaluation of the heuristics on the dynamic FMS due date problems

| TEST | $\mathrm{n}_{\mathrm{p}} \times$ NOP | Cost of Tardıness |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $\begin{gathered} \text { Heuristıc } \\ H_{1} \end{gathered}$ | $\begin{gathered} \text { Heurıstıc } \\ \mathrm{H}_{2} \end{gathered}$ | SLACK | SIP |
| A | $7 \times 4$ | *155.5 | 185.5 | 177.8 | 164.8 |
|  | $7 \times 4$ | 2018.5 | *1742.5 | 2000 | 1887.3 |
|  | $7 \times 4$ | 14673 | 1483.3 | *1401.3 | 14353 |
|  | $7 \times 4$ | 53 | *39 | 568 | 58.8 |
|  | $7 \times 5$ | 16595 | *1643.5 | 1777.5 | 2006 |
|  | $7 \times 5$ | 1404 | *12538 | 1341.5 | 1393 |
|  | $7 \times 5$ | *889 5 | 915 | 957 | 989.7 |
|  | $7 \times 5$ | *141.3 | 175.3 | 1415 | 1553 |
|  | $7 \times 6$ | *2324 5 | 2716 | 2587.5 | 2503 |
| B | $7 \times 4$ | 61 | 68 | *58 | 94 |
|  | $7 \times 4$ | 522 | 465 | 573 | *453 |
|  | $7 \times 4$ | 274 | *246 | 286 | 357 |
|  | $7 \times 4$ | *15 | *15 | 17 | 48 |
|  | $7 \times 5$ | *343 | *343 | 431 | 453 |
|  | $7 \times 5$ | *366 | 371 | 459 | 489 |
|  | $7 \times 5$ | *221 | *221 | 242 | 295 |
|  | $7 \times 5$ | *39 | 69 | 47 | 70 |
|  | $7 \times 6$ | 726 | 726 | *701 | 759 |

[^2]Table 12. Ranking for the heuristics on the dynamic FMS due date problems
Total number of tests $=18$

|  | Heuristic <br> $H_{1}$ | Heurıstic <br> $H_{2}$ | SLACK | SIP |
| :--- | :---: | :---: | :---: | :---: |
| Number of occurence of <br> mınimum cost of tardıness | ${ }^{* * 9}$ | 8 | 3 | 1 |
| Rankıng | ${ }^{* * 1.945}$ | 2.22 | 2.56 | 3.28 |

Here interest is centred on reducing the cost of tardiness in a dynamic FMS situation, values of this measure are presented in Table 11. Upon examınation of the ranking in Table 12 , it can be seen that the heuristics compare favourably with the SLACK rule and SIP rule, providing the 14 best results out of the 18 tests. The SIP rule gives the worst result since it has not considered the due date.

### 6.2 Dynamic FMS with makespan/average lead time problems

In the static system, makespan represents a time length from the beginning of the first operation of the first job to the end of the last operation of the last job. If a dynamic system is assumed to be a non-stop manufacturıng plant, then the term makespan is not applicable since new jobs will arrive from time to time. In this paper, the dynamic system is defined as follows:

1. Some jobs are available at the beginning, but new jobs will arrive at some later time, and
2. Production demand is pre-determined, once the production demand is met, production is stopped.

Hence the heuristics can still be compared with other methods by comparing their values of makespan and average lead tıme.

In a static system, due dates of jobs are initially set very close to their mean total processing time. Then after the first simulation trail, due dates are adjusted to the corresponding completion tımes, this follows by a second simulation trail. This procedure will continue until there is no further improvement on the desıred measure of performance, i.e. makespan or average lead time. In dynamic system, new jobs will arrive in future time, and it is proposed to assume the initial due date $d_{j}=t_{a j}+\sum_{k=1}^{K_{J}} p_{j, k}$. This can best be illustrated by the following example.

## Example: Dynamic flow-shop with makespan/average lead time problems (Figure 5)

Job 1 and job 2 are available at $t=0$, job 3 and job 4 will arrıve at time $t_{3}$ and $t_{4}$ respectıvely. There are only two operations for each job. The desired production demand is the manufacturing of these four jobs. Hence the due date for each job in the first simulation is assumed as follows ${ }^{-}$
$d_{1}=0+\sum_{k=1}^{2} p_{1, k}=\sum_{k=1}^{2} p_{1, k}$
$d_{2}=0+\sum_{k=1}^{2} p_{2, k}=\sum_{k=1}^{2} p_{2, k}$

$$
\begin{aligned}
& d_{3}=t_{3}+\sum_{k=1}^{2} p_{3, k} \\
& d_{4}=t_{4}+\sum_{k=1}^{2} p_{4, k}
\end{aligned}
$$

The assumed results are presented in Figure 5. After the first trail, a set of completion tımes have been obtained, i.e. $L_{1}, L_{2}, L_{3}$ and $L_{4}$ The next step is to adjust the due dates and then run the simulation again. Two methods of due date adjustment are now proposed.
1 This method has already been shown for the static case, i.e. due dates are adjusted to the corresponding completion tımes which have been determined from the previous schedule, i.e $\left[\begin{array}{ll}d_{1} & L_{1} \\ d_{2} & L_{2} \\ d_{3} & L_{3} \\ d_{4} & L_{4}\end{array}\right]$


## Figure 5 Gantt chart of dynamic flow-shop with makespan/average lead tıme problem

This approach entirely depends on the previous completion times, hence this method is known as 'full adjustment' of due date.
2. The second method of due date adjustment is simpler than the method of 'full adjustment'. During the iteration procedure, this method only adjusts the due dates of those components which are avalable at $t=0$, 1.e. job 1 and job 2 , hence due dates of job 1 and job 2 are adjusted to $d_{1}=L_{1}$ and $d_{2}=L_{2}$ respectively For the components which will arrive in future tıme, i.e. job 3 and job 4 , due date is assumed such that $d_{J}=t_{a j}+\sum_{k=1}^{K_{J}} p_{J, k}$ which is equal to the imitial value appeared in the first simulation trall. Since only part of the components will be adjusted, this method is known as 'partial adjustment' of due date.

These two methods of due date adjustment are evaluated by applying the heuristics to several dynamic FMS with different input rate of new components and varied production demands.

## CASE 1

In this analysis, the following assumptions have been made.
(a) Input a batch of jobs in every 80 time units, where the batch consists of one job of each
part-mix, and
(b) Desired production: 3 jobs of each part-mix

## CASE 2

Assumptions:
(a) Input rate = output rate, i.e. whenever there is a job leaving the system, another job of the same part-mix will be launched into the system, and
(b) Desired production: five jobs of each part-mix

Table 13. Ranking for the heuristics on the dynamic FMS makespan/average lead time problems (CASE 1)

Total number of tests $=8$

|  | $H_{1}$ |  | $H_{2}$ |  | FIFO | SIP |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
|  | partally <br> adjusted | fully <br> adjusted | partally <br> adjusted | fully <br> adjusted |  |  |
| Number of best $m s$ <br> performance of $l$ | 5 | ${ }^{* * 8}$ | 4 | 4 | 0 | 5 |
| Ranking $\quad m s$ | 3.25 | 5 | 4 | ${ }^{* * 2.125}$ | 3.688 | 3.375 |
|  | $l$ | 3.688 | 2.688 | 2.875 | ${ }^{* * 2}$ | 5.313 |

Table 14. Ranking for the heuristics on the dynamic FMS makespan/average lead time problems (CASE 2)

Total number of tests $=12$

|  | $\mathrm{H}_{1}$ |  | $\mathrm{H}_{2}$ |  | FIFO | SIP |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | partially adjusted | $\begin{gathered} \text { fully } \\ \text { adjusted } \end{gathered}$ | partally adjusted | $\begin{gathered} \text { fully } \\ \text { adjusted } \end{gathered}$ |  |  |
| Number of best $m s$ performance of $l$ | $\begin{array}{r} * * 6 \\ 2 \end{array}$ | $\begin{array}{r} * * 6 \\ 3 \end{array}$ | $\begin{array}{r} 1 \\ * * 8 \end{array}$ | $\begin{aligned} & 1 \\ & 3 \end{aligned}$ | $\begin{aligned} & 3 \\ & 0 \end{aligned}$ | $\begin{array}{\|l\|} \hline 3 \\ 3 \end{array}$ |
| Ranking ${ }_{l}^{m s}$ | $\begin{aligned} & 2.542 \\ & 3.042 \end{aligned}$ | $\begin{array}{r} * * 2.458 \\ 3.167 \end{array}$ | $\begin{array}{r} 4.417 \\ * * 2.042 \end{array}$ | $\begin{aligned} & \hline 4.5 \\ & 3.042 \end{aligned}$ | $\begin{aligned} & 3.083 \\ & 5.833 \end{aligned}$ | $\begin{array}{\|l\|} \hline 4 \\ 3875 \end{array}$ |

The comparative evaluation of the heuristics on these two cases are presented in Table 13 and Table 14
Upon examination on Table 13, heuristic $H_{1}$, with the method of full adjustment of due dates appears to be the best technique to obtain the optimal makespan. This can be observed from the results, which show that the technıque offers the optımal values of makespan in all the eight tests. On the other hand, the best technique of obtaining the optımal average lead time is granted to the heuristic $H_{2}$ with the method of full adjustment of due date According to the results which have been presented in Table 10, Table 13 and Table 14, heuristic $H_{1}$ and heuristic $\mathrm{H}_{2}$ always provide the best solution of the makespan and average lead time in both of the static and dynamic systems respectively.

For the technique of partial adjustment of due dates, only those components which are available initially will be adjusted. Hence the optimal solution by this technique would not be expected to be obtained. This has been proved by the results which have been presented in Table 13 where the technique of full adjustment of due date works better than the partial

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adjustment of due date in determining both of the optimal makespan and average lead time.
According to the results shown in Table 14, the heuristics which use the techniques of due date adjustment again out perform the other dispatching rules. For CASE 2, the technique of partial adjustment of due date appears to improve the system performance as compared to that in CASE 1. This is reflected by the ranking which the technıque has been granted, 1.e. 2.542 for the makespan (the second best), and 2.042 for the average lead time (the best one). This seems to contradict the previous statement, i.e. full adjustment of due date is better than the partial adjustment. Further analysis of the results of CASE 2 will be followed in this paper.

For the technique of partial adjustment of due date, due dates for future arrival jobs are governed by the relation of $d_{j}=t_{a j}+\sum_{k=1}^{K_{j}} p_{j, k}$. In CASE $1, t_{a j}$ values are exactly the same in each iteration. Hence $d_{j}$ values for the future jobs will not be adjusted by the technique of partial adjustment of due date. Consequently, results which have been obtained by this technique are unsatisfactory. However, in CASE 2, it has been assumed that whenever there


Figure 6 (a) Results from the first simulation


Figure 6(b) Results from the second simulation with the partial adjustment of due dates
is a job leaving the system, a job of the same part-mix will be launched. Hence the arrival time for a future job is dependent upon the completion time of the corresponding job with the same part-mix. This is best illustrated by the Gantt chart as shown in Figure 6 (a) and Figure 6 (b).

From Figure 6 (a), job 1 and job 2 are avalable at $t=0$, and job 1 is assumed to have higher priority to load on the machine. According to the previous assumption of inputing new jobs, $t_{a 3}=L_{1}$ and $t_{a 4}=L_{2}$ are obtained, and the resulting schedule is $1,2,3,4$. In the second iteration, the due dates of job 1 and job 2 are adjusted to $d_{1}=L_{1}$ and $d_{2}=L_{2}$ (where $L_{1}$ and $L_{2}$ are taken from Figure 6 (a)). From Figure 6 (b), it has been assumed that job 2 is loaded on the machine first, hence the arrival times for job 3 and job 4 are different from the first schedule. As a result, the due dates for future jobs may also be adjusted even though only the technique of partial adjustment of due dates has been applied. Consequently, this technıque performs satisfactorily as seen in Table 14.

## 7. PRACTICAL IMPLEMENTATION

The implementation of the system requires firstly that the factory data (e.g. transportation time between machines) be interpreted and set up into the files of information. Secondly, the developed heuristic procedures have to be built into each station as a software control module Thirdly, the developed simulation program must be organised into a practical offline computer system.

In this paper, work has concentrated on the optimisation of the cost of tardiness, makespan and average lead time. In order to obtain the optımal solution of an objective measure of performance, the data files for production have been prepared in a period of 'scheduled time' (e.g. each day or each week). Within this 'scheduled tıme', data files should remain unchanged, e.g. the speed of robots, input rate of new jobs, routing, due dates of jobs (if they are given), etc. According to the given information within this 'scheduled tıme', the best heuristic procedure which corresponds to the objective measure of performance can then be determined by the off-line simulation computer system. A set of data values which represent this selected heuristic will be transmitted from the off-line computer system to the local control module. Moreover, if the objective measure is either the makespan or the average lead time, a set of 'optimal due dates' will need to be transferred as well. During the stage of actual manufacturing, jobs will be scheduled to the machines according to the selected heuristic procedure which has been determıned by the off-line simulation program. However, if some disturbances occur (e.g. machine breakdown, a new production design, change of speed of robot and etc.), rescheduling is required. This can be done by simulating the system with all the up-dated information, and consequently determining another best heuristic approach with optımal due dates. Therefore, the system should have an efficient up-dating scheme so that the preparation time of new data is reduced and the best heuristic can quickly be redetermıned as disturbances occur. The computation time for the developed simulation program on a reasonably large schedule is small, and it therefore offers an economic proposition to small, as well as large, manufacturing systems In addition, the scheduling calculation time is very small for the developed heuristics, hence the heuristics could be practically implemented on each station.

## 8. CONCLUSION

In this paper two heuristic algorithms for solving the FMS scheduling problems in both static and dynamic cases have been developed and tested. The objective measures of performance are the minimum makespan, minimum average lead time and mınimum cost of tardiness.

For the due date problem, the heuristics have been used to obtain a schedule such that the respective due dates are met, or failing this, the cost of tardiness is minımised. For the

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makespan and average lead time problems, the heuristics find an optımal due date, $d_{l}^{*}$, for each job iteratıvely. Using these values of $d_{j}^{*}$, the algorithms can be applied locally at each station to decide which job should be scheduled next. The approach is such that the operation of the system can be computer simulated.
Simulation results show that the developed heuristics appear to out perform the other published techniques used in obtaining the schedules associated with minımum makespan, mınimum average lead tıme and mınımum cost of tardıness. Finally the sımulation of the dynamic cases indicates that the heuristics could also be implemented locally on each station for the scheduling calculation.

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[^0]:    *Completed Installations
    +Small system/duplex cell

[^1]:    Table 6.16 Data structure for the FMS supervisory computer execution program

[^2]:    $n_{p}=$ number of part-mix

