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DYNAMIC SCHEDULING STRATEGIES
FOR FMS HUB NETWORKS
WITH FLOW TIME CONSIDERATION

by

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Thesis submitted to
The School of Graduate Studies and Research
for the Degree of
Master of Applied Science
in
Systems Science

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ABSTRACT

This thesis investigates the effects of dynamic rescheduling strategies of jobs at multiple revisited workstations called hubs on the performance of Flexible Manufacturing Systems (FMS). The objective of rescheduling jobs at workstations is to improve various aspects of the production flow and manufacturing productivity.

Compared to fixed queue scheduling rules, dynamic changes in queue scheduling rules for hubs at certain intervention times, are shown in some cases to reduce total job flow time (maximum completion time of all jobs in a fixed total "Makespan") and average flow time (average completion time) simultaneously. The development of dynamic hub scheduling rules including intervention time specification to improve job flow measures establish the basis for an Expert System rules base for dynamic scheduling.

The rationale for dynamic queue scheduling rules are developed from analysing the machine idle time structure for a simple single hub system operated under fixed queue scheduling rules. The intervention and rescheduling procedure is applied to increasingly complex and concrete FMS cases use a flexible simulation model including animation of the production facility. Specifically, this thesis provides a methodology for developing and evaluating the rescheduling rules with respect to the trade-off between Makespan and average completion time for a fixed number of jobs in an FMS defined by hub and non-hub workstations.

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CHAPTER 1.

INTRODUCTION

A Flexible Manufacturing System (FMS) can be defined as a group of flexible workstations connected by a material handling system and controlled by both computers and human operators. All processed parts (jobs) go through the network of workstations conveyed by handling systems or wait for workstation and handling systems availability. Most FMS involve complex queuing systems for processing jobs in a workstation network.

In most implemented systems, FMS networks are a part of a multi-step manufacturing system. The input consists of jobs that have undergone one or more processing steps and finished jobs are assembled into different final products.

In order to improve productivity, the FMS can process jobs related by similar operational requirements or belonging to the same final assembly. All jobs in the parts family can be processed simultaneously. The jobs are introduced into the FMS system at a loading station, and leave the system at an unloading station after undergoing a specified sequence of operations. The machines in an FMS are capable of performing operations on a certain sequence of parts with negligible changeover time from one part to the next. The flexibility of the system allows the choice of parts of one or more stations for each operation. This also allows production to continue even when a workstation is out of service because of failure or maintenance.

The change-over setup time for jobs at workstations can be negligible in these systems because workstations are numerically controlled with a number of tools used for each operation or because operations are performed by robots. The ability of an FMS to produce jobs simultaneously results in reducing work-in-process inventories, and faster response to changes in demand requirements when compared to the traditional production methods. However, careful attention must be paid to production scheduling. The high initial capital cost of an FMS network means that efficient use of system resources is very important.

Flexible manufacturing technology has been more and more adopted by many discrete-parts manufacturing industries in an attempt to increase the productivity and quality and reduce high costs of production. Excellence in Flexible Manufacturing System (FMS) has been recognised as very important in the success of modern manufacturing processes (Gunasekaran, et al. 1993), and new technologies of manufacturing processes play a significant rule in the development of the FMS. Achieving the full potential of these new production methods, necessitates a broad range of management, engineering, and system control issues. The implementation of the modern manufacturing method and technology represents an opportunity for significant contributions from the operations research (OR) / management science (MS), methodologies.

The Integrated Circuit (IC) industry provides many examples of applied Flexible Manufacturing processes. The IC manufacturing involves complex process flows in a demanding production environment containing multiple processes and production types (Atherton and Dayhoff, 1986). With many machines costing over a million dollars, it is therefore vital that scheduling methodologies perform efficiently production goals.

In an FMS, the operations at the workstations and material handling system are entirely under computer control. Decisions, such as, which jobs should be loaded into the system and what workstations particular jobs should visit next, are taken by the hierarchical FMS control computer systems. Human intervention is necessary only when unusual or unanticipated events take place. It is important therefore, to develop computerized models and scheduling rules that allow the FMS controller to generate production schedules to satisfy demand requirements and to exercise control over the system so that productivity is maintained.

One critical FMS problem is the scheduling of jobs at workstations, which are visited repeatedly during the production cycle. In the processing sequence of jobs, two or more revisits to the same workstation are often required. These revisited workstations are called "hubs". For example, wafer fabrication and silicon integrated circuit manufacturing provide many examples of production processes with multiple hubs. The silicon wafer fabrication process in Northern Telecom Electronics Advanced Technology Centre consists of more than one hundred individual steps. Many machines are used for several repeated steps in the process steps (Edwards, 1989). The nature of the process is such that these cycles repeat processing steps so that the same machine and equipment types are used at each cycle.

The multi-purpose machine or workstation called a "hub" in the FMS network is often a source of significant bottlenecks which affect job flow and system performance significantly. Analysis and studies on the queuing characteristics of hubs and scheduling strategies for FMS to reduce the total flow time of jobs processed in FMS will result in more efficient utilisation of these critical and costly system components.

At any machine in the manufacturing sequence, circumstances arise when more than one job is waiting at the hub workstation to be processed. The decision on which job should be processed next is referred to the queue scheduling decision. Queue scheduling decisions are made by selecting from classes of scheduling rules based on the type and location of information used in the decision criteria. In general, if the information required can be found in the local queue the rule is referred to as a "local scheduling rule". A "global rule" requires information found over the entire system of machine queue and production flows.

1.1 The focus of thesis

This thesis investigates the effects of Dynamic Scheduling Strategies for jobs at hubs on the performance of the Flexible Manufacturing System. The Dynamic Scheduling Strategy (DSS) denotes the intervention and rescheduling of queue dispatching rules at the most opportune intervention time in order to improve the production flow while keeping the work in process inventory as low as possible. It is hypothesized that dynamic changes in queue scheduling rules for hubs at certain intervention times may improve job flow time (total completion time) and average flow time (average completion time).

The development of dynamic scheduling rules and the intervention time specification that improve job flow measures will establish the basis for the development of a database for an Expert System in dynamic queue scheduling. The intervention and rescheduling procedures developed are applied to increasingly complex FMS cases using a flexible simulation system that includes animation of the production facility. This thesis also provides methodology for developing and evaluating rescheduling rules with respect to the trade-off between total and average completion time for a fixed number of jobs in an FMS network containing hub and non-hub workstations.

A series of discrete simulation models built on a theoretical analysis (Lane and Sidney, 1993) are used as a major vehicle for this research. Three increasingly complex hub network models are selected for more detailed studies. Simulation experiments are carried out and analysed to evaluate system performance under alternative Dynamic Scheduling Strategy rules at different intervention times. The routine between successive visits to the hub is modelled as single time delay, which represents the aggregation of several tasks in between. The effects of revisits to the individual workstations is thereby isolated and then studied with respect to the dynamic scheduling strategies and evaluated in terms of total completion time and average completion time.

1.2 The plan of thesis

Beginning with the literature review, the organisation of this thesis is as follows:

Chapter 2 reviews the literature and history of research and development of Flexible Manufacturing Systems (FMS), control and management through workstation network and queue scheduling decisions.

Chapter 3 presents the methodology used to examine flow time considerations in FMS hubs, including notation, terminology and descriptions of models held in the analysis of Dynamic Scheduling Strategy rules.

In Chapter 4, the analysis and results of small, medium, and large representative FMS networks are presented. This chapter describes the Dynamic Scheduling Strategy which leads to flow time improvements and the simulation results for applying the heuristic rules to the more complex FMS networks.

The final chapter (Chapter 5) summarises the results of the thesis. Extensions for further research in this area are also discussed.

CHAPTER 2.

LITERATURE REVIEW

Typically, production facilities have two conflicting objectives: flexibility and productivity. Flexibility refers to the capacity to produce a number of distinct products in a job shop environment. Productivity refers to efficient volume of production output. Increasing job shop productivity while maintaining production flexibility has been the goal of many industries. Emergence of FMS, as a flexible and productive system, reflects the concerted movement in this direction.

An FMS usually includes a set of flexible machine tools, connected by a material handling system. The high capital cost requirements of Flexible Manufacturing Systems means that achieving the full potential of FMS is of great significance. During the last decade, extensive literature has developed around FMS operations research. Early published work dates back in the 1950's, including the research work of Jackson, (1957) and Rowe, (1958) on job shop scheduling and decision making. As computer technology and its computational performance grew, the scope and complexity of FMS research have improved considerable.

Efficient utilisation of FMS can be obtained by appropriate planning, scheduling, control and management strategies. A classification based on the nature and application of FMS models is proposed for an easy understanding of research work on FMS (Gunasekaran, et al., 1993).

Modelling of an FMS ---- the high cost of an FMS network requires understanding the potential benefits of the specific application before it is implemented. Modelling and simulation has become a useful technique for this purpose. Specific topics are:

- Facility and layout design ---- determination of long term managerial objectives, such as optimal number of robots, types of parallel machines needed, material handling equipment, robot assignments in each flexible manufacturing cell for balancing the production line, job flow or dispatching and work in process control routines; mathematical programming is often used to optimise the design and operation of an FMS network to achieve prestated objectives;

Buzacott and Yao (1986) had employed queuing models to discuss on-line scheduling control in an FMS with random processing times. They described a control mechanism of job dispatching heuristics using the results obtained from a simulation model.

Hitomi et al (1989) solved the design and scheduling problems for FMS as a two-machine flow shop problem with finite buffer space and automatic set up equipment. They proposed that the setup and machine operations can be simultaneously conducted on an index-pallet changer which has a multiple number of clamping devices serving as centre, machining and buffer station.

Montazeri and Van Wassenhove (1990) analysed the characteristics of a general-purpose user-oriented simulator for FMS. They used a dedicated modular simulator to mimic the operation of a real FMS.

- Global planning and scheduling -- production planning process and operations, such as estimation of number of machines, number of pallets and fixtures required, analysis of machine grouping technology, single and multiple server queuing networks, multiple server queues.

Suri (1981) considered problems of optimising the performance of Flexible Manufacturing Systems (FMS). The FMS control problem can be formulated as a time-optimal feedback control problem for a dynamic system. He described a method for modelling and control of FMS, and showed the models can be used for optimal feedback control.

Suri and Whiteney (1984) dealt with the decision support requirements in flexible manufacturing systems. Because efficient operation of these systems is such a complex task, their capacity is often under-utilised. The concept of computer-based decision support systems promises to remedy the situation. Three levels of operational decision making systems were designed for implementing this concept. The third level involves short-term decisions of scheduling, dispatching and tool management, such as which job should be processed next to the system. Normally, these decisions are made by the FMS control computer, which includes decision support software such as a work order dispatching program, operation and tool reallocation program and on-line simulation.

Mazzola et al., (1989) presented a hierarchical production planning model which integrates FMS production planning and scheduling into a closed-loop MRP (Materials Requirements Planning) system.

- Strategic analysis and economic justification of FMS design and operation ---- providing better business plans, such as operation investigation in terms of system point of view, system performance measures, economic or cost-benefit analysis, competition capacity estimation and so on (Airey, 1983; Burstein, 1984; Kusiak, 1987).

Problem-solving techniques ---- different techniques and methodology have been applied to problem solving in FMS networks. Advances in computer technology and improved handling of more complicated problems of FMS has enabled researchers to develop optimizing approaches.

- Computer simulation ---- to represent the dynamic behaviour of FMS network by a computer system. This refers to the use of computation to implement a model of FMS to move FMS experimental measurements into a computer environment. It will assist the theoretical analysis of operational research and management issues of FMS;

Blackstone et al (1982) discussed analytical approaches, simulation techniques and evaluation criteria of scheduling rules. Job shop simulation studies of scheduling rules were emphasized because of the difficulty of analytical methods applied to job shop problems. For job shops having no control over due dates, the SPT rule appears to show the best performance. For shops having control over due dates, which were set at six or less times total processing time, the SPT rule still seems best. For other cases, other duedate rules were recommended.

Atherton and Dayhoff (1986) introduced a discrete simulation model in the analysis of an integrated circuit manufacturing process. They used illustrative examples to demonstrate the potential of their model for analysis of inventory level, cycle time and factory capacities. Based on this research , they showed the evaluation of three rules -- pure "lowest step first", pure "highest step first", and "round robin"-- on several performance measures. The "highest step first" rule performed better than the other two, especially for high factory demand rates ensuring a steady stream of lots leaving the factory.

- Artificial Intelligence and Expert System ---- a computer program that reasons, using knowledge to solve complex problems. Expert Systems achieve a level of competence of problem solving in some work domain that rivals the performance of human specialists (experts) in those domain. It allows the integration of job rescheduling rules within knowledge-based, decision-making frameworks to establish an expert scheduling system.

An intelligent autonomous system in FMS requires suitably co-ordinated scheduling and control tasks. Rabelo and Alptekin (1989) presented the design and implementation of an intelligent scheduling system in an FMS scheduling/control architecture using Artificial intelligence/expert system technologies.

FMS queue scheduling rules ---- queue scheduling rules are important issues for the efficient performance of FMS networks and are the central focus of this thesis. In general, scheduling rules can be catalogued as follows:

- Rules based upon operations and processing;
- Rules based upon due date;
- Rules based upon other attributes, such as cost.

A queue scheduling rule is used to select the order of jobs to be processed at a workstation from among a set of jobs awaiting service. Panwalker and Iskander (1977) itemised 113 different queue scheduling rules to date, and more have since been developed. These rules can also be used to introduce jobs into the system, to order jobs during operation and to dispatching jobs to facilities. In this thesis, we consider only the queue scheduling rules for ordering jobs at workstation queues.

With the increase of modern manufacturing system complexity, scheduling rule problems become more and more important for efficient whole system performance. In most cases, the scheduling problem which is modelled initially by discrete methods can not be solved by formal theoretical analysis. Computer simulation techniques are most often developed for evaluating the policies or scheduling strategies in a hub FMS. In the following, the literature of queue scheduling rules for FMS is reviewed.

Conway (1965) was among the first researchers who analysed a large number of scheduling rules for a complex production system. His criteria for comparison were various measures of work-in-process and job lateness. He tested 16 scheduling rules in a dedicated FMS for the case of minimising work-in-process and concluded that the Shortest Process Time (SPT) rule performed better than other rules. Critical Ratio (CR) appeared to be the best among the due date based rules for duedate performance related criteria.

Ballakur and Steudel (1984) in their review of job shop control systems, and comparison of several scheduling rules, concluded that: (a) the SPT rule appears to be the best queue scheduling rule for relatively loose due date and moderate machine utilisation, (b) most researchers found that MINSLK (minimum slack) dominates all other due date based rules, (c) combined rules involving (MINSLK) and Shortest Process Time(SPT) are most promising queue scheduling rules.

Neelamkavil and Thomson (1986) introduced a manufacturing system that incorporated a scheduling system with a real-time interface. They presented a flexible scheduling strategy when an FMS was in operation, and provided three key modules for their system using a heuristic methodology. The first was used to assess production plans and to provide detailed shop schedules; the second to perform discrete simulations of "what if" scenarios and planning requirements; and the third to process job shop floor data and update the database.

Dobson, Karmarker and Rummel (1987) discussed using batching to minimise flow times on one machine. They provided item-flow and batch-flow formulations to study the performance of systems. Because the batch-flow problem is more difficult they only provided the formulation for single product cases. The heuristic and bound methods were still valid for the multi-product case.

Edwards (1989) examined simulation results of different rules on several FMS scenarios. The ranking of rescheduling rules was very important for queue-time versus throughput trade-off. Job scheduling rules were ranked in order of lowest queue time first (according to different batch sizes and arriving rates). LOWSTEP and SPT were two extreme ends of trade-off between throughput (or maximum flow time, C_{max}) and queue time (or average completion time, $\overline{C}$). A problem raised in the simulation experiments was that even if SPT ranked first with respect to queue time performance it may leave longer jobs in the queue for extended periods while shorter jobs continue to arrive.

Lane and Sidney (1993) examined the flow time performance of a single-hub FMS using a theoretical analysis, that considered two extreme queue scheduling rules, LPF (lowest process first) and HPF (highest process first). The performance of the system under different batching and scheduling priority rules was measured by the time it takes to complete processing of a fixed number of lots through the facility. The total completion time or makespan, denoted by C_{max}, was defined to be the time it takes to complete all N lots that require processing. A second performance measure, the average completion time, defined by $\overline{C}$, measured the arithmetic mean of completion times for all lots. Average completion time is a surrogate measure of the work-in-process (WIP) of the production facility, in the sense that lower average completion time is associated with lower WIP costs.

The investigations were based on instantaneous arrivals of n lots and fixed workstation processing times for a defined workstation visit schedule including at least one hub. Trade-offs between maximum flow time of a fixed number of lots, and the average completion time of all lots through the production facility were examined .

To provide consistency with common usage in a queuing network, Lane and Sidney let $n/m/SH/OF$ denote the n lots (jobs), m processes (operations), single hub (SH) problem with objective function OF (total completion time, C_{max}, or average completion time, $\overline{C}$). A single revisit hub problem consists of $w=m-1$ workstations. In a simple single hub model Lane and Sidney show that LPF is the best priority rule for minimizing total completion time, C_{max}, and HPF is the best single priority rule for minimizing average completion time, $\overline{C}$.

Lane and Sidney (1993) presented results for improving the performance of FMS, but only for pure scheduling strategies. It is also possible to mix "pure" scheduling strategies during the processing of jobs to develop dynamic scheduling strategies. In this thesis, It is shown that dynamic scheduling strategies can improve flow performance in most FMS networks.

Summing up the results presented in the above papers, a large number of queuing scheduling rules have been investigated. There is no single rule judged seems to be the best in general, although some rules dominate in special cases, e.g., SPT and HPF rules perform well in minimum work-in-process criteria.

Table 1 summarizes the common queue scheduling rules. Two scheduling rules are of particular interest for this thesis.

Table 1 The definition of the most common scheduling rules

No.	RULES	FULL NAME	DESCRIPTIONS
1	DUEDATE	Due Date	lot with earliest due date has priority
2	HPF	Highest Process First	lot farthest along in its process steps has priority
3	SPT	Shortest Process First	lot with shortest processing has priority (does not include set up time)
4	LPF	Lowest Process First	lot that are least processed to date has priority
5	CR	Critical Ratio	lot with minimum critical ratio next to be served, CR=(duedate-Tnow)/sum(processing time remaining)
6	MINSLK	Minimum Slack	lot with minimum slack =(duedate-Tnow-sum(processing time remained)) next to be served
7	APO	Allowance Per Operation	lot with minimum allowance =(duedate-Tnow)/(# of remaining processing steps) next to be served
8	SPO	Slack Per Operation	lot with minimum slack =(duedate-Tnow-sum(processing time remained))/(# of remaining steps) has priority
9	FIFO	First In First Out	lot with earliest start time has priority
10	NINQ	Number In Next Queue	lot with the fewest number of lots in its queue has priority
11	LPT	Longest Processing time	lot with the longest processing time has priority
12	CR2	Critical Ratio #2	lot with minimum adjusted critical ratio =(duedate-Tnow)/(sum(processing time remaining)*1.2) where queue factor is 20% has priority

Fig. 1 and Fig. 2 show that the effects of different common scheduling rules on the system performance for the single hub model with three processes, two workstations, with process times 25, 15, and 1, revisiting the first workstation at process 1 and 3 and required completion of $n=10$ jobs (see also Appendix A, case #4 for detailed results).

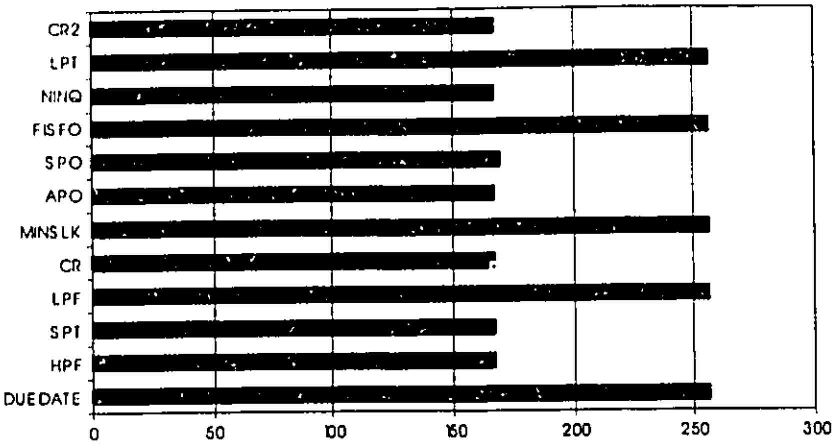

Fig.1 Average completion time, $\overline{C}$ for pure hub scheduling strategies on single hub model

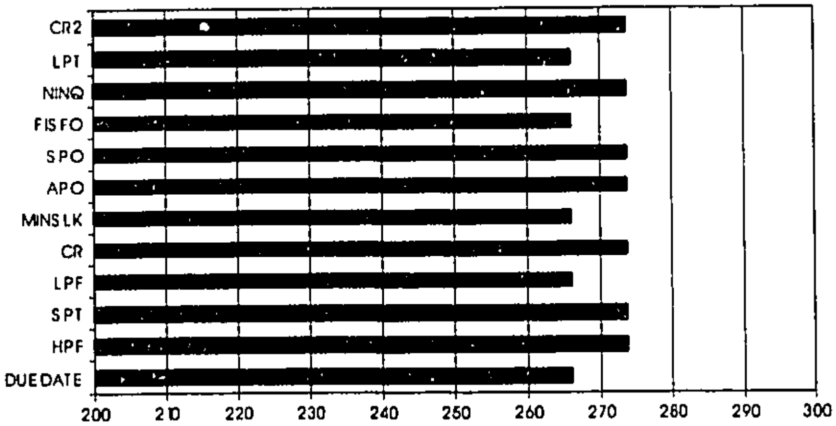

Fig.2 Total completion time, C_{max} for pure hub scheduling strategies on single hub model

In this thesis, queue scheduleing rules LPF and HPF are examined in detail with consideration of job flow time over workstations. From the definitions of the most common scheduling rules, the LPF and HPF scheduling rules are simple scheduling rules of 12 common scheduling rules. First Come First Served (FIFO) is used as the tie breaking rule for any situation. Simulation analyses such as shown in Fig. 1 and Fig. 2 confirm the theoretical analysis (Lane and Sidney, 1993) that the LPF scheduling rule minimizes C_{max} (total completion time), and the HPF scheduling rule minimizes $\overline{C}$ (average completion time). Thus from among the entire set of "common" queue scheduling rules, LPF and HPF represent the spectrum of potential flow time performance measures.

CHAPTER 3
METHODOLOGY

The analysis of Dynamic Scheduling Strategy (DSS) on FMS network is based on a single hub workstation network production facility for one product type. The results are extended using simulation modelling to increasingly complex medium and large-size FMS networks. This section includes definitions and terminology which are used in the sections that follow.

3.1 *Basic Terminology*

A basic unit in the manufacturing process is the "job". A set of jobs that are treated together in the processing activity are known as a lot. For example, in integrated circuit manufacturing a job is comprised of a number of silicon wafers located on a receptacle called a "boat". In the classical job shop theory, the term job is often used interchangeably with lot. A batch is a set of jobs that must be processed together without interruption.

Let:

n – the number of identical jobs assumed to be immediately available for processing at time $t=0$;

m – the number of processes required by each job to be completed in a deterministic sequential processing order from p_1 to p_m;

w = the total number of workstations in a FMS workshop (or a manufacturing centre), generally, $w \leq m$, w is strictly less than the number of processes m;

C_{max} = total completion time for a series of n jobs, or makespan;

$\overline{C}$ = the average completion time for a series of n jobs.

Because the total number of workstations w is strictly less than the number of processes m, different processes must take place at the same workstation more than once during the processing of each job. Let $i = 1, \ldots, n$ denote job orderes, let $j = 1, \ldots, m$ denote the index of each Process at individual workstation, WS_j at process j.

We assume that the following data are known:

p_j = the time to process job i on workstation WS_j; $j=1,2, \ldots, m$

WS_j = the workstation where process j is carried out

and that no setup is required to process jobs at any workstation in the system.

A scheduling rule is used to select the next job to be processed from a set of jobs awaiting service. These rules can be used to introduce jobs into the system, to route parts through the system and to assign parts to system components. Scheduling rules can be static, i.e., they can be applied at the beginning of the schedule period and result in a fixed schedule for the period; or dynamic, i.e., changing over time. The scheduling rules can be classified in different categories according to their specific attributes. In the thesis, the HPF and LPF scheduling rules are tested on a static and dynamic basis to examine the flow time impact on various hub networks.

HPF scheduling: HPF stands for Highest Process First The HPF strategy resolves conflicts between different jobs demanding service at the same workstation by choosing the job which is more advanced in its processing. Among pure queue scheduling strategies, Lane and Sidney (1993) show that the HPF strategy will result in minimum $\overline{C}$ (minimum average completion time) for the single hub model with only three processes..

LPF scheduling: LPF stands for Lowest Process First. In LPF scheduling, no job at a hub can begin processing as long as another job that is waiting has completed fewer processing steps toward completion. Lane and Sidney show that the LPF strategy minimise C_{max} , makespan for the single hub model.

HPF and LPF fall into a low level class of queue scheduling strategies that uses only local information. These rules consider no information outside of the local queues. The attractiveness of these rules is their simplicity and ease of use, and their good performance levels when used as pure strategies. For example, suppose two jobs are waiting for service at a hub workstation, both jobs require same process steps for completion. However, job no.1 is closer to completion than job no.2. Under the HPF scheduling strategy, job no.1 will be processed at the hub ahead of job no.2 and vice versa for the LPF. FIFO is used as a tie break scheduling rule to schedule the jobs of equal priorities at the hub workstation.

We know that the $n/m/SH/C_{max}$ and the $n/m/SH/\overline{C}$ are NP-hard problems for $n \geq 3$ (Lane and Sidney, 1993). A decrease of processing time on some workstation does not mean that the average completion time is automatically reduced. In fact, depending on queue scheduling rule, it may increase the average completion time $\overline{C}$. Idle time on hub workstations for the same problem can be the cause of this change in value of average completion time, $\overline{C}$. In order to analyse this particular effect, simulation models were developed for the LPF and HPF scheduling rules to examine the performance of scheduling rules on networks containing hubs.

3.2 Assumptions of Simulation models

Simulation systems for FMS are developed to analyse queue scheduling rule experiments. The system is implemented in the C language and the SLAM II simulation language with a modular design which accepts manufacturing data as input including process time and job flows, machine models, and production start plan. The usual flow shop assumptions apply. These include:

- set-up times at all workstations are zero;
- transit times between workstations are zero;
- no machine breakdowns;
- all n jobs are available for processing at time $t=0$.

There may be two or more processes required at each hub workstation. Each multi-purpose workstation or hub can only service one type of job at a time. The status of a workstation during simulation experiments is described in two ways: (1) busy or idle, (2) size of queue. Two events can change the states of a hub workstation:

- Arrival of a job at the workstation,
- Departure of a job from the workstation.

The rules of representation of job flow over a FMS network are: the order of letters represents the order of process steps. The number following the letter represents the job. For example, *a, b, c* represent the order of processing in a three step system, i.e., $m=3$, $p_1=a$, $p_2=b$, $p_3=c$. The first process is step *a*, second process is step *b* and third process is step *c*. *a1* denotes the first process of job 1, *b2* denotes the second process of job2, and *c4* denotes the third process of job 4.

3.3 Flow Time Measures

There are two performance measures of flow time for *n* jobs. The total completion time, C_{max} is defined as the total time required to complete *n* jobs through the hub network; the average completion time, $\overline{C}$ is the mean time of all job finishing times.

Let f_{ij} denote the finishing time of the i^{th} job, where $i=1,\dots,n$, at process sequence WS_j, $j=1,\dots,m$. System performance measures for total production flow time(makespan), average completion time are then:

Total completion time:

$$C_{max} = f_{nm}$$

Average Completion Time:

$$\overline{C} = \frac{1}{n}\left(\sum_{i=1}^{n} f_{im}\right)$$

Since all processing times for all jobs are known, the problem is to determine a suitable queue scheduling rule to keep total completion time C_{max} and average completion time $\overline{C}$ as low as possible.

3.4 *Simulation Methodology*

Flow time conflicts may arise in attempting to keep multiple criteria as low as possible. In this thesis, we take total completion time C_{max} and average completion time $\overline{C}$ as two major and perhaps conflicting criteria to evaluate FMS network performance. Heuristic methods are also applied to test the system rules of an FMS along with the simulation models. The research methodology is illustrated in Fig.5 below.

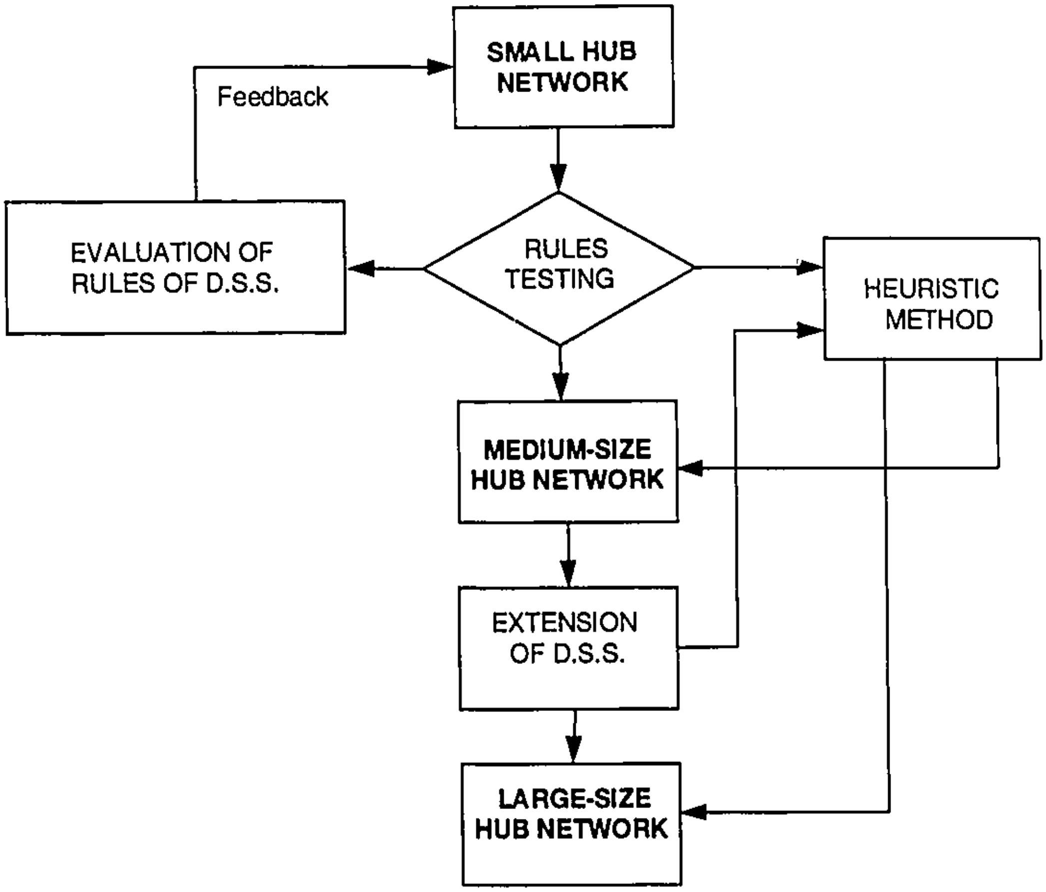

Fig. 3 Simulation methodology for the development and testing of the Dynamic Scheduling Strategy (D.S.S)

The increasing complex FMS networks, i.e., the small hub network, medium-size hub network and large-size hub network are defined in the following sections. The modelling and simulation experiments discussed in the thesis begin with a small hub network using a variety of parameter combinations to identify the idle time in that system, and to evaluate the LPF and HPF rules and their Dynamic Scheduling Strategy (DSS). The existing idle time of the small hub network is considered as a feedback to the Dynamic Scheduling Strategy to be able to improve the system flow performance through strategic changes in the hub scheduling rule at specific intervention times.

Rules developed for the small model are then applied to the medium-size hub networks. A heuristic method is used to set policy variables in the simulation experiments. The heuristic method developed in this thesis is called the Fraction of C_{max} Estimation (FCE). The calculations for Fraction of C_{max} Estimation are based on the single hub network emulation of the medium-size three hub network. The results of FCE give a recommended intervention time. In simulation experiments, we can find the best intervention time by testing only a few intervention time points around the FCE recommended intervention time.

A selected large size five hub network is tested using this Dynamic Scheduling Strategy from the previous model. The heuristic method, i.e., Fraction of C_{max} Estimation, is still valid. The calculations of Fraction of C_{max} Estimation will be based on the single hub network emulation of large-size five hub network. Intervention times can be found by simulating a few intervention time points around the FCE recommended intervention time as before.

The following section details the analysis and results for the small hub model system.

3.5 *Small System Network: Cases and Conditions*

In the small system simulation, there are four parameters to be considered, *a* ,*b*, *c*, and *n*, where: $p_1=a$, $p_2=b$, $p_3=c$, $m=3$.

The routing procedure of jobs to be processed is shown as in Fig. 4. Different values for parameters yield different result cases for either LPF and HPF scheduling rules (Lane and Sidney, 1993). The cases and conditions of HPF and LPF scheduling rules are shown in Table 2 and Table 3 and Fig. 5.

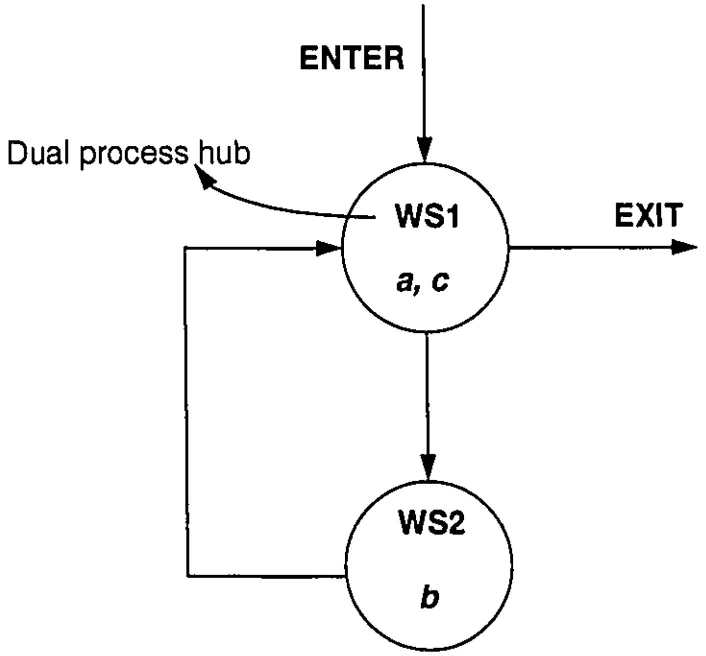

Fig. 4 The job routing on a single hub network, $m=3$, and $w=2$ workstation

Table 2. LPF cases and Conditions (Lane and Sidney, 1993)

CASE	FORMAL CONDITIONS	DESCRIPTION
1	$b \leq (n-1)a,\ b \leq (n-1)c,\ b \leq (a+c)(n-1)/n$	*b dominated*
2	$b > a,\ b > c,\ b > (a+c)(n-1)/n$	*b dominant*
3	$c \geq b \geq (n-1)a$	*c dominant*
4	$a \geq b \geq (n-1)c$	*a dominant*

Table 3. HPF cases and conditions (Lane and Sidney, 1993)

CASE	FORMAL CONDITIONS	DESCRIPTION
1	$b < (n-1)a,\ b \leq c$	*b dominated*
2	$b < (n-1)a,\ b > c,\ b < a+c,\ b \geq a$	*b determinant*
3	$(a+c) \leq b < (n-1)a$	*b cycles*
4	$a \geq b > c$	*a dominant*
5	$b \geq (n-1)a,\ b > c$	*b dominant*
6	$c \geq b \geq (n-1) \geq a$	*c dominant*

Job processing time and the system performance depend on hub process time settings and batch job size. The corresponding expressions for C_{max} and $\bar{C}$ under the LPF and HPF are provided in Lane and Sidney (1993) and depend on the cases specified above. In the analysis of case conditions for the single hub model, there are six cases for HPF scheduling rule and four cases for LPF scheduling rule.

To further illustrate the comparison of the flow measures on the LPF and HPF scheduling rules, values of (a, b, c) were generated for $n=10$ jobs and subject to the relation $a+b+c = 1.00$. The simplex of the space $a+b+c=1$ projected onto two-dimensional space for all LPF and HPF are presented in Fig.5.

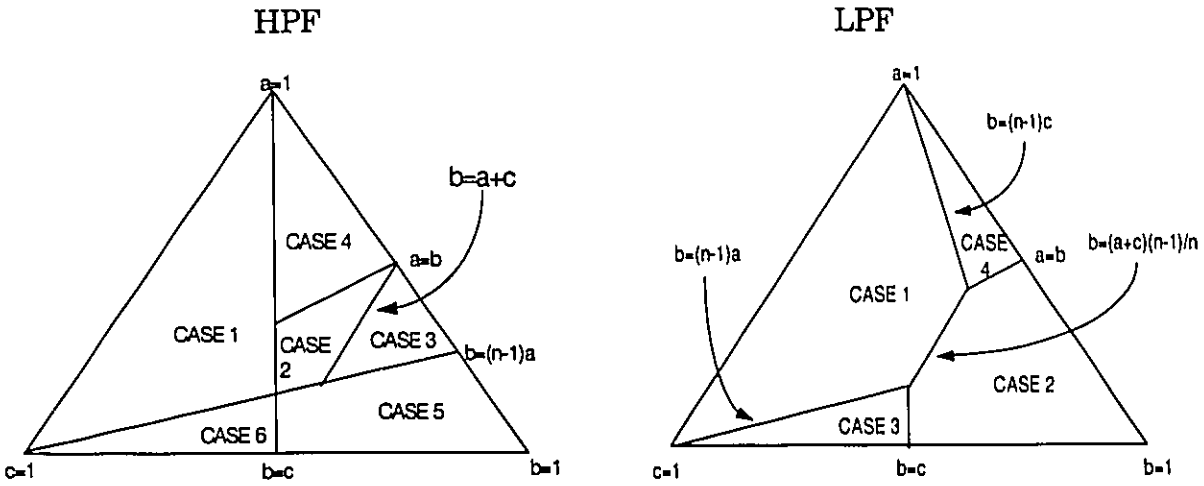

Fig. 5 Unit simplex for HPF and LPF cases of parameter combinations, where $a + b + c = 1$

3.6 Idle Time (IT) determination:

Idle Time is defined as the period of time during which the hub workstation is not busy processing a job. In the time interval, the hub status is idle. The occurrence of idle time in the job scheduling period not only leaves workstation resources idle but also may increase general system flow time performance. Minimizing the idle time is one of the most important goals the improvement of FMS network performance. In the example shown in Fig.6, we may take advantage of both minimum C_{max} from the LPF job scheduling and minimum $\overline{C}$ from the HPF job scheduling by applying Dynamic Scheduling Strategy to this single hub network.

Idle time may be introduced as a result of using a pure hub scheduling rule HPF or LPF. In such a case, elimination of the idle time through switching the scheduling rule from one pure strategy to another, may actually improve the flow time measures of the system. The idle time may be categorised into two ways: Soft Idle Time (Soft IT) and Hard Idle Time (Hard IT), defined as follows:

- Soft IT ---- the Idle Time can be reduced by applying an appropriate intervention methodology, such as changing the queue scheduling rules at a particular time. In the following examples, we examine how a shift from HPF to LPF might be of advantage.

Example 1, suppose there are $n=5$ jobs going to be processed on a single hub network which consists of a hub workstation (processes 1 and 3, time a and c) and a non-hub workstation (process 2, time b). When a=1, b=2, and c=4, and n=5, the total completion time can be reduced by changing the queue scheduling rule from the HPF to the LPF at the intervention time shown in Fig. 6, which eliminates the soft Idle Time.

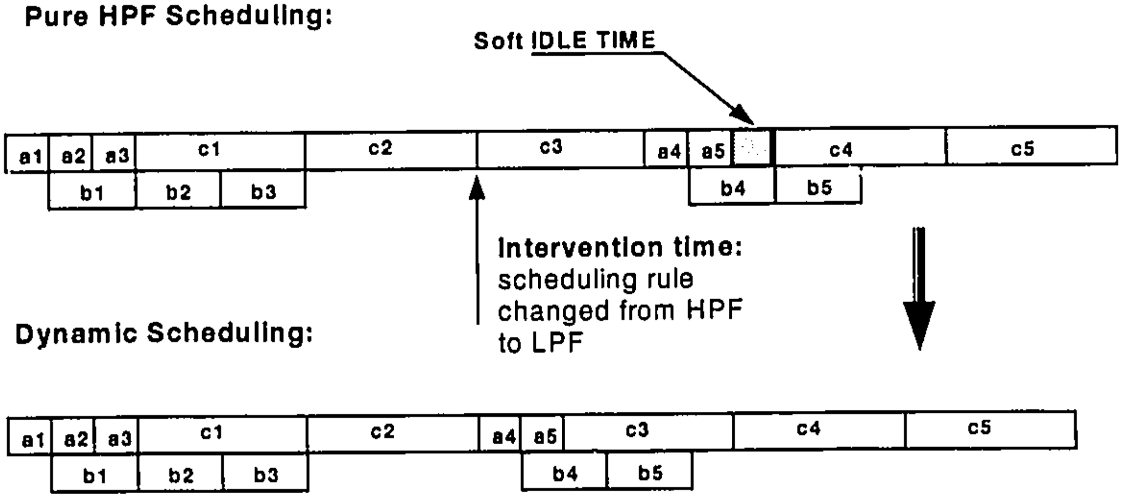

Fig. 6 Illustration of Soft IDLE TIME elimination

- Hard IT---- Idle Time that can not be reduced due to system parameter values (Fig.7).

Example 2, now suppose there are 4 jobs to be processed in a single hub workstation as described above. for the case a=6, b=11, and c=3, the procedure is as follows, a2 is processed directly after a1 on the hub workstation because c1 is not yet available. Due to the large process time b, the Idle Time can not be reduced in any way that has been taken into consideration. This Idle Time is called Hard Idle Time.

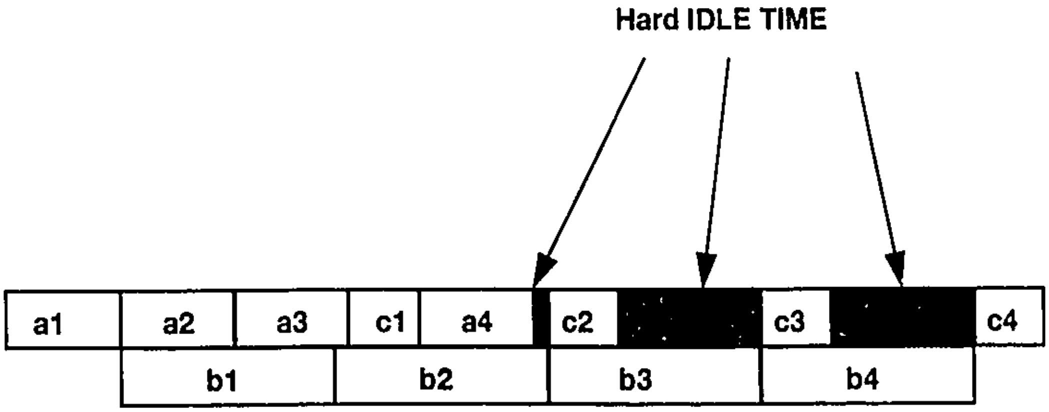

Fig. 7 Illustration of Hard IDLE TIME

3.7 Analysis of Dynamic Scheduling Strategies (DSS) with one intervention on the Small System

Dynamic Scheduling Strategies (DSS) can be used to improve the performance of FMS by changing scheduling rules during processing. The DSS can be defined as a scheduling rule switching during the processing of jobs in order to reduce the total completion time C_{max} and average completion time $\overline{C}$. In this thesis, dynamic scheduling implies changing from HPF to LPF at specific intervention times. Switching scheduling rules from HPF to LPF at $t=0$ results in a "pure LPF" case; switching scheduling rules from HPF to LPF at the end of processing time is a "pure HPF" case.

To further illustrate the comparison of cases and conditions for Dynamic Scheduling Strategy, the simplex of the HPF cases is matched onto the simplex of the LPF cases. So that the cases and conditions of DSS can be derived from the combination of both HPF and LPF case conditions. These overlapping cases are considered as the cases of dynamic scheduling strategy, i.e., from the HPF scheduling rule to the LPF scheduling rule or from the LPF scheduling rule to the HPF scheduling rule. In the previous discussion, the LPF scheduling rule is the best pure scheduling strategy for total completion time C_{max} and the HPF scheduling rule is best pure scheduling strategy for the average completion time $\overline{C}$. To minimize the total job flow time, switching from the LPF scheduling rule to the HPF scheduling rule can not make the total completion time any better. So this thesis will focus on the Dynamic Scheduling Strategy that switches scheduling rules from the HPF scheduling rule to the LPF scheduling rule. We are going to exam the flow time performance C_{max} and $\overline{C}$ by applying DSS to each of these cases in detail.

According to the cases and conditions presented above in Tables 2 and 3 above (for the different combinations of processing time), there are eight overlapping cases to be considered on our investigation of switching from HPF scheduling to LPF scheduling using an intervention rescheduling strategy (Fig. 8). It will be shown that the flow time performance of the FMS network can be improved in many of these cases by eliminating existing soft Idle Time. For example, the performance of DSS of overlapping case no.1 (Table 4) reduces the minimum C_{max} under LPF and $\overline{C}$ under HPF simultaneously.

The combination of cases and conditions of pure HPF and LPF scheduling rules, for the single hub network is shown in Table 4 and Fig. 8.

Table 4 Case of overlapping LPF and HPF conditions on a single hub network

OVERLAPPING NO.	FROM	TO	FORMAL CONDITIONS
1	*HPF case#1*	*LPF case#1*	$b \le (n-1)a$, $b \le (n-1)c$, $b \le (a+c)(n\_1)/n$
2	*HPF case#2*	*LPF case#1*	$a \le b < a+c$, $c < b \le (n-1)c$, $b \le (a+c)(n-1)/n$
3	*HPF case#2*	*LPF case#2*	$a < b < (n-1)a$, $c < b$, $(a+c)(n-1)/n < b < a+c$
4	*HPF case#3*	*LPF case#2*	$a+c \le b < (n-1)a$
5	*HPF case#4*	*LPF case#1*	$c < b \le a$, $c < b \le (n-1)c$, $b \le (a+c)(n-1)/n$
6	*HPF case#4*	*LPF case#4*	$b \le a$, $c < b$
7	HPF case#5	LPF case#2	$a < b$, $c < b$, $b > (a+c)(n-1)/n$
8	HPF case#6	LPF case#3	$b \le c$, $(n-1)a \le b$

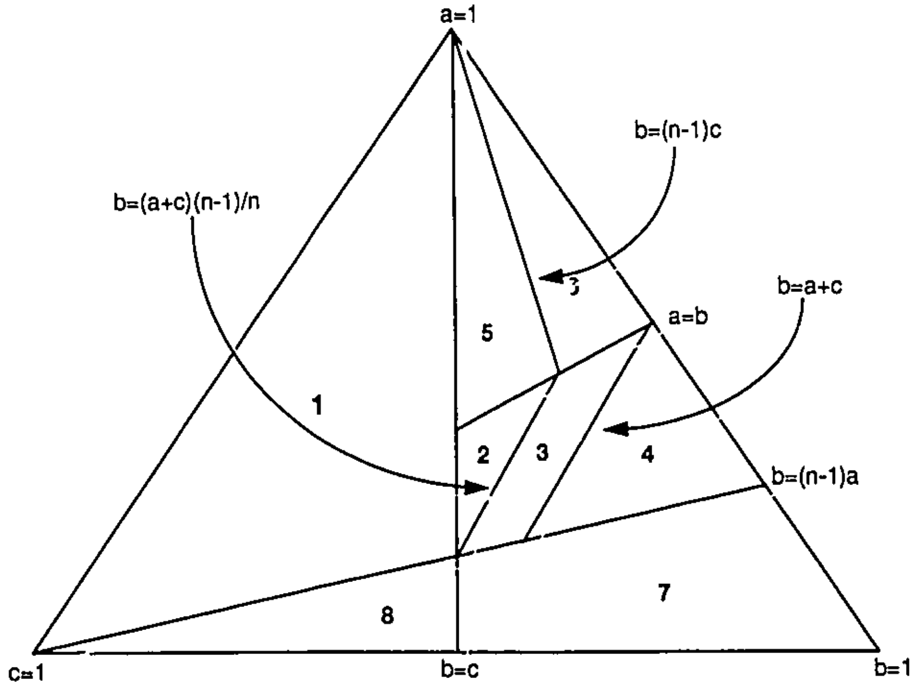

Fig. 8 Case of overlapping LPF and HPF conditions on a single hub network

3.8 Medium-size hubs network

The medium-size hub network for simulation experiments to examine the dynamic scheduling strategies includes three hubs. The job routing on the three hub network is shown in Fig. 9.

Two objectives are pursued in this three hub network network. The first is to examine the effect of the dynamic scheduling strategies developed from single hub network on the more complex three hub network.

The second is to explore a heuristic method to improve system performance using dynamic scheduling rules developed for the single hub network, and to make some recommendations comparing the application of dynamic scheduling rules on all hubs at different or same intervention time.

The medium size network with defined routing has been chosen as a means of illustrating these larger problems. These is no attempt to imply that real networks are symmetrical or to imply that the chosen network is representative of this scale of actual manufacturing system.

The characters of *a, b, c, d, e, f* represent the p_i, $i=1,2,...,6$, processing steps on three hub workstations respectively. The numbers following the letter represent the job number being processed. The jobs entering the three hub network are processed firstly at *WS1* processing step *a*; jobs then go to *WS2* to be processed at step *b;* next to *WS3* and step *c* and then go back to *WS1* to be processed on step *d* and so on to the end at *WS3* after process time. The simulation experiments evaluate the pure HPF or pure LPF strategies to explore the idle time gaps. We emulate this three hub network with the single hub network by considering the three single hub networks, i.e., each time taking one of the three workstations as a hub and other two workstations as off-hubs. We apply the dynamic scheduling methodologies we developed from the single hub network to these three hub to estimate Idle Time determination and the Intervention Time to improve flow measures as before. Results for the three hub "medium" network are presented in the next chapter.

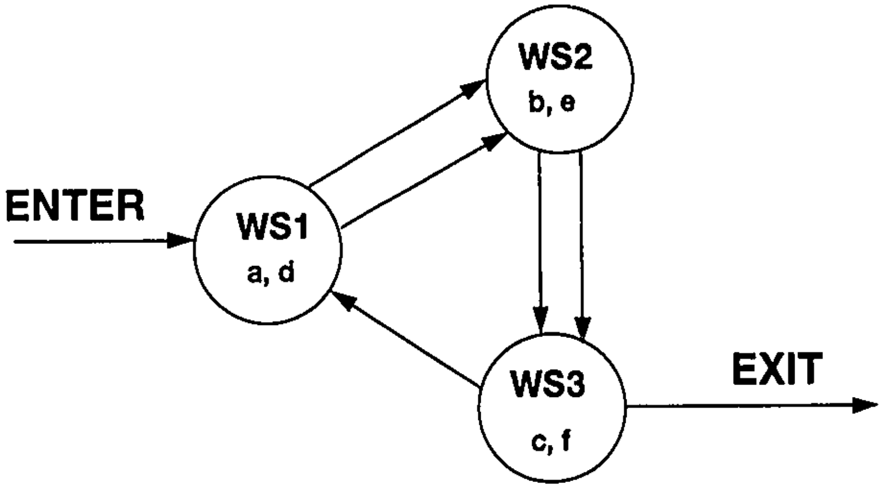

Fig. 9 The job routing of three hub network

3.9 Large size hubs network

Actual FMS includes many hub and off-hub workstations. The process of integrated circuit (IC) manufacturing , for example, requires an extension of the previous models. Subject to the limitations of the simulator (Fig.10), we apply the dynamic scheduling strategies to a network including five hubs. The simulation experiments are designed to evaluate the heuristic methods developed from previous models compared to pure strategies (HPF and LPF).

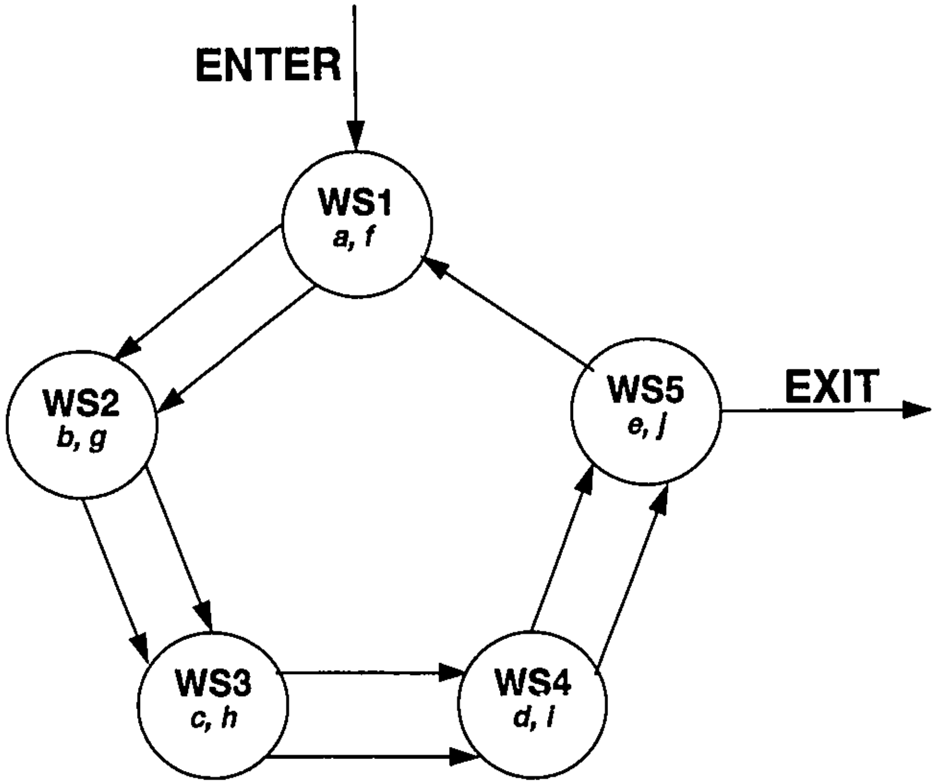

Fig. 10 The job routing of a five hub network

The large size network with defined routing has been chosen as a means of illustrating these larger problems. These is no attempt to imply that real networks are symmetrical or to imply that the chosen network is representative of this scale of actual manufacturing system.

The presentation of process sequence and job number in this large size five hub workstation is similar to that in medium size three hub workstation. The characters *a, b, c, d, e, f, g, h, i , j* stand for the processing steps on five hub workstations respectively. The jobs entering the five hub network are processed firstly at *WS1*, processing step a; then go to *WS2* to be processed at step b and sc on. The simulation experiments begin from the pure HPF or pure LPF strategies to compare C_{max} and $\overline{C}$ between LPF and HPF and idle time for the HPF and LPF rules. Then we emulate this five hub network into five single hub networks, i.e., each time taking one of the five workstations as a single hub and other four workstations as off-hubs. The dynamic scheduling methodologies developed from the single hub network are applied to these five emulating single hub networks to determine the Idle Time, and the Intervention Time to improve network flow.

Based on the methodology and assumptions discussed above, a number of experiments have been analyzed to explore the performance of these different hub workstation networks under pure and dynamic scheduling strategies. The result and performance analyses are presented below.

CHAPTER 4
RESULTS AND ANALYSIS

Simulation experiments have been performed on all three levels of increasingly complex networks: the single hub, the three hub, and the five hub process network. In this chapter, the results of these experiments are presented.

4.1 Single hub network

The single hub network consists of two workstations, i.e., one is a dual-purpose workstation called a "hub" and one is an off-hub workstation (Fig.4).

In the previous chapter, it was shown that system flow time might be improved by eliminating any existing soft Idle Time. In the following section, we show more precisely how the system performance can be improved on this single hub network.

4.1.1 An example of improvement

Suppose there are 5 jobs ($n=5$) to be processed on a single single hub system. It consists of a hub (process steps a and c) and an off-hub workstation (process step b). Now, assume that $a=1$, $b=2$, *and* $c=4$ processing time units. This corresponds to overlap case #1(Fig.8) and Fig.6 described previously. The pure HPF and LPF scheduling rules are used to first to explore any "gap" between the total completion time and average completion time. For this particular example, it is easy to obtain that C_{max}(HPF) $=26$, $\overline{C}$(HPF)$=16.2$, and C_{max}(LPF) $=25$, $\overline{C}$(HPF)$=17$. So the gap between C_{max}(HPF) and C_{max}(LPF) is one time unit (recall that LPF is a minimizing pure strategy for C_{max}). It means there must be one time unit of idle time existing in the operation of this hub network and improvement of system performance can be sought using dynamic scheduling strategy.

As shown in Fig. 6, the system performance can be improved by switching the scheduling rule from HPF to LPF at the time of the finish of *c2*, i.e., job no.2 just being completed at $t=11$. Suppose we switch the scheduling rule from HPF to LPF at the intervention time $t=11$. To compare the Dynamic Scheduling Strategy (DSS) with the pure HPF and pure LPF, the system performance is shown as follows:

Table 5. An example of flow improvement using the dynamic scheduling strategy

	C_{max}	$\overline{C}$
HPF	*26*	*16.2*
LPF	*25*	*17.2*
DSS	*25*	*16.2*

From this example, we can confirm that the system performance with flow time consideration can be improved by using Dynamic Scheduling Strategy (DSS), i.e., switching the scheduling rule at an appropriate intervention time (here, $t=11$). Under the Dynamic Scheduling Strategy (DSS) we can take advantage of improvement in performance of both the LPF scheduling rule on total completion time C_{max} and the HPF scheduling rule on average completion time $\overline{C}$.

In the following section, the Dynamic Scheduling Strategy on the single hub network is described, then applied to the medium size hub network and the large size hub network.

4.1.2 Case study of a single hub network

A number of single hub experiments are tested for the case of n=10 and varying values for a, b, c corresponding to the cases described in Table 2. These experiments are as follows:

Table 6 Processing parameters of Single Hub Network

EXPERIMENT	CASE IN	DESCRIPTION	A	B	C
1	*1*	*b dominated*	*25*	*15*	*20*
2	*2*	*b dominant*	*25*	*50*	*20*
3	*3*	*c dominant*	*1*	*15*	*20*
4	*4*	*a dominant*	*25*	*15*	*1*

All jobs are available at time t = 0. The scheduling rules do not reduce the total machine-processing time but they do affect the queuing property and queuing time. The following sections discuss the simulation experiments with no intervention, and with one intervention, namely a switch from HPF to LPF respectively.

4.1.3 No intervention

In Lane and Sidney's paper(1993), one interesting observation is that not only are there significant trade-offs between various performance measures (e.g., C_{max} and $\overline{C}$) for different scheduling rules as will be seen below, but that there exists also "pathological" or counterintuitive behaviour displayed in the response to the individual rules. For example, consider the 4/3/SH/ $\overline{C}$ problem in which $(a, b, c) = (3, 2, 2)$. The HPF scheduling has a completion time vector (8, 10, 18, 20) and a value of $\overline{C} = 14$. If the value of c is decreased from 2 to 1.9, the resulting HPF scheduling has a completion time vector of F = (7.9, 12.18, 17.7, 19.7) and hence the reduction in the value of the processing time *c* actually increases the value of $\overline{C}$ from 14 to 14.525. This situation will be investigated later.

Simulation results of total completion time C_{max} and average completion time $\overline{C}$ are presented in Figure 11 for the four cases defined in Table 6 above.

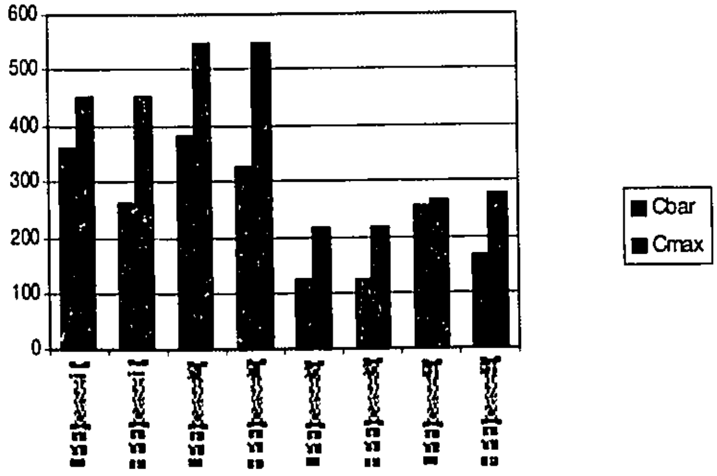

Fig.11 Scheduling rules LPF and HPF on single hub FMS without intervention

The results show that the completion time C_{max} stays the same in the experiments 1, 2, 3 for both LPF and HPF rules (see also Appendix A for detailed results for the four cases) But the average completion time varies from case to case. From the simulation experiments, we note that as expected, LPF is best for C_{max} and HPF the best for $\overline{C}$. In experiments 1, 2, 3, the HPF rule dominates the flow performance. In case 4, however, there is a trade off between best performance of C_{max} (using LPF) versus $\overline{C}$ (using HPF). The use of dynamic scheduling strategy attempts to improve overall flow performance and reduce the flow trade off possibilities.

4.1.4 Dynamic Scheduling Strategy

To determine the Dynamic Scheduling Strategy, the appropriate intervention time to switch from HPF to LPF must be determined. Preliminary analysis has shown that interventions which eliminate soft idle time are most efficient. Thus, the search for intervention times will focus on the occurrence of soft idle time in the schedules

Identification of Idle Time

From simulation experiments, if under HPF there is still "idle time" occurring during job processing, then we are able to identify when and how long the "idle time" will occur. Given this information, we can carefully select the intervention rules and intervention time to eliminate the "soft idle time" to improve the performance of FMS networks.

For example, the exact idle times of the four experiments from Table 6 are as follows

Table 7 Idle Time of 4 experiments on single hub network

EXPERIMENT	PARAMETERS: a/b/c	IDLE TIME: LPF	IDLE TIME:HPF
1	*25/15/20*	*0*	*0*
2	*25/50/20*	*95*	*95*
3	*1/15/20*	*6*	*6*
4	*25/15/1*	*6*	*14*

The existence of idle time provides room for improving the flow performance of the FMS network. The exact idle time for a single hub network can be calculated. For example, in experiment 4 under HPF, the idle time equals to *14* time units. The first idle time occurs at *t=259*, at which time *10* jobs of process *a* and *9* jobs of process *c* have been processed, the last job will be processed at *WS1* (process c) only after process *b* is completed. This leaves the idle time *15-1 = 14* idle time units on the hub (*WS1*). The point is that we may switch HPF to LPF at a time that leaves enough unprocessed jobs *c* to fill in this idle time gap, by letting the remaining unprocessed job *a* be processed first. In that case, we eliminate the idle time by 8 time units (14-6). C_{max} with this switch is reduced to its minimum level, as under the LPF scheduling strategy, while at the same time maintaining $\overline{C}$ at its lowest level under HPF.

Dynamic Scheduling Strategy on a single hub network

To generalise this principle, we have to investigate all of the cases from HPF to LPF. Lane and Sidney (1993) showed there are 4 cases of parameter combinations for LPF and 6 cases of parameters combination for HPF. By combining the HPF and LPF cases, there are 8 overlapping cases to be considered in switching from HPF to LPF using one intervention dynamic scheduling strategy (see also Fig.8 and Table 4). From a number of simulation experiments, we find that the performance of about half of these overlapping cases can be improved by eliminating soft Idle Time. We also find the best performance on some cases that exist minimum C_{max} without increasing the $\overline{C}$.

A single hub network was tested using the C language Simulator on Sun Workstation with a value of the hub processing time parameters a+b+c=35 and a batch size of job n=10. The intervention times were selected at every 20 time units. About 560 different cases were tested generating trials from all overlapping LPF and HPF cases. Analysis of these simulation results leads to a number of intuitive observations. On the basis of these hypotheses can be drawn toward the development of heuristics for the Dynamic Scheduling Strategy:

- If there is no idle time incurred, it means that C_{max}(HPF) is equal to C_{max}(LPF). The HPF scheduling rule is kept until the end of simulation because there is an advantage of its minimum average completion time $\overline{C}$.

- If C_{max}(HPF) is greater than C_{max}(LPF), it means that there is idle time during the period of processing. In order to get best flow time performance, the intervention time was selected at the time just one intervention time interval before the idle time incurred.
- For some cases with constant total completion time C_{max} and idle time, it means that there is a hard idle time incurred during the period of job processing. No improvement can be made to the job scheduling, The HPF scheduling rule is kept until the end of simulation to take the advantage of its minimum average completion time $\overline{C}$.

The general results of these simulation is summarized in Table 8.

Table 8 Case overlapping of dynamic scheduling strategies

Overlapping NO.	from HPF	To LPF	Improvement	No. Trials
1	*HPF case#1*	*LPF case#1*	*yes, existing best point*	*280*
2	*HPF case#2*	*LPF case#1*	*yes*	*30*
3	*HPF case#2*	*LPF case#2*	*no*	*15*
4	*HPF case#3*	*LPF case#2*	*no*	*99*
5	*HPF case#4*	*LPF case#1*	*yes*	*82*
6	*HPF case#4*	*LPF case#4*	*yes, but not for all scenario*	*9*
7	*HPF case#5*	*LPF case#2*	*no*	*36*
8	*HPF case#6*	*LPF case#3*	*no*	*9*

The interesting point is that from the simulation report shown in Tables 9, 10, 11 and in the cases tested in the previous section, i.e., in DSS case #1 a best intervention time exists. Applying DSS at that point of time we can get improved flow time measures -- minimum C_{max} which is equal to C_{max} (LPF) and minimum $\overline{C}$ which may even be a little better than $\overline{C}$ (HPF) [i.e., less than $\overline{C}$ (HPF)].

The flow time performance is very dependent on the FMS hub process time settings and batch job size. For example, the case of "b dominated" can be defined as

$\{b<(n-1)a, b\leq c\}$, the case of b cycles can be defined as $a+c\leq b<(n-1)a$. There are additional various cases under the case of "b determinant" defined as $\{b<(n-1)a, b>c, b<a+c, b\geq a\}$. For the comparison of total completion time C_{max}, if C_{max} (HPF) is greater than C_{max} (LPF), there must be an idle time incurred in the system which is either a soft idle time or hard idle time. It gives us a possibility to improve the flow time measures of a network. For example, in the DSS case#1, the comparison of strategies and their flow time performance provides information about the effects and efforts of considering the HPF and LPF cross cases and calculating differences in the flow time measures as a function of a, b, c, and n provided by Lane and Sidney.

Calculation of Idle Time and Intervention Time

The idle time can calculated in many overlapping cases. For example, in the case of overlapping #1 (Table 8), let a, b, c be processing time parameters, and n the number of jobs in a single hub network (Fig.4).

Let $i = \lceil b/a \rceil$:

then:

1. Idle time condition:

$$I = b - [n - (i+3)a] \begin{cases} > 0, & \text{Idle Time occurs;} \\ \leq 0, & \text{No Idle Time;} \end{cases}$$

2. Idle time units

$$b-[n-(i+2)a]$$

3. Idle time occurs at

$$(n-i)a+(i+1)c+b$$

For the example discussed at the beginning of this Chapter, we can calculate the idle time directly from the parameters by using this formula. For $a=1$, $b=2$, $c=4$, $n=5$, so $I=2$, for "idle time condition": $b-[n-(i+3)a]=2$ means there is a idle time; for "idle time units": $b-[n-(i+2)a]=1$, idle time is one time unit, for "idle time occurs at": $(n-i)a+(i+1)c+b=17$. Fig.12 illustrates the idle time.

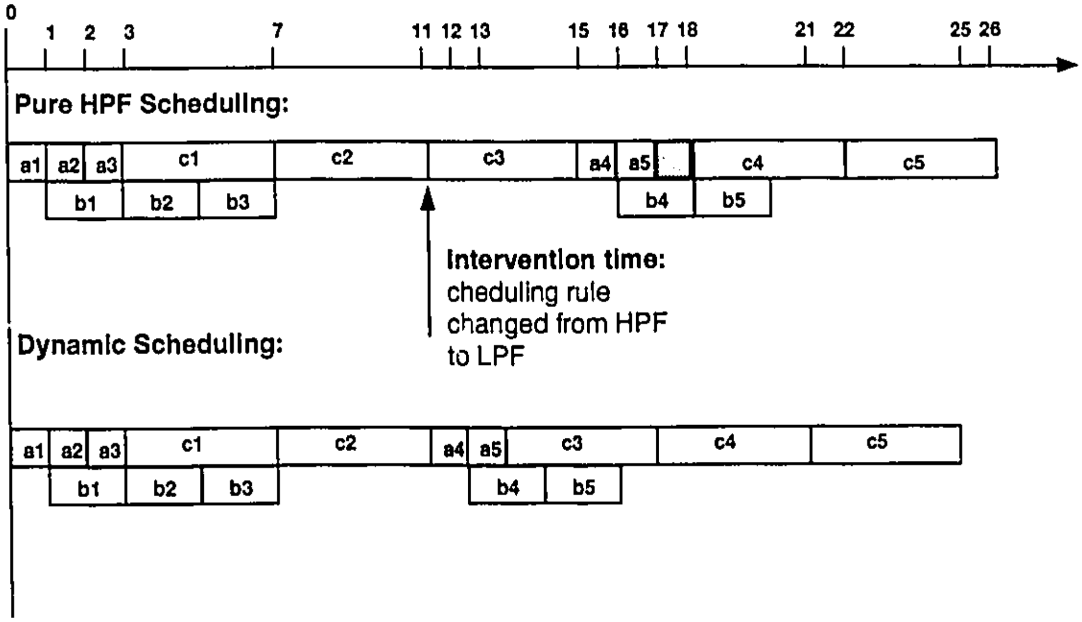

Fig. 12 The idle time and its improvement

Simulator and Simulation experiments

To investigate further the various cases of parameters combinations, a simulator using C Language has been developed to calculate the effects on flow performance of different intervention times. The program provides C_{max} and $\overline{C}$ values for the single hub network when one intervention occurs and the scheduling rule is switched from HPF to LPF. The flow chart of the C Language simulator is shown in Fig.13. Appendix B contains the program listing of the source code for the intervention time simulation.

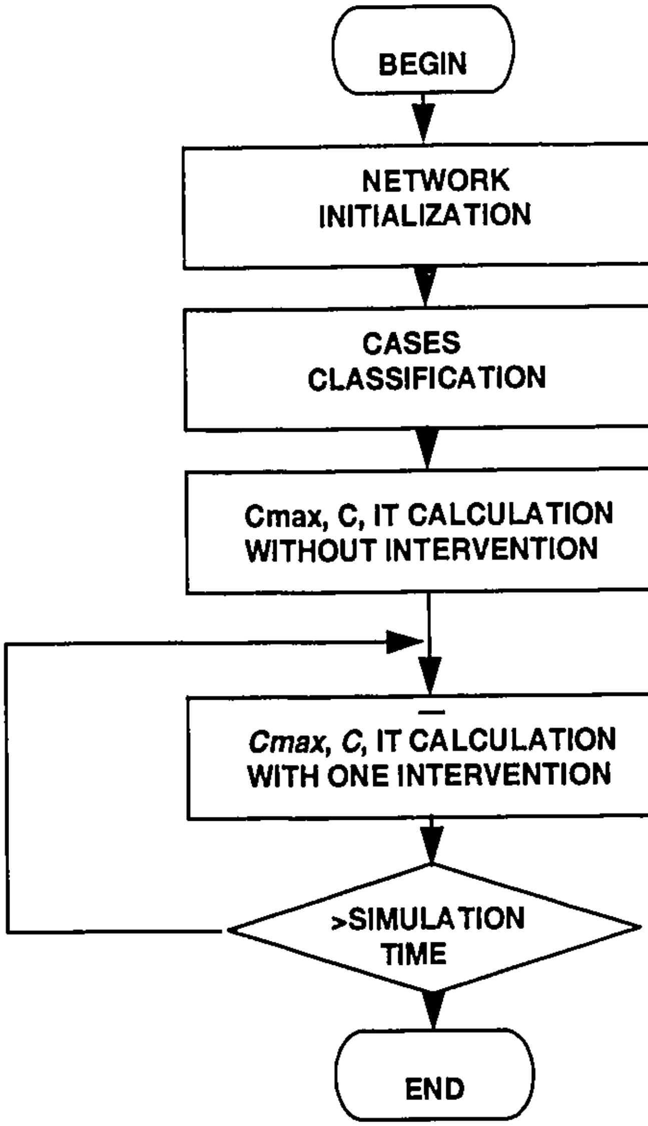

Fig. 13 Flow chart of the C program simulator for determining idle time

From the case partition simplex (Fig 8) and from observations of simulation tests, the overlapping case no. 1 (i.e., case 1 of HPF to case 1 of LPF) dominates 40 % or more of all the overlapping cases. Three simulation results are shown in Table 9, 10, and 11below.

Table 9 Simulation report of Example #1

```
The Simulation Report:
======================
    Notes: one intervention on one HUB FMS.

a=   1,  b=   5,  c=   6,  n=  10

in:CASE 1 (HPF)-- b dominated
in:CASE 1 (LPF)-- b dominated

Intervention       Cmax        Cbar          IDLE
  at time                                    time
     0             70.00       43.00          0
     5             70.00       43.00          0
    10             70.00       42.60          0
    15             70.00       42.20          0
    20             70.00       41.80          0
    25             70.00       41.40          0
    30             70.00       41.00          0
    35             70.00       41.00          0
    40             72.00       41.40          2
    45             72.00       41.40          2
    50             72.00       41.40          2
    55             72.00       41.40          2
    60             72.00       41.40          2
    65             72.00       41.40          2
    70             72.00       41.40          2
    75             72.00       41.40          2
```

Table 10 Simulation report of Example #2

```
The Simulation Report:
======================
    Notes: one intervention on one HUB FMS.

a=   2,  b=   9,  c=  10,  n=  10

in:CASE 1 (HPF)-- b dominated
in:CASE 1 (LPF)-- b dominated

Intervention       Cmax        Cbar          IDLE
  at time                                    time
     0            120.00       75.00          0
     5            120.00       75.00          0
    10            120.00       75.00          0
    15            120.00       74.20          0
    20            120.00       74.20          0
    25            120.00       73.40          0
    30            120.00       73.40          0
    35            120.00       72.60          0
    40            120.00       72.60          0
    45            120.00       71.80          0
    50            120.00       71.80          0
    55            120.00       71.00          0
    60            120.00       71.00          0
    65            123.00       71.40          3
    70            123.00       71.40          3
    75            123.00       71.40          3
    80            123.00       71.40          3
    85            123.00       71.40          3
    90            123.00       71.40          3
    95            123.00       71.40          3
   100            123.00       71.40          3
   105            123.00       71.40          3
   110            123.00       71.40          3
   115            123.00       71.40          3
   120            123.00       71.40          3
   125            123.00       71.40          3
```

Table 11 Simulation report of Example #3

```
The Simulation Report:
----------------------
     Notes: one intervention on one HUB FMS.

  A-   3,  B-  16,  C-  18,  N-  10

  in:CASE 1 (HPF)-- b dominated
  in:CASE 1 (LPF)-- b dominated

  Intervention        Cmax         Cbar          IDLE
    at time                                      time
       0            210.00       129.00           0
      10            210.00       129.00           0
      20            210.00       129.00           0
      30            210.00       128.10           0
      40            210.00       127.20           0
      50            210.00       127.20           0
      60            210.00       126.30           0
      70            210.00       126.30           0
      80            210.00       125.40           0
      90            210.00       125.40           0
     100            210.00       124.50           0
     110            210.00       124.50           0
     120            210.00       123.60           0
     125            210.00       123.60           0
     130            220.00       125.70          10
     135            220.00       125.70          10
     140            220.00       125.70          10
     150            220.00       125.70          10
     180            220.00       125.70          10
     200            220.00       125.70          10
     220            220.00       125.70          10
     225            220.00       125.70          10
```

Intervening at *t=0* results in the pure LPF scheduling strategy, and intervening at the end of simulation (i.e., beyond C_{max}) is the pure HPF scheduling strategy. The results show that intervening at times between these two extreme points give us times at which switching the HPF scheduling rule to the LPF scheduling rule will result in the improvement of performance on this one hub network. Switching scheduling rule from HPF to LPF at a time before the idle time occurs (such as *t= 35* in Example #1, *t=60* in Example #2 or *t=120* in Example #3), may lead to the improved performance of the flow time. Note that in some case, switching at the best point results in a situation in which both C_{max} and $\overline{C}$ were at their minimum values.

4.1.5 *Development of heuristic Formula for intervention time*

Optimal intervention times can be determined by testing every intervention time using small time steps with computer simulation. Based on the analysis of a single hub FMS network performance, the approximately optimal intervention time can be calculated in most overlapping cases of parameter combinations. The following provides a heuristic method for determining the approximately optimal intervention time.

Consider the example from the beginning of this Chapter. We can calculate the intervention time directly from the parameters For $a=1$, $b=2$, $c=4$, $n=5$, so $i=2$, for "process cycle": $n/(i+1) = 1.67 \leq 2$ which implies there is no cycle; the approximately optimal intervention time and no cycle (Table 11 and Fig.12) is $(i+1)a+ic = 11$. So switching the scheduling rule from HPF to HPF at this intervention time improves system flow performance on this particular single hub network.

The process cycle can be defined as $n/(i+1)\leq 2$ for no cycle and $n/(i+1)>2$ for multiple cycles. During the process of job scheduling, the process cycle looks like the process sequences of batch job are repeated at different time interval.

For example, suppose there is a batch size of job n=10 to be processed in a single hub network with a values of (a=2, b=4, c=29) using the HPF scheduling rule. The job sequence on the hub is {a1, a2, a3, c1, c2, c3} at t in {0, 93} time interval. After t=93, there is no job of process type c available, so the hub workstation begins processing the next new job of process type of a. At the next time interval {93, 186}, the job process sequence is {a4, a5, a6, c4, c5, c6}. It repeats the same job process sequence as in the previous time interval {0, 93}. At third time interval {186, 279}, the hub repeats the same job process sequence as previous one in {a7, a8, a9, c7, c8, c9}. This batch job finished at t=314, i.e., $C_{max}(HPF)=314$.

Simply speaking, the reason is that switching time from the HPF scheduling rule to LPF scheduling rule must have a leading time before the idle time occurs. For the cases#1 and no process cycle of this single hub network, the leading time is (n-2i-1)a+b+c, the difference between the approximately optimal intervention time and idle time. From this leading time, obviously, we have to at least advance a time of process step b and process step c for processing last job. How many process steps a we have to leave for this idle time gap depends on the coefficients b, a, and n. The principle is that to improve the system flow performance, we leave just enough unprocessed steps *a* plus one step *b* and *c* to fill up the idle time gap. In this we may make best use of these multi-purpose workstations (hubs).

Table 12 Heuristic method of intervention time determination

From HPF	**To LPF**	**Approximately Optimal Intervention**	**Avg Improve on C_{max}**	**Avg Improve on $\bar{C}$**	**No. Trials**
1	1	for no cycle*: (i+1)a+ic for multiple cycle*: p(i+1)a+[p(i+1)-1]c here $p=\lfloor n/(i+1)\rfloor$	3.59%	.29%	280
2	1	(n-1)a+(n-3)c	4.32%		30
2	2	no			15
3	2	no			99
4	1	(n-1)a+(n-3)c	1.53%		82
4	4	no			9
5	2	no			36
6	3	no			9

* Cycle: see Lane and Sidney, 1990, "work report" 90-28, Faculty of Administration, University of Ottawa

For simple identification of process cycle: $n/(i+1) \leq 2$ for no cycle;

$n/(i+1) > 2$ for multiple cycle

There are two ways to find the approximately optimal intervention time to improve network performance of a small FMS network. One is to use the simulations to choose this best intervention time. These simulators can be set into an on-line system or as a part of expert systems; another way is to use the heuristic method described in the above table to determine the best intervention time. For some cases which do not have improvement potential we will keep the HPF strategy throughout.

4.1.6 Summary

In this section, the performance on a small single hub network including implementation of pure LPF and HPF scheduling rules, exploration of idle time and the Dynamic Scheduling Strategy have been investigated. It is also a starting point for following an investigation of a medium and large size hub network in this thesis.

Using a simple example, it is shown that network performance on a single hub network with flow time consideration can be improved by using a Dynamic Scheduling Strategy. Under the Dynamic Scheduling Strategy in many cases, the flow performance of the LPF scheduling rule on total completion time C_{max}, and the HPF scheduling rule on average completion time $\overline{C}$ can both be improved.

The Dynamic Scheduling Strategy improves the system performance is by eliminating the existing soft idle time in the operation of hub networks. A expression for the idle time occurs in a single hub network and its length is derived.

There are eight overlapping cases from the HPF to LPF scheduling rule for a single hub network using Dynamic Scheduling Strategy with one intervention time. Simulation experiments were carried out first using a C Language simulator to explore the system performance of pure HPF and pure LPF scheduling rules, the gap between the total completion time C_{max}, and the average completion time $\overline{C}$, operating idle time.

In many cases, the idle time and the approximately optimal intervention time can be calculated by a heuristic algorithm. This is of great help to reducing search for the intervention time in an FMS network with more than one hub workstation.

4.2 Medium size FMS hub network

A medium size FMS network includes three multi-purpose workstations *WS1*, *WS2* and *WS3* (Fig. 9). For Example, in a wafer board manufacturing systen one "stepper" and two furnace workstations could comprise a hub network of fabrication of semiconductors linked by a material handling system.

Suppose each hub has only one dual purpose workstation in this three-hub network. The process steps *a, d* are processing times p_1 *and* p_4 on *WS1*, process steps *b, e* are processing parameters on *WS2*, and process steps *c, f* are processing parameters on *WS3*. A fixed number of jobs *n* pass through the hub network according to the alphabetical order of processing, i.e.,

$$enter \Rightarrow a \Rightarrow b \Rightarrow c \Rightarrow d \Rightarrow e \Rightarrow f \Rightarrow exit$$

Two objectives are pursued in the simulation experiments on this three-hub network. The first is to examine the effect of pure HPF and LPF scheduling strategies on the performance of the three-hub network. The second objective is to explore the improvement of the three-hub network by using the intervention strategies on all hubs.

4.2.1 A simulation example of a three hub network

In following experiments, the switching rule for each hub of this three-hub network begins with the HPF scheduling rule. A generic FMS simulator using SLAM II simulation language on a DEC VAX workstation has been used for the three-hub network simulation experiments.

Experience and heuristic methodology gained from the single-hub network help us to reduce the testing set of queue scheduling rule combinations.

Suppose the network configuration is as follows (Table 13):

Table 13 System parameters for three-hub network: Example #1

	WS1	**WS2**	**WS3**
Parameters	*a=1, d=4*	*b=2, e=5*	*c=1, f=3*
Starting Scheduling rules	*HPF*	*HPF*	*HPF*
Number of machines	*1*	*1*	*1*
Maximum Load	*1*	*1*	*1*
Uptime	*Simulation time*	*Simulation time*	*Simulation time*
Yield	*100%*	*100%*	*100%*

Effects on system flow performance at different intervention times under the queue scheduling strategy is of interest. The observation and comparison of the simulation experiment results rank different intervention times based on the criteria, i.e., average completion time, total completion time, and hub utilisation (idle time determination). The rankings of intervention time also lead to recommendations about how the performance can be improved during on-line operation of an FMS. The simulation results of the Dynamic Scheduling Strategy on the hub network configured as in Table 13 is presented in Fig. 14.

We investigate the system performance with flow time consideration at each intervention time from the HPF to LPF scheduling rule. From Fig. 14, the best performance with flow time consideration is obtained using Dynamic Scheduling strategy. The application of the Fraction of C_{max} Estimation (FCE) is shown in the next section.

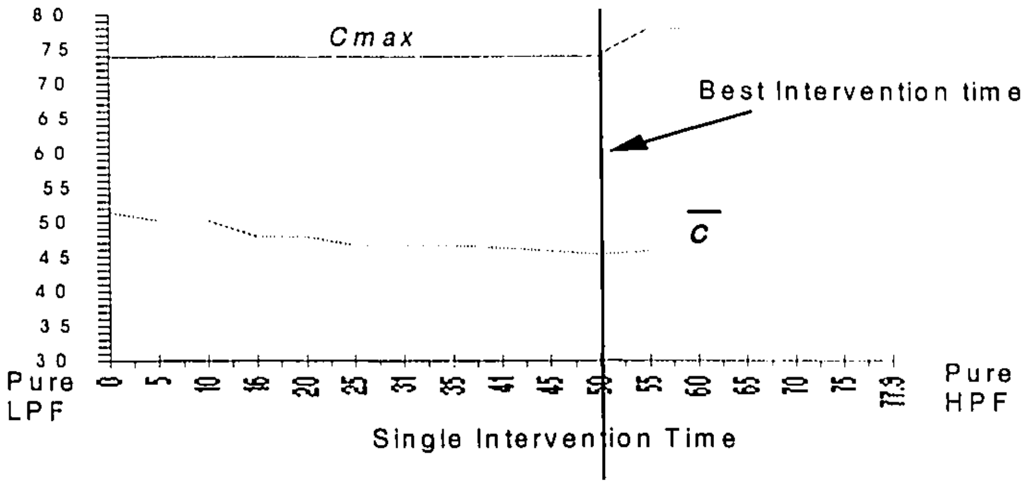

Fig. 14 System performance of three-hub network with different intervention times

4.2.2 *Application of heuristic method for intervention time*

In order to improve the performance of the three-hub network, the most important thing is to choose a suitable intervention time for switching all three hub scheduling rules from HPF to LPF. One way to choose a suitable intervention time is to use a heuristic method called Fraction of C_{max} Estimation (FCE).

The results of FCE calculations only give us a recommended intervention time because the performance nature of the three hubs network is not as straightforward as that in the single hub network. So the FCE intervention time point can be thought of as a starting point to search for the approximately optimal intervention time quickly. The approximately optimal intervention time point can be less than, equal to or greater than the FCE intervention point. The following section discusses the Dynamic Scheduling Strategy based on these possibilities.

The idea is to search for the approximately optimal intervention time in the three hubs network. In the calculation of the intervention time, we consider one workstation at a time as the sole hub as in the single hub model and the other two workstations as non-hub workstation. In this way, we emulate this single model as single hub network. This is done in order to apply the single hub strategy to each workstation alternatively. For example, consider processing parameter *a* of the three-hub network as parameter *a* of single hub network; parameters *b*+*c* of three-hub network as *b* of the single hub network; parameter *d* of three-hub network as parameter *c* of the single hub network. The parameters *e*, *f* are not required parameters with respect to a "single hub network" for *WS1* in the three-hub network.

For a three-hub network configured as above parameters, the calculations of FCE to determine the approximately optimal intervention time are shown below:

Table 14 Fraction of C_{max} Estimation (FCE) calculation: example #1

WS #	a	b	c	C_{max}	BEST IT*	FRACTION
1	1	3	4	50	35	f1=35/50 =0.7
2	2	5	5	70	50	f2=50/70 =0.71
3	1	9	3	94	94	f3=94/94 =1

* IT – intervention time as determined using the C Language simulator described previously in Table 9-11 of Appendix B

One purpose of the above calculation (Table 14) is to determine a "good" intervention time. Each of the three workstation-based models yields a fraction F=(Best IT)/ C_{max} for a particular case, and we shall use the smallest of these fraction as our chosen fraction. The second purpose of Table 14 is to estimate a "good" value of C_{max} which we hope to obtain; we calculate this "good" value as an average of the three values of C_{max} in Table 14. This averaged value is, in our example, C_{max}(estimated)=(50+70+94)/3=71.33. From the simulation model, we get C_{max}(LPF)=74 and C_{max}(HPF)=78. In Table 15 we apply the three fractions from Table 14 to each of the three values of C_{max} described above to get estimated intervention times. We take the smallest of smallest of the nine estimated intervention times to be our chosen one, i.e., our estimation of a good intervention time. In effect, we calculate the intervention time as the product of the smallest of { C_{max}(estimated), C_{max}(LPF), C_{max}(HPF)} multiplied by the smallest fraction from the last column of Table 14. In our example, the difference of 4 between C_{max}(HPF) and C_{max}(LPF) indicates idle time, and the potential opportunity for improvement.

The hub intervention time is determined as a fraction of its total completion time C_{max}. Table 15 compares three results for the multiple hub network for C_{max}: (1) estimated C_{max}, (2) pure HPF C_{max}, and (3) pure LPF C_{max}. For the estimated C_{max}, we use the average time of three emulating single hub networks C_{max}. In this case, estimated C_{max} equals to (50+70+94)/3=71.33. From the simulation model, we get C_{max}(LPF) = 73.91, $\overline{C}$(LPF) = 51.45, C_{max}(HPF) = 77.91, $\overline{C}$(HPF)=77.91. The gap of C_{max} between HPF and LPF equals 4 time units, which implies that there is room for performance improvement. The chosen FCE intervention time is scheduled as the global minimum of all intervention times calculated at each workstation and for each C_{max} estimation.

Table 15 FCE Intervention Time Calculation: example #1

INTERVENTION TIME BASED ON	WS1	WS2	WS3
C_{max}(estimated)=71.33	71.33*35/50=49.93	71.33*50/70=50.95	71.33*94/94=71.33
C_{max}(LPF)=74	74*35/50=51.8	74*50/70=52.85	74*94/94=74
C_{max}(HPF)=78	78*35/50=54.6	78*50/70=55.71	78*94/94=78

From simulation analysis, the approximately optimal intervention time as determined by exhaustive simulation is at *t=50*. This is close to the time of 49.091 recommended by the FCE approach. The comparison of the total completion time C_{max}, and average completion time $\overline{C}$ using the pure scheduling rules and Dynamic Scheduling strategy (DSS) is as follows (Table 16):

Table 16 Improvement of system performance: example #1

	C_{max}	$\overline{C}$
HPF	*78*	*45.86*
LPF	*74*	*50.26*
DSS	*74*	*45.25*

The approximately optimal intervention time using the Dynamic Scheduling Strategy minimizes the total completion time, C_{max} while decreasing the average completion time below that under the HPF scheduling rule. Thus, based on the intervention strategies, improvement in the flow performance of the medium hub network is attainable for some cases using the heuristic approach developed from the small hub network.

Even though the FCE does not give us the approximately optimal intervention time, it is very close to that. From the FCE recommended intervention time point, a suitable intervention time is quickly determined. A small seeries of simulation experiments around the determined intervention time could be carried out to conform an approximately optimal intervention time.

The next two experiments show the approximately optimal intervention time of the Dynamic Scheduling Strategy on the three-hub workstation. In the first example, the approximately optimal intervention time occurs before the FCE recommended intervention time point, In last example, this point occurs after FCE recommended intervention time point.

Consider the following three-hub network configuration (Table 17):

Table 17 Parameters of three-hub network: example #2

	WS1	**WS2**	**WS3**
Parameters	*a=2, d=5*	*b=3, e=6*	*c=1, f=4*
Starting Scheduling rules	*HPF*	*HPF*	*HPF*
Number of machine	*1*	*1*	*1*
Maximum Load	*1*	*1*	*1*
Uptime	*Simulation time*	*Simulation time*	*Simulation time*
Yield	*100%*	*100%*	*100%*

The calculations of FCE to determine the approximately optimal intervention time are similar to the previous discussion (Table 18).

Table 18 Fraction of C_{max} Estimation (FCE) calculation of Example #2

WS #	**a**	**b**	**c**	C_{max}	**BEST IT**	**FRACTION**
1	*2*	*4*	*5*	*70*	*55*	*fi=55/70=0.785*
2	*3*	*6*	*6*	*90*	*70*	*f2=70/90=0.777*
3	*1*	*11*	*4*	*115*	*115*	*f3=115/115=1*

Table 19 FCE point calculation of Example #1

INTERVENTION TIME BASED ON	WS1	WS2	WS3
C_{max}*(estimated)=92*	*92*55/70=72.28*	*92*70/90=71.55*	*92*115/115=92*
C_{max}*(LPF)=96*	*96*55/70=75.42*	*96*70/90=74.66*	*96*115/115==96*
C_{max}*(HPF)=100*	*100*55/70=78.57*	*100*70/90=77.77*	*100*115/115=100*

From local simulation runs, the approximately optimal intervention time is at t=66, which is before the FCE recommended intervention point at about t=72. Nevertheless, the DSS realizes improved flow times: C_{max}(DSS)=95.91, $\overline{C}$(DSS)=50.95 as shown in Table 20 below.

Table 20 Improvement of system performance for example #2

	C_{max}	$\bar{C}$
HPF	*100*	*60.15*
LPF	*96*	*60.56*
DSS	*96*	*50.95*

Another example gives the following hub network configuration (Table 21):

Table 21 Parameters of three-hub network Example #3

	WS1	**WS2**	**WS3**
Parameters	*a=1, d=6*	*b=2, e=10*	*c=3, f=18*
Starting Scheduling rules	*HPF*	*HPF*	*HPF*
Number of machine	*1*	*1*	*1*
Maximum Load	*1*	*1*	*1*
Uptime	*Simulation time*	*Simulation time*	*Simulation time*
Yield	*100%*	*100%*	*100%*

The calculations of FCE to determine the approximately optimal intervention time are shown below (Table 22):

Table 22 Fraction of C_{max} Estimation (FCE) calculation of Example #3

EMULATING WS NO.	a	b	c	C_{max}	BEST IT	FRACTION
1	*1*	*5*	*6*	*70*	*36*	*f1=36/70=0.514*
2	*2*	*9*	*10*	*120*	*62*	*f2=62/120=0.516*
3	*3*	*16*	*18*	*210*	*129*	*f3=129/210=0.614*

* Note: the results of the emulating single network can be found in Appendix C

Table 23 FCE intervention time point calculation of Example #3

INTERVENTION TIME BASED ON	WS1	WS2	WS3
$C_{max}(est.)=134$	$134*36/70=68.91$	$134*62/120=69.23$	$134*129/210=82.31$
$C_{max}(LPF)=213$	$213*36/70=109.54$	$213*62/120=110.05$	$213*129/210=130.84$
$C_{max}(HPF)=222$	$222*36/70=114.17$	$222*62/120=114.7$	$222*129/210=136.37$

Like previous examples, after testing using simulation model for this three hub case, the approximately optimal intervention time is at $t=95$, which occurs after the FCE recommended intervention time point near $t=69$. The results C_{max}(DSS)=214.9, $\overline{C}$(DSS)=128.0 are a little worse than C_{max}(LPF) and a little better than $\overline{C}$(HPF). These results are summaried in Table 24.

Table 24. Improvement of system performance for example #3

	C_{max}	$\overline{C}$
HPF	222	129.6
LPF	213	132.0
DSS	215	128.9

4.2.3 Summary

The experiments and results obtained from the three-hub FMS network is the reflection and strengthening of the conclusions from the previous single hub network. At the best intervention time, the performance of the three-hub network can reach the best performance on the minimum total completion time C_{max} and keep the average completion time $\overline{C}$ as low as possible. Furthermore, for many cases the results of the Dynamic Scheduling Strategy (DSS) on the average completion time $\overline{C}$ of the three-hub network may be even better than that of the pure HPF scheduling strategy.

Three examples of different parameter combinations of a three-hub network are tested. The heuristic method, i.e., Fraction of C_{max} Estimation (FCE) is applied to each of these examples. Because the system performance of three-hub network is not as straightforward as that of a single hub network, the algorithm of the approximately optimal intervention time calculation may not lead to improved flow time. The calculation of a FCE intervention time point only gives us the recommended approximately optimal intervention time. The real intervention time can be the time point near, before or after the FCE recommended intervention time point. The approximately optimal intervention time can be found by testing a few intervention time points around the FCE recommended intervention time point using the system simulator.

The heuristic method developed from a medium-size FMS network can become an on-line knowledge-based expert system for FMS scheduling rules. In the next section we extend this DSS with a heuristic method into a large size FMS hub network.

4.3 Large FMS network

The large system tested here includes five dual-purpose workstations (hubs). The processing step parameters for each workstation are processing steps a, f on *WS1*, processing steps b, g on *WS2*, processing steps c, h on *WS3*, d, i on *WS4*, and processing steps e, j on *WS5* (see also Fig. 10). The job routing still uses the cycle style, i.e.,

$$\text{enter} \Rightarrow a \Rightarrow b \Rightarrow c \Rightarrow d \Rightarrow e \Rightarrow f \Rightarrow g \Rightarrow h \Rightarrow i \Rightarrow j \Rightarrow \text{exit}$$

The objectives investigated here for large FMS hub network are similar to the previous section. The first is to examine the performance of pure HPF and LPF on the five hubs network; the second is to improve the system performance by applying the dynamic scheduling strategy to the network.

4.3.1 Simulation Experiment

The large size FMS network is simulated using the SLAM II simulator. The experiment designed for a five-hub network is used to validate the extension of the FCE method in this larger network. Consider the configuration of a example five hub network as shown in Table 25. Appendix D contains details of the intervention time simulator and scheduling rule simulation results for this case.

Table 25 Five-hub network configuration example

	WS1	WS2	WS3	WS4	WS5
Parameters	a=1, f=6	b=2, g=10	c=1, h=1	d=2, i=8	e=1, j=5
Starting Scheduling rules	HPF	HPF	HPF	HPF	HPF
Number of machine	1	1	1	1	1
Maximum Load	1	1	1	1	1
Uptime	Simulation time	Simulation time	Simulation time	Simulation time	Simulation time
Yield	100%	100%	100%	100%	100%

The calculation of FCE to determine the approximately optimal intervention time is shown in Table 26.

Table 26 Fraction of C_{max} Estimation (FCE) calculation of 5 hub network example

EMULATING WS NO.	a	b	c	C_{max}	BEST IT	FRACTION (BIT/ C_{max})
1	*1*	*6*	*6*	*175*	*140*	*0.8*
2	*2*	*10*	*10*	*300*	*275*	*0.92*
3	*1*	*19*	*1*	*477*	*477*	*1*
4	*2*	*18*	*18*	*500*	*380*	*0.76*
5	*1*	*35*	*5*	*881*	*881*	*1*

* Note: the results of the emulating single network can be found in Appendix D

Table 27 Heuristic point of intervention time calculation

INTERVENTION TIME BASED ON	WS1	WS2	WS3	WS4	WS5
C_{max}(estimated)	467*0.8=373.6	467*0.92=429.64	467*1	467*0.76=354.92	467*1
C_{max}(LPF)	517*0.8=413.6	517*0.92=475.64	517*1	517*0.76=392.92	517*1
C_{max}(HPF)	526*0.8=420.8	526*0.92=483.92	526*1	526*0.76=399.76	526*1

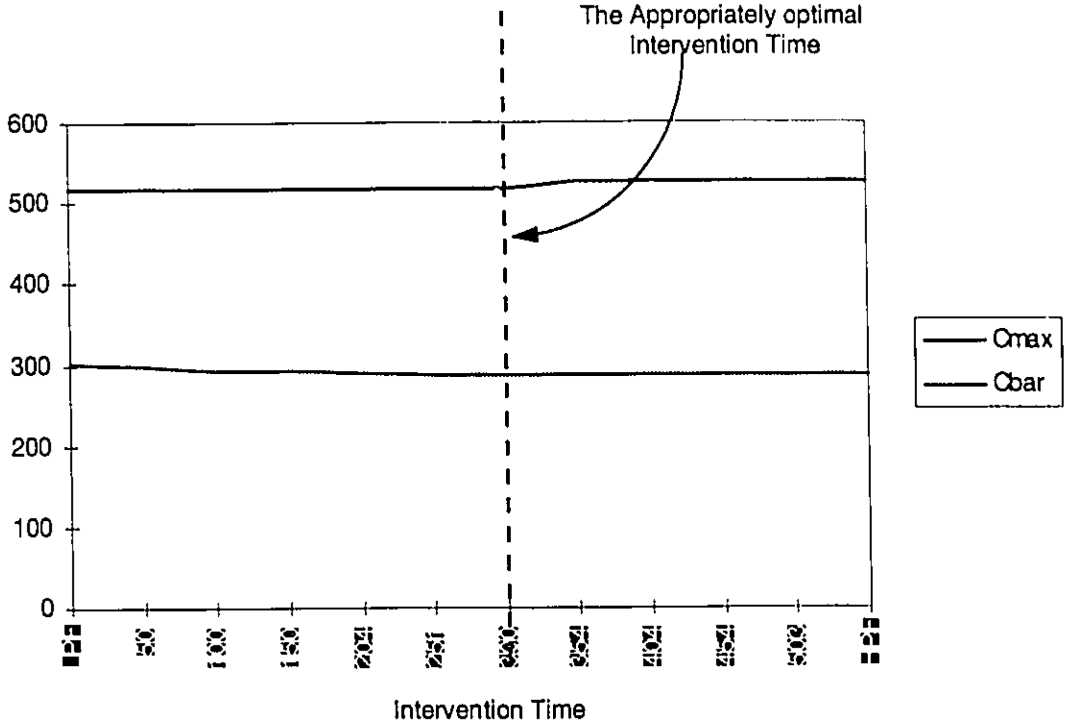

Fig. 15 System performance of Dynamic Scheduling Strategy on a five-hub network

System performance of Dynamic Scheduling Strategy on a five-hub network is shown in Fig.15. Based on these simulation experiments, the approximately optimal intervention time is at t=300, which is after the FCE intervention point at t=373.3. The DSS gives improved values of C_{max} (DSS)=516.8, which is the value of C_{max} (pure LPF), and $\overline{C}$(DSS)=286.7 which is better than the value of $\overline{C}$(HPF)=287.6. Therefore the system performance of the five-hub network is improved for this case by applying the Dynamic Scheduling Strategies. These results are summaried in Table 28.

Table 28 Improvement of system performance for this five-hub network

	C_{max}	$\overline{C}$
HPF	527	297.8
LPF	517	287.6
DSS	517	286.7

4.3.2 Summary

The application of approximately optimal intervention time to improve the performance of a five hubs network is another extension of DSS (Dynamic Scheduling Strategy). From the analysis of case by case examples, the strategy can lead to flow time improvements compared to pure scheduling strategies.

4.4 Summary of Model Results

The simulation experiments and results in this chapter represent the methodology discussed in the previous chapter. The network flow performance was investigated on three levels of increasingly complex hub networks: a single hub FMS network, a medium-size hub network (three hubs) and a large-size hub network (five hubs). Examinations of the results from these networks focused on three issues:

- system performance with regards to flow time considerations relative to pure HPF and LPF scheduling rules;
- the idle time in the operation of hubs in the FMS network; and
- system performance with flow time consideration using the Dynamic Scheduling Strategy.

Pure LPF and HPF scheduling rules and idle time

The pure LPF and HPF scheduling rules have been proved to be the most promising scheduling rules on the performance of total completion time and average completion time in most situations of a FMS network. For example, in the case #4 of a single hub network, the total completion time of the pure LPF scheduling rule of C_{max} (LPF) is shorter than the total completion time of the pure HPF scheduling rule of C_{max} (HPF) by 3%, but the average completion time of the pure HPF scheduling rule of $\overline{C}$(HPF) is shorter than the average completion time of the pure LPF scheduling rule of $\overline{C}$(LPF) by as much as 53%. The difference between C_{max} (HPF) and C_{max} (LPF) is the system operation idle time on a hub workstation. This idle time leaves room for performance improvement on hub networks.

The idle time in a single hub network can be calculated using an algorithm shown in the chapter or can be determined using a simulator. We are able to determine in advance when the idle time occurs in a single hub network and its length. However, in medium and large size hub networks, the principle remains the same, but the algorithm developed from the single hub network does not neccessarily lead to flow time improvement because the nature of the medium and large size hub networks is not as straightforward as in the single hub network. The algorithm and simulators are extended to medium-size and large-size hub networks.

Dynamic Scheduling Strategy and approximately optimal intervention time

The Dynamic Scheduling Strategy is developed for eliminating the idle time of system operation to improve the system performance. Because the HPF scheduling rule has much better performance on the average completion time, in the Dynamic Scheduling Strategy we begin with the HPF scheduling rule then switch to the LPF scheduling rule at approximately optimal intervention time to minimise the total completion time and keep the average completion time as low as possible.

The reason that the Dynamic Scheduling Strategy can improve the system performance is that Dynamic Scheduling Strategy eliminates existing soft idle time during the operation of hub networks. A simulator using the C Language has been developed to identify the idle time that a small single hub network would have with or without intervention.

There are four cases of parameter combinations of a single hub network for the pure LPF scheduling rule, and six cases of parameter combinations of a single hub network for the pure HPF scheduling rule (Lane and Sidney, 1993). Using the Dynamic Scheduling Strategy, eight overlapping cases switching the scheduling rule from pure HPF scheduling rule to pure LPF scheduling rule are obtained. Only four overlapping cases of system performance over eight can be improved by the Dynamic Scheduling Strategy. The system performance of the other four overlapping cases cannot be improved because of the hard idle time existing in the operation of hub networks. The identification of soft idle time or hard idle time helps reduce the number of trial-and-error simulation experiments.

Heuristic Method: Algorithm and Fraction of C_{max} Estimation

The performance of FMS hub networks with more than one hub workstation is more complicated than in a single hub network. The algorithm and the C Language simulator to identify the idle time may not be valid in the situation of FMS hub networks with more than one hub workstation.

To solve the problem of the Dynamic Scheduling Strategy on FMS hub networks with more than one hub workstation, a heuristic method called Fraction of C_{max} Estimation is developed to provide a recommended intervention time point. From this recommended intervention time point, the approximately optimal intervention time is determined by testing a few intervention times around the recommended intervention time point using the system simulators. The Fraction of C_{max} Estimation (FCE) comes from the emulation of the multiple hub network to a single hub network. After decomposing the multiple hub network into a single hub network, the algorithm and the simulator are used to analyse the idle time in the operation of the hub network. Then the lowest intervention time among the Fraction of C_{max} Estimation (FCE) intervention time is selected as the recommended intervention time.

CHAPTER 5
CONCLUSIONS AND FUTURE WORK

Many simulation experiments have been analyzed on three levels of increasingly complex models. The discrete simulation models and simulators developed in this thesis permit the examination of all cases of parameter combinations from a single hub network to a five-hub network that would be difficult to study by analytical methods. The trade-off between total completion time and average completion time is investigated on these three levels. The simulators developed by the C Language under UNIX platform provide useful tools for investigating the performance of a single hub network in detail, such as C_{max} , $\overline{C}$, Idle Time, Intervention time point. They are also very useful for the heuristic method to choose the right point of intervention time for medium and large size FMS networks. A generic FMS simulation model developed by SLAM under DEC VAX platform (Morton, 1989) provides an efficient, powerful tool to study general FMS operations.

5.1 Conclusions

The objective of this research is to simulate and test a generic Flexible Manufacturing System(FMS) that involves complex queuing systems. To avoid the complication of the $n/m/SH/C_{max}$ and $n/m/SH/\overline{C}$ problems on the theoretical analysis of system performance for more than one hub FMS network, discrete simulators have been developed. The simulation results and performance analysis demonstrate that the system performance can be improved in many cases by eliminating the Soft Idle Time and smoothing job flow by using dynamic scheduling strategies.

The interventions and rescheduling procedures have been applied to increasingly complex and concrete FMS cases using a flexible simulation model including animation of the production facility. This thesis also evaluates the performance of rescheduling rules with respect to the trade-off between total completion time and average completion time for a fixed number of jobs in an FMS defined by hub and non-hub workstations.

As we know, each FMS has its own unique characteristics and objectives. The application of a particular queue strategy will depend on these factors. Although some queue scheduling rule strategies operate well in many cases of FMS environments, the generalisation of results will lead to erroneous conclusions. The analysis and conclusions that we have gained in this thesis will be very useful for solving the queue scheduling rule problems in many complex situations.

5.1.1 Idle Time and performance

Usually, each job to be processed on a hub network needs different processing times on many hub workstations, or even on the same workstation in different processing steps. The Idle Time and Queue Length are the two most important problems that need to be solved for FMS networks since these two factors relate closely to performance measures such as C_{max} and $\overline{C}$. The Idle time can be classified into Soft IT and Hard IT.

.

The performance of the hub network is closely related to how much Idle Time exists at *WS's* or queue time on processed jobs. The dynamic scheduling strategies can only improve such hub networks with Soft Idle Time. To improve the system performance of hub networks with Hard Idle Time, the system parameters must be changed, i.e., the network components must be replaced by a suitable latest model, or reallocating the hub network.

5.1.2 Dynamic Scheduling Strategies

The dynamic scheduling strategies have been shown to be an effective way to improve the performance of hub networks in many cases, especially for the system with large soft Idle Time. In this thesis, we investigate the scenarios on a single hub network based on pure scheduling strategies and the overlapping cases from the HPF scheduling rule to the LPF scheduling rule. Even though we can not obtain an "optimal" intervention time for the more complex hub networks, recommended intervention time points are found that lead to improved flow time performance in the network.

5.1.3 Heuristic method for intervention time

The heuristic concepts presented here can be part of an on-line expert system for the scheduling rule decision making of a large FMS system. The heuristic method may take advantage of the information available on the factory floor. Theoretically, any large system can be decomposed as the combination of several emulating single hub networks.

5.1.4 Idle Time simulators for emulating a single hub network

The discrete simulators developed principally use C under UNIX platform. The goal of this single hub simulator is to associate the idle time of the network with total completion time and average completion time consideration. It is a basis of the heuristic method for the hub network with a single hub or many hubs. The code of the intervention simulator is listed in Appendix B.

5.1.5 Network management and performance analysis

The idea and methodology could be extended to network management that involves queuing problems and management issues, applied for example to communication network or other service systems. By eliminating the Idle Time and smoothing the job flow, the system performance would be improved in many situations, especially in networks with soft idle time. The results can indicate the direction for the potential improvement of a hub network that has hard idle time. The discrete simulators provide powerful tools for performance evaluation of the systems.

5.2 Future work

Modern manufacturing systems are often structured as complex networks of workstations. Some workstations of the network may be bottleneck hubs. Flow time and idle time considerations provide a clearer understanding of such systems. In this thesis, idle time simulators and heuristics are developed for a single hub network under common and easily implemented scheduling rules -- LPF and HPF. We have also shown how our methodology can be extended to the examination of different sizes of hub networks. But for the generalization of this methodology to be useful for real systems, there is still an enormous amount of work to be done.

Combining dynamic scheduling strategies with various batch sizes strategies in the computer simulation of FMS networks might be very interesting. The batch size of jobs in this thesis is fixed. Because the number of jobs affect the idle time and queue length, various batch sizes of jobs will result in different dynamic scheduling strategies. Applying the dynamic scheduling strategy to full processes or real problems will be another challenging task. Real FMS networks are more complicated than the FMS networks discussed in this thesis. Finally, considering setup time and machine failure probability is another extension of the Dynamic Scheduling Strategy. Adding graphic user interfaces to the simulators will improve understanding of the system performance, for example by helping to identifying the causes of the soft idle time or hard idle time.

The presence of soft idle time can lead to reduced flow time measures as demonstrated on several simulated examples in the thesis. The extent of this flow time improvement however is not known. In some cases, results were improved below the pure strategy minimums. Theoretical analysis of lower flow time limits using a dynamic scheduling strategy would be an interesting formal extension of this these.

The simulation results reported in this thesis for illustration purposes come from a narrow range of parameter values for a, b, c, etc., and n, the number of jobs. An extension of the current analysis into the sensitivity of flow results for different values for n is considered. Results of simulations for determining n carried out as part of thesis, show the dependence of flow measures on the selective of value of n and all other parameters a, b, c, etc.,.

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APPENDIX A:

This appendix contains the simulation data of single hub network on 12 common scheduling rules for four typical cases discussed in this thesis. See also Chapter 2, for discussion of common scheduling rule (Table 1).

Case 1: *a=10, b=15, c=20, n=10*

RULE	$\bar{C}$	Cmax
DUEDATE	*210.0*	*299.9*
HPF	*175.5*	*314.9*
SPT	*210.0*	*299.9*
LPF	*210.0*	*299.9*
CR	*189.0*	*299.9*
MINSLK	*210.0*	*299.9*
APO	*184.5*	*314.9*
SPO	*180.0*	*304.9*
FISFO	*210.0*	*299.9*
NINQ	*182.0*	*299.9*
LPT	*175.5*	*314.9*
CR2	*189.0*	*299.9*

Case 2: *a=25, b=50, c=20, n=10*

RULE	$\bar{C}$	Cmax
DUEDATE	*380.0*	*544.9*
HPF	*325.0*	*544.9*
SPT	*380.0*	*544.9*
LPF	*330.0*	*544.9*
CR	*380.0*	*544.9*
MINSLK	*330.0*	*544.9*
APO	*330.0*	*544.9*
SPO	*330.0*	*544.9*
FISFO	*380.0*	*544.9*
NINQ	*325.0*	*544.9*
LPT	*380.0*	*544.9*
CR2	*330.0*	*544.9*

Case 3: *a=1, b=15, c=20, n=10*

RULE	$\overline{C}$	Cmax
DUEDATE	*126*	*215.9*
HPF	*126*	*215.9*
SPT	*126*	*215.9*
LPF	*126*	*215.9*
CR	*126*	*215.9*
MINSLK	*126*	*215.9*
APO	*126*	*215.9*
SPO	*126*	*215.9*
FISFO	*126*	*215.9*
NINQ	*126*	*215.9*
LPT	*126*	*215.9*
CR2	*126*	*215.9*

Case 4: *a=25, b=15, c=1, n=10*
(See also Fig.1, Fig.2, Fig.11 in text)

RULE	$\overline{C}$	Cmax
DUEDATE	*256.1*	*265.9*
HPF	*166.9*	*273.9*
SPT	*166.9*	*273.9*
LPF	*256.1*	*265.9*
CR	*166.9*	*273.9*
MINSLK	*256.1*	*265.9*
APO	*166.9*	*273.9*
SPO	*169.4*	*273.9*
FISFO	*256.1*	*265.9*
NINQ	*166.9*	*273.9*
LPT	*256.1*	*265.9*
CR2	*166.9*	*273.9*

APPENDIX B:

This appendix contains source code of Simulator for Intervention time determination. This code is written in Unix C under SunOs workstation.

```
/**********************************************************************/
/*  This program is used for testing scheduling rule from HPF to LPF  */
/*  with one intervention on different intervention time basis and    */
/*  all cases (different a, b, c parameters) on a small model of      */
/*  FMS including one HUB (multipurpose workstation)                  */
/*                                                                    */
/*                    Designer: Yimin Mao                             */
/*                                                                    */
/*                        Feb.,  1994                                 */
/*                                                                    */
/**********************************************************************/

# include "stdio.h"
# include "math.h"

Definition of system parameters of signal hub network:
A: the processing time of jobs needed on WS1
B: the processing time of jobs needed on WS2
C: the processing time of jobs needed on WS1(revisiting)
T: the simulation time of the simulator

# define A 1
# define B 15
# define C 20
# define N 10
# define T N*(A+B+C)

Definition of the status of jobs and workstations:
job: not ready, ready, process(WS being occupied), finish(released).
workstation: idle, busy

# define not_ready 0
# define ready 1
# define process 2
# define finish 3

# define idle 8
# define busy 9

main()
{
  int i,j,n,t,h,time,time1,x,x1,x2,x3,x4;
```

```
  int a[T][6], b[T][6], c[T][6]; /* col 0: time
                             col 1: job#
                             col 2: job state
                                     col 3: queue size
                                     col 4: time pointer  */
  int time_a, time_b, time_c;   /*  time pointer counter  */
  int n_a, n_b, n_c;
  int que_a, que_b, que_c;      /*  queue size counter  */
  int flag_a, flag_b, flag_c;   /*  switching flags    */
  int idle_time, intv_time;
  float cmax, cbar, cbar_sum, fm, p;
  int ws1[T][2], ws2[T][2];     /*  col 0: time
                                    col 1: state of WS   */

  int para_a,para_b,para_c;

  for (para_a=1;para_a<=10;para_a+=1)  /*  for change of parameter A */
  {

  for (para_b=1;para_b<=10-para_a;para_b+=1)  /*  for change of parameter B */
  {

  para_c=10-(para_a+para_b);

  intv_time=0;

  if (((para_a+para_b+para_c)>10)||(para_c==0)) continue;
   /* for A+B+C <= 10 and C<>0  */

   printf("\n");
   printf("  The Simulation Report:\n");
   printf("  ======================\n");
   printf("      Notes: one intervention on one HUB FMS.\n");
   printf("\n");
   printf("  A=%4d,  B=%4d,  C=%4d,  N=%4d\n",para_a,para_b,para_c,N);
   printf("\n");

   case_recog_lpf(para_a,para_b,para_c);
   case_recog_hpf(para_a,para_b,para_c);

   printf("  Intervention      Cmax        Cbar          IDLE  \n");
   printf("    at time                                  time  \n");


while (intv_time<=T-N)  /* for one intervention looping  */
{

  for (i=0;i<=T-1;++i)          /* initialization of job */
  for (j=0;j<=4;++j)
    {  a[i][j]=0;
       b[i][j]=0;
       c[i][j]=0;  }
  for (i=0;i<=T-1;++i)     /* initialization of workstation */
```

```
  {  ws1[i][0]=0;
     ws1[i][1]=8;
     ws2[i][0]=0;
     ws2[i][1]=8; }

t=0;
time_a=0;  que_a=0; n_a=1, flag_a=1;
time_b=0;  que_b=0; n_b=0, flag_b=0;
time_c=0;  que_c=0; n_c=1, flag_c=0;

cmax=0;
cbar=0;
cbar_sum=0;
idle_time=0;

a[t][1]=0;
a[t][2]=ready;
a[t][3]=N;
a[t][4]=para_a;


while (t<=T-N) /* for one HUB looping  */
  {
     t=t+1;
     a[t][0]=b[t][0]=c[t][0]=t;   /* time demention   */
     ws1[t][0]=ws2[t][0]=t;
     ws1[t][1]=ws1[t-1][1];
     b[t][3]=que_b;
     c[t][3]=que_c;

         /* deal with job c  */
     if (flag_c==1)
       {
         time_c=time_c+1;
         flag_a=0;
         c[t][1]=n_c;
         c[t][2]=process;
         c[t][3]=que_c-1;
         c[t][4]=para_c-time_c;
         ws1[t][1]=busy;
         a[t][3]=a[t-1][3];
         if (c[t][4]==0)
           {
              time_c=0;
              n_c=n_c+1;
              que_c=que_c-1;
              c[t][2]=finish;
              ws1[t][1]=idle;
              flag_c=0;
           }
       }
    else
      {
        if ((flag_a==1)&&(n_a<=N))
```

```
          {
             time_a=time_a+1;
             a[t][1]=n_a;
             a[t][2]=process;
             a[t][3]=N-n_a;
             a[t][4]=para_a-time_a;
             ws1[t][1]=busy;
             if (a[t][4]==0)
               {
                 n_a=n_a+1;
                 a[t][2]=finish;
                 time_a=0;
                 ws1[t][1]=idle;
                 que_b=que_b+1;        /*  queue size of job b  */
                 b[t][3]=que_b;
               }
          }
     }
if (b[t][0]<para_a)   continue;    /*  control the beginning period of b  */

x=(para_a>=para_b? 1: 2) ;
switch (x)
  { case 1:
    {
       if ((ws2[t][1]==idle)&&(b[t][3]!=0))
          {
            n_b=n_b+1;
            b[t][2]=ready;
            ws2[t+1][1]=busy;
            b[t][3]=que_b;
            b[t][4]=para_b-time_b;
            que_b=que_b-1;
          }
      else
          {
             if (b[t-1][4]!=0)
               {
                  time_b=time_b+1;
                  b[t][1]=n_b;
                  b[t][2]=process;
                  b[t][3]=que_b;
                  b[t][4]=para_b-time_b;
                  ws2[t+1][1]=busy;
               }
          }
   if ((b[t][4]==0)&&(b[t-1][4]!=0))
       {
         b[t][1]=n_b;
         b[t][2]=finish;
         time_b=0;
         ws2[t+1][1]=idle;
         que_c=que_c+1;        /*  queue size of job c  */
         c[t][3]=que_c;
       }
```

```
    }; break;  /*  get out of "switch statement", important!  */
case 2:     /*    a<b    */
    {
       if ((ws2[t][1]==idle)&&(b[t][3]!=0))
         {
            n_b=n_b+1;
            ws2[t+1][1]=busy;
            b[t][3]=que_b;
            b[t][4]=para_b-time_b;
         }
      else
         {
            if (b[t-1][4]!=0)
               {
                  time_b=time_b+1;
                  b[t][1]=n_b;
                  b[t][2]=process;
                  b[t][3]=que_b-1;
                  b[t][4]=para_b-time_b;
                  ws2[t+1][1]=busy;
               }
          }
   if ((b[t][4]==0)&&(b[t-1][4]!=0))
       {
         b[t][1]=n_b;
         b[t][2]=finish;
         time_b=0;
         que_b=que_b-1;
         ws2[t+1][1]=idle;
         que_c=que_c+1;       /*  queue size of job c  */
         c[t][3]=que_c;
       }
        if ((ws2[t+1][1]==idle)&&(b[t][3]!=0))
          {
             n_b=n_b+1;
             ws2[t+1][1]=busy;
             b[t][3]=que_b;
             b[t][4]=para_b-time_b;
           }
     }
    }

 /*   testing intervention time  */

     if ((t<=intv_time)||(a[t][3]==0))  /* test for LPF  */
     if ((c[t][3]!=0)&&(ws1[t][1]==idle))  flag_c=1;
     if (flag_c==0)  flag_a=1;

  }  /*  end of one HUB looping  */


  /*  for output  */
```

```
  for (t=0;t<=T-1;++t)    /* calculate Cbar and Cmax  */
  {
    if (c[t][2]==finish)  cbar_sum=cbar_sum+t;
    if ((c[t][1]==N)&&(c[t][2]==finish))  cmax=t;
    if ((b[t][1]!=0)&&(a[t][1]==0)&&(c[t][1]==0))
         idle_time=idle_time+1;
  }

/* for intervention printing  */

   printf("%8d%18.2f%12.2f%12d\n",intv_time,cmax,cbar_sum/N,idle_time);

   if (intv_time>cmax)  break;

   intv_time=intv_time+5;

}  /* end of intervention looping  */

   printf("\n");
     printf("   =========  stop  ============\n");
   printf("\n");
   printf("\n");

}   /*  for change of parameter B */
}   /*  for change of parameter A */


}  /*  end of main  */


case_recog_lpf(para_a,para_b,para_c)
int para_a,para_b,para_c;
{
   int a,b,c,n;

   a=para_a;
   b=para_b;
   c=para_c;
   n=N;

   if ((a>=b)&&(b>=(n-1)*c))
     printf("  Now we are in:  CASE 4 (LPF) -- a dominant\n ");

   if ((c>=b)&&(b>=(n-1)*a))
     printf("  Now we are in:  CASE 3 (LPF) -- c dominant\n ");

   if ((b>a)&&(b>c)&&(b>(n-1)*(a+c)/n))
     printf("  Now we are in:  CASE 2 (LPF) -- b dominant\n ");

   if ((b<=(n-1)*a)&&(b<=(n-1)*c)&&(b<=(n-1)*(a+c)/n))
     printf("  Now we are in:  CASE 1 (LPF) -- b dominated\n ");

     printf("\n");
```

```
}


case_recog_hpf(para_a,para_b,para_c)
int para_a,para_b,para_c;
{
   int a,b,c,n;

   a=para_a;
   b=para_b;
   c=para_c;
   n=N;

   if ((c>=b)&&(b>=(n-1)*a))
     printf("  Now we are in:  CASE 6 (HPF) -- c dominant\n ");

   if ((b>=(n-1)*a)&&(b>c))
     printf("  Now we are in:  CASE 5 (HPF) -- b dominant\n ");

   if ((a>=b)&&(b>c))
     printf("  Now we are in:  CASE 4 (HPF) -- a dominant\n ");

   if ((b<(n-1)*a)&&(b>=(a+c)))
     printf("  Now we are in:  CASE 3 (HPF) -- b cycles\n ");

   if ((b<(n-1)*a)&&(b>c)&&(b<(a+c))&&(b>=a))
     printf("  Now we are in:  CASE 2 (HPF) -- b determinant\n ");

   if ((b<=(n-1)*a)&&(b<=c))
     printf("  Now we are in:  CASE 1 (HPF) -- b dominated \n ");

     printf("\n");


 }
```

APPENDIX C:

This appendix contains simulation reports for the three hub network presented in Chapter 4, Table 21, example #3.

C.1 Reports of emulating single hub model for the hree hub network Example #3 (Table 22)

The Simulation Report.1: (hub 1 heuristic analysis)

```
A=   1,  B=   5,  C=   6,  N=  10

  in:CASE 1 (HPF)-- b dominated
  in:CASE 1 (LPF)-- b dominated

  Intervention        Cmax        Cbar          IDLE
    at time                                     time
0            70.00        43.00            0
       5            70.00       43.00         0
      10            70.00       42.60         0
      15            70.00       42.20         0
      20            70.00       41.80         0
      25            70.00       41.40         0
      30            70.00       41.00         0
      35            70.00       41.00         0
      40            72.00       41.40         2
      45            72.00       41.40         2
      50            72.00       41.40         2
      55            72.00       41.40         2
      60            72.00       41.40         2
      65            72.00       41.40         2
      70            72.00       41.40         2
      75            72.00       41.40         2
```

The Simulation Report.2: (hub 2 heuristic analysis)

```
  A=   2,  B=   9,  C=  10,  N=  10

  in:CASE 1 (HPF)-- b dominated
  in:CASE 1 (LPF)-- b dominated

  Intervention        Cmax        Cbar          IDLE
    at time                                     time
       0           120.00       75.00         0
       5           120.00       75.00         0
      10           120.00       75.00         0
      15           120.00       74.20         0
```

```
  20           120.00      74.20       0
  25           120.00      73.40       0
  30           120.00      73.40       0
  35           120.00      72.60       0
  40           120.00      72.60       0
  45           120.00      71.80       0
  50           120.00      71.80       0
  55           120.00      71.00       0
  60           120.00      71.00       0
  65           123.00      71.40       3
  70           123.00      71.40       3
  75           123.00      71.40       3
  80           123.00      71.40       3
  85           123.00      71.40       3
  90           123.00      71.40       3
  95           123.00      71.40       3
 100           123.00      71.40       3
 105           123.00      71.40       3
 110           123.00      71.40       3
 115           123.00      71.40       3
 120           123.00      71.40       3
 125           123.00      71.40       3
```

The Simulation Report.3: (hub 3 heuristic analysis)

```
A=   3,  B=  16,  C=  18,  N=  10

in:CASE 1 (HPF)-- b dominated
in:CASE 1 (LPF)-- b dominated

Intervention       Cmax        Cbar          IDLE
  at time                                    time
     0            210.00      129.00          0
     5            210.00      129.00          0
    10            210.00      129.00          0
    15            210.00      129.00          0
    20            210.00      129.00          0
    25            210.00      128.10          0
    30            210.00      128.10          0
    35            210.00      128.10          0
    40            210.00      127.20          0
    45            210.00      127.20          0
    50            210.00      127.20          0
    55            210.00      127.20          0
    60            210.00      126.30          0
    65            210.00      126.30          0
    70            210.00      126.30          0
    75            210.00      125.40          0
    80            210.00      125.40          0
    85            210.00      125.40          0
    90            210.00      125.40          0
```

95	210.00	124.50	0
100	210.00	124.50	0
105	210.00	124.50	0
110	210.00	124.50	0
115	210.00	123.60	0
120	210.00	123.60	0
125	210.00	123.60	0
130	220.00	125.70	10
135	220.00	125.70	10
140	220.00	125.70	10
145	220.00	125.70	10
150	220.00	125.70	10
155	220.00	125.70	10
160	220.00	125.70	10
165	220.00	125.70	10
170	220.00	125.70	10
175	220.00	125.70	10
180	220.00	125.70	10
185	220.00	125.70	10
190	220.00	125.70	10
195	220.00	125.70	10
200	220.00	125.70	10
205	220.00	125.70	10
210	220.00	125.70	10
215	220.00	125.70	10
220	220.00	125.70	10
225	220.00	125.70	10

C. 2 SLAM reports of pure HPF and LPF scheduling rules

Pure HPF rule report for the example of Table 13

```
0   ***   SLAM INPUT DATA SUPPLIED BY USER   ***
 NO INPUT DATA WILL BE STORED

 INPUT DATA WILL BE READ FROM LOGICAL UNIT 31

 DATA ACCEPTED:
   SIMULATION WILL END AT TIME  200.000

 DATA ACCEPTED:
    # OF WORK STATIONS =   3
    # OF PROCESSES =  6
    # OF PRODUCTS =  1

 ***   PRODUCT INFORMATION   ***

 DATA ACCEPTED FOR PRODUCT  1
    # OF PROCESS STEPS = 6
    SEQUENCE OF PROCESSES:  1  2  3  4  5  6
    LOT SIZE =  1
    NUMBER OF LOTS =     10
    TIME OF FIRST CREATE = 0.000
    TIME BETWEEN CREATES = 0.010

 ***   PROCESS INFORMATION   ***

 DATA ACCEPTED FOR PROCESS  1
    WORK STATION = 1
    PROCESS TIME =   1.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  2
    WORK STATION = 2
    PROCESS TIME =   2.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  3
    WORK STATION = 3
    PROCESS TIME =   1.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  4
    WORK STATION = 1
    PROCESS TIME =   4.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  5
    WORK STATION = 2
    PROCESS TIME =   5.000
```

```
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS  6
   WORK STATION = 3
   PROCESS TIME =    3.000
   PERCENTAGE OF YIELD = 100.000%

***   WORK STATION INFORMATION   ***

DATA ACCEPTED FOR WORK STATION  1
  QUEUING PRIORITY RULE = HIGHSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:   MEAN= 200.000    STD DEV=   0.000
  DOWN TIME: MEAN=   0.000    STD DEV=   0.000

DATA ACCEPTED FOR WORK STATION  2
  QUEUING PRIORITY RULE = HIGHSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:   MEAN= 200.000    STD DEV=   0.000
  DOWN TIME: MEAN=   0.000    STD DEV=   0.000

DATA ACCEPTED FOR WORK STATION  3
  QUEUING PRIORITY RULE = HIGHSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:   MEAN= 200.000    STD DEV=   0.000
  DOWN TIME: MEAN=   0.000    STD DEV=   0.000

***   SYSTEM INTERVENTION INFORMATION   ***

DATA ACCEPTED:
  NUMBER OF INTERVENTIONS =  19
  TYPE OF INTERVENTION    = TIME
```

```
1
                                         S L A M   I I   S U M M A R Y   R E P O R T

                                SIMULATION PROJECT SLAM WITH FRONTEND        BY YIMIN

                                DATE 12/ 5/1994                              RUN NUMBER    1 OF     1

                                CURRENT TIME   0.2000E+03
                                STATISTICAL ARRAYS CLEARED AT TIME  0.0000E+00


                                **STATISTICS FOR VARIABLES BASED ON OBSERVATION**

                         MEAN          STANDARD      COEFF. OF     MINIMUM       MAXIMUM       NUMBER OF
                         VALUE         DEVIATION     VARIATION     VALUE         VALUE         OBSERVATIONS

CYCLE TIME PRD 1    0.4586E+02    0.2111E+02    0.4603E+00    0.1700E+02    0.7791E+02         10
PROC TIME PRD 1     0.1001E+03    0.4338E+02    0.4334E+00    0.3600E+02    0.1600E+03         10
CYCLE TIME PRD 2                      NO VALUES RECORDED
PROC TIME PRD 2                       NO VALUES RECORDED
CYCLE TIME PRD 3                      NO VALUES RECORDED
PROC TIME PRD 3                       NO VALUES RECORDED
CYCLE TIME PRD 4                      NO VALUES RECORDED
PROC TIME PRD 4                       NO VALUES RECORDED
CYCLE TIME PRD 5                      NO VALUES RECORDED
PROC TIME PRD 5                       NO VALUES RECORDED
CYCLE TIME          0.4586E+02    0.2111E+02    0.4603E+00    0.1700E+02    0.7791E+02         10
```

Pure LPF scheduling rule report for the example of Table 13

```
0   ***   SLAM INPUT DATA SUPPLIED BY USER   ***
 NO INPUT DATA WILL BE STORED

 INPUT DATA WILL BE READ FROM LOGICAL UNIT 32

 DATA ACCEPTED:
   SIMULATION WILL END AT TIME  200.000

 DATA ACCEPTED:
    # OF WORK STATIONS =    3
    # OF PROCESSES =  6
    # OF PRODUCTS =  1

 ***   PRODUCT INFORMATION   ***

 DATA ACCEPTED FOR PRODUCT  1
    # OF PROCESS STEPS = 6
    SEQUENCE OF PROCESSES:  1  2  3  4  5  6
    LOT SIZE =  1
 .  NUMBER OF LOTS =      10
    TIME OF FIRST CREATE = 0.000
    TIME BETWEEN CREATES = 0.010

 ***   PROCESS INFORMATION   ***

 DATA ACCEPTED FOR PROCESS  1
    WORK STATION = 1
    PROCESS TIME =   1.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  2
    WORK STATION = 2
    PROCESS TIME =   2.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  3
    WORK STATION = 3
    PROCESS TIME =   1.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  4
    WORK STATION = 1
    PROCESS TIME =   4.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  5
    WORK STATION = 2
    PROCESS TIME =   5.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  6
```

```
   WORK STATION = 3
   PROCESS TIME =    3.000
   PERCENTAGE OF YIELD = 100.000%

***   WORK STATION INFORMATION   ***

DATA ACCEPTED FOR WORK STATION  1
  QUEUING PRIORITY RULE = LOWSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:    MEAN= 200.000    STD DEV=   0.000
  DOWN TIME: MEAN=    0.000    STD DEV=   0.000

DATA ACCEPTED FOR WORK STATION  2
  QUEUING PRIORITY RULE = LOWSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:    MEAN= 200.000    STD DEV=   0.000
  DOWN TIME: MEAN=    0.000    STD DEV=   0.000

DATA ACCEPTED FOR WORK STATION  3
  QUEUING PRIORITY RULE = LOWSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:    MEAN= 200.000    STD DEV=   0.000
  DOWN TIME: MEAN=    0.000    STD DEV=   0.000

***   SYSTEM INTERVENTION INFORMATION   ***

DATA ACCEPTED:
  NUMBER OF INTERVENTIONS =  19
  TYPE OF INTERVENTION    = TIME
```

```
1
                                     S L A M   I I   S U M M A R Y   R E P O R T


                            SIMULATION PROJECT SLAM WITH FRONTEND        BY YIMIN

                            DATE 17/ 5/1989                              RUN NUMBER    1 OF    1


                            CURRENT TIME   0.2000E+03
                            STATISTICAL ARRAYS CLEARED AT TIME  0.0000E+00


                            **STATISTICS FOR VARIABLES BASED ON OBSERVATION**

                      MEAN          STANDARD      COEFF. OF     MINIMUM       MAXIMUM       NUMBER OF
                      VALUE         DEVIATION     VARIATION     VALUE         VALUE         OBSERVATIONS

CYCLE TIME PRD 1   0.5145E+02    0.1511E+02    0.2936E+00    0.2900E+02    0.7391E+02        10
PROC TIME PRD 1    0.1176E+03    0.3207E+02    0.2727E+00    0.6400E+02    0.1600E+03        10
CYCLE TIME PRD 2                     NO VALUES RECORDED
PROC TIME PRD 2                      NO VALUES RECORDED
CYCLE TIME PRD 3                     NO VALUES RECORDED
PROC TIME PRD 3                      NO VALUES RECORDED
CYCLE TIME PRD 4                     NO VALUES RECORDED
PROC TIME PRD 4                      NO VALUES RECORDED
CYCLE TIME PRD 5                     NO VALUES RECORDED
PROC TIME PRD 5                      NO VALUES RECORDED
CYCLE TIME         0.5145E+02    0.1511E+02    0.2936E+00    0.2900E+02    0.7391E+02        10
```

APPENDIX D:

D. 1. simulation report of emulating single hub model for five hub network (Table 25)

The Simulation Report.1: (hub 1 heuristic analysis)

```
A=   1,  B=   6,  C=   6,  N=  25

in:CASE 1 (HPF)-- b dominated
in:CASE 1 (LPF)-- b dominated


Intervention       Cmax        Cbar          IDLE
  at time                                    time
     0            175.00      103.00          0
     5            175.00      103.00          0
    10            175.00      102.28          0
    15            175.00      101.56          0
    20            175.00      100.84          0
    25            175.00      100.12          0
    30            175.00      100.12          0
    35            175.00       99.40          0
    40            175.00       98.68          0
    45            175.00       97.96          0
    50            175.00       97.96          0
    55            175.00       97.96          0
    60            175.00       97.52          0
    65            175.00       97.08          0
    70            175.00       96.64          0
    75            175.00       96.20          0
    80            175.00       95.76          0
    85            175.00       95.76          0
    90            175.00       95.32          0
    95            175.00       94.88          0
   100            175.00       94.88          0
   105            175.00       94.72          0
   110            175.00       94.72          0
   115            175.00       94.56          0
   120            175.00       94.40          0
   125            175.00       94.24          0
   130            175.00       94.08          0
   135            175.00       93.92          0
   140            175.00       93.92          0
   145            178.00       94.24          3
   150            178.00       94.24          3
   155            178.00       94.24          3
   160            178.00       94.24          3
```

```
   165             178.00        94.24          3
   170             178.00        94.24          3
   175             178.00        94.24          3
   180             178.00        94.24          3
```

The Simulation Report.2: (hub 2 heuristic analysis)

```
A=   2,  B=  10,  C=  10,  N=  25

in:CASE 1 (HPF)-- b dominated
in:CASE 1 (LPF)-- b dominated


Intervention        Cmax          Cbar          IDLE
  at time                                       time
     0             300.00        180.00          0
    10             300.00        180.00          0
    50             300.00        173.92          0
   100             300.00        168.80          0
   150             300.00        164.64          0
   155             300.00        164.64          0
   160             300.00        164.08          0
   165             300.00        164.08          0
   170             300.00        163.52          0
   175             300.00        163.52          0
   180             300.00        162.96          0
   185             300.00        162.96          0
   190             300.00        162.40          0
   195             300.00        162.40          0
   200             300.00        161.84          0
   205             300.00        161.84          0
   210             300.00        161.28          0
   215             300.00        161.28          0
   220             300.00        161.28          0
   225             300.00        161.28          0
   230             300.00        161.20          0
   235             300.00        161.20          0
   240             300.00        161.12          0
   245             300.00        161.12          0
   250             300.00        161.04          0
   255             300.00        161.04          0
   260             300.00        160.96          0
   265             300.00        160.96          0
   270             300.00        160.88          0
   275             300.00        160.88          0
   280             310.00        161.20         10
   285             310.00        161.20         10
   290             310.00        161.20         10
   295             310.00        161.20         10
   300             310.00        161.20         10
   305             310.00        161.20         10
   310             310.00        161.20         10
   315             310.00        161.20         10
```

The Simulation Report.3: (hub 3 heuristic analysis)

```
A=   1,  B=  19,  C=   1,  N=  25

in:CASE 3 (HPF)-- b cycles
in:CASE 2 (LPF)-- b dominant


Intervention       Cmax        Cbar          IDLE
  at time                                    time
    0            477.00      249.20         427
   10            477.00      249.20         427
   15            477.00      249.20         427
   20            477.00      249.00         427
   50            477.00      249.00         427
  100            477.00      249.00         427
  150            477.00      249.00         427
  180            477.00      249.00         427
  200            477.00      249.00         427
  220            477.00      249.00         427
  240            477.00      249.00         427
  260            477.00      249.00         427
  280            477.00      249.00         427
  300            477.00      249.00         427
  320            477.00      249.00         427
  340            477.00      249.00         427
  360            477.00      249.00         427
  380            477.00      249.00         427
  385            477.00      249.00         427
  390            477.00      249.00         427
  395            477.00      249.00         427
  400            477.00      249.00         427
  405            477.00      249.00         427
  410            477.00      249.00         427
  415            477.00      249.00         427
  420            477.00      249.00         427
  425            477.00      249.00         427
  430            477.00      249.00         427
  435            477.00      249.00         427
  440            477.00      249.00         427
  445            477.00      249.00         427
  450            477.00      249.00         427
  455            477.00      249.00         427
  460            477.00      249.00         427
  465            477.00      249.00         427
  470            477.00      249.00         427
```

```
      475             477.00       249.00         427
      480             477.00       249.00         427
```

The Simulation Report.4: (hub 4 heuristic analysis)

```
A=   2,  B=  18,  C=  18,  N=  25

  in:CASE 1 (HPF)-- b dominated
  in:CASE 1 (LPF)-- b dominated


  Intervention        Cmax        Cbar          IDLE
    at time                                     time
       0             500.00      284.00          0
      10             500.00      284.00          0
      50             500.00      281.60          0
     100             500.00      278.00          0
     150             500.00      274.40          0
     200             500.00      272.00          0
     250             500.00      271.20          0
     300             500.00      270.00          0
     305             500.00      270.00          0
     310             500.00      269.60          0
     315             500.00      269.60          0
     320             500.00      269.60          0
     325             500.00      269.60          0
     330             500.00      269.20          0
     335             500.00      269.20          0
     340             500.00      269.20          0
     345             500.00      269.20          0
     350             500.00      268.80          0
     355             500.00      268.80          0
     360             500.00      268.80          0
     365             500.00      268.40          0
     370             500.00      268.40          0
     375             500.00      268.40          0
     380             500.00      268.40          0
     385             510.00      270.00         10
     390             510.00      270.00         10
     395             510.00      270.00         10
     400             510.00      270.00         10
     420             510.00      270.00         10
     440             510.00      270.00         10
     460             510.00      270.00         10
     480             510.00      270.00         10
     485             510.00      270.00         10
     490             510.00      270.00         10
     495             510.00      270.00         10
```

```
   500              510.00         270.00          10
   505              510.00         270.00          10
   510              510.00         270.00          10
   515              510.00         270.00          10
```

The Simulation Report.5: (hub 5 heuristic analysis)

```
  A=   1,  B=  35,  C=   5,  N=  25

  in:CASE 5 (HPF)-- b dominant
  in:CASE 2 (LPF)-- b dominant


  Intervention      Cmax         Cbar          IDLE
    at time                                    time
       0          881.00       461.00          731
      10          881.00       461.00          731
      50          881.00       461.00          731
     100          881.00       461.00          731
     150          881.00       461.00          731
     200          881.00       461.00          731
     250          881.00       461.00          731
     300          881.00       461.00          731
     350          881.00       461.00          731
     400          881.00       461.00          731
     450          881.00       461.00          731
     500          881.00       461.00          731
     550          881.00       461.00          731
     600          881.00       461.00          731
     650          881.00       461.00          731
     700          881.00       461.00          731
     750          881.00       461.00          731
     800          881.00       461.00          731
     805          881.00       461.00          731
     810          881.00       461.00          731
     815          881.00       461.00          731
     820          881.00       461.00          731
     825          881.00       461.00          731
     830          881.00       461.00          731
     835          881.00       461.00          731
     840          881.00       461.00          731
     845          881.00       461.00          731
     850          881.00       461.00          731
     855          881.00       461.00          731
     860          881.00       461.00          731
     865          881.00       461.00          731
     870          881.00       461.00          731
     875          881.00       461.00          731
     880          881.00       461.00          731
     885          881.00       461.00          731
```

D. 2 SLAM reports of pure HPF and LPF

Pure HPF scheduling rule report for the example of Table 25

```
1
1                                                   **INTERMEDIATE RESULTS**


0   ***   SLAM INPUT DATA SUPPLIED BY USER   ***
 NO INPUT DATA WILL BE STORED

 INPUT DATA WILL BE READ FROM LOGICAL UNIT 51

 DATA ACCEPTED:
   SIMULATION WILL END AT TIME 1000.000

 DATA ACCEPTED:
    # OF WORK STATIONS =    5
    # OF PROCESSES = 10
    # OF PRODUCTS =  1

 ***   PRODUCT INFORMATION   ***

 DATA ACCEPTED FOR PRODUCT  1
    # OF PROCESS STEPS =10
    SEQUENCE OF PROCESSES:  1  2  3  4  5  6  7  8  9 10
    LOT SIZE =  1
    NUMBER OF LOTS =     25
    TIME OF FIRST CREATE = 0.000
    TIME BETWEEN CREATES = 0.010

 ***   PROCESS INFORMATION   ***

 DATA ACCEPTED FOR PROCESS  1
    WORK STATION = 1
    PROCESS TIME =   1.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  2
    WORK STATION = 2
    PROCESS TIME =   2.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  3
    WORK STATION = 3
    PROCESS TIME =   1.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  4
    WORK STATION = 4
    PROCESS TIME =   2.000
```

```
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS  5
   WORK STATION = 5
   PROCESS TIME =   1.000
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS  6
   WORK STATION = 1
   PROCESS TIME =   6.000
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS  7
   WORK STATION = 2
   PROCESS TIME =  10.000
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS  8
   WORK STATION = 3
   PROCESS TIME =   1.000
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS  9
   WORK STATION = 4
   PROCESS TIME =  18.000
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS 10
   WORK STATION = 5
   PROCESS TIME =   5.000
   PERCENTAGE OF YIELD = 100.000%

***   WORK STATION INFORMATION   ***

DATA ACCEPTED FOR WORK STATION  1
  QUEUING PRIORITY RULE = HIGHSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:    MEAN=1000.000    STD DEV=    0.000
  DOWN TIME: MEAN=    0.000    STD DEV=    0.000

DATA ACCEPTED FOR WORK STATION  2
  QUEUING PRIORITY RULE = HIGHSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:    MEAN=1000.000    STD DEV=    0.000
  DOWN TIME: MEAN=    0.000    STD DEV=    0.000

DATA ACCEPTED FOR WORK STATION  3
  QUEUING PRIORITY RULE = HIGHSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
```

```
  MAXIMUM LOAD =      1
  UP TIME:    MEAN=1000.000    STD DEV=    0.000
  DOWN TIME: MEAN=    0.000    STD DEV=    0.000

DATA ACCEPTED FOR WORK STATION  4
  QUEUING PRIORITY RULE = HIGHSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:    MEAN=1000.000    STD DEV=    0.000
  DOWN TIME: MEAN=    0.000    STD DEV=    0.000

DATA ACCEPTED FOR WORK STATION  5
  QUEUING PRIORITY RULE = HIGHSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:    MEAN=1000.000    STD DEV=    0.000
  DOWN TIME: MEAN=    0.000    STD DEV=    0.000

***   SYSTEM INTERVENTION INFORMATION    ***

DATA ACCEPTED:
  NUMBER OF INTERVENTIONS =    9
  TYPE OF INTERVENTION    = TIME
```

```
1
                                   S L A M   I I   S U M M A R Y   R E P O R T

                           SIMULATION PROJECT SLAM WITH FRONTEND         BY YIMIN

                           DATE 17/ 5/1989                               RUN NUMBER    1 OF    1

                           CURRENT TIME   0.1000E+04
                           STATISTICAL ARRAYS CLEARED AT TIME  0.0000E+00


                           **STATISTICS FOR VARIABLES BASED ON OBSERVATION**

                      MEAN         STANDARD      COEFF. OF     MINIMUM       MAXIMUM       NUMBER OF
                      VALUE        DEVIATION     VARIATION     VALUE         VALUE         OBSERVATIONS

 CYCLE TIME PRD 1   0.2876E+03    0.1485E+03    0.5164E+00    0.4700E+02    0.5258E+03        25
 PROC TIME PRD 1    0.7145E+03    0.3213E+03    0.4497E+00    0.1380E+03    0.1175E+04        25
 CYCLE TIME PRD 2                     NO VALUES RECORDED
 PROC TIME PRD 2                      NO VALUES RECORDED
 CYCLE TIME PRD 3                     NO VALUES RECORDED
 PROC TIME PRD 3                      NO VALUES RECORDED
 CYCLE TIME PRD 4                     NO VALUES RECORDED
 PROC TIME PRD 4                      NO VALUES RECORDED
 CYCLE TIME PRD 5                     NO VALUES RECORDED
 PROC TIME PRD 5                      NO VALUES RECORDED
 CYCLE TIME         0.2876E+03    0.1485E+03    0.5164E+00    0.4700E+02    0.5258E+03        25
```

Pure LPF scheduling rule report for the example of Table 25

```
1                                                        **INTERMEDIATE RESULTS**
0   ***   SLAM INPUT DATA SUPPLIED BY USER   ***
 NO INPUT DATA WILL BE STORED

 INPUT DATA WILL BE READ FROM LOGICAL UNIT 51

 DATA ACCEPTED:
   SIMULATION WILL END AT TIME 1000.000

 DATA ACCEPTED:
    # OF WORK STATIONS =   5
    # OF PROCESSES = 10
    # OF PRODUCTS =  1

 ***   PRODUCT INFORMATION   ***

 DATA ACCEPTED FOR PRODUCT  1
    # OF PROCESS STEPS =10
    SEQUENCE OF PROCESSES:  1  2  3  4  5  6  7  8  9 10
    LOT SIZE =  1
    NUMBER OF LOTS =     25
    TIME OF FIRST CREATE = 0.000
    TIME BETWEEN CREATES = 0.010

 ***   PROCESS INFORMATION   ***

 DATA ACCEPTED FOR PROCESS  1
    WORK STATION = 1
    PROCESS TIME =   1.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  2
    WORK STATION = 2
    PROCESS TIME =   2.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  3
    WORK STATION = 3
    PROCESS TIME =   1.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  4
    WORK STATION = 4
    PROCESS TIME =   2.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  5
    WORK STATION = 5
    PROCESS TIME =   1.000
    PERCENTAGE OF YIELD = 100.000%

 DATA ACCEPTED FOR PROCESS  6
```

```
   WORK STATION = 1
   PROCESS TIME =   6.000
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS  7
   WORK STATION = 2
   PROCESS TIME =  10.000
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS  8
   WORK STATION = 3
   PROCESS TIME =   1.000
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS  9
   WORK STATION = 4
   PROCESS TIME =  18.000
   PERCENTAGE OF YIELD = 100.000%

DATA ACCEPTED FOR PROCESS 10
   WORK STATION = 5
   PROCESS TIME =   5.000
   PERCENTAGE OF YIELD = 100.000%

***   WORK STATION INFORMATION   ***

DATA ACCEPTED FOR WORK STATION  1
  QUEUING PRIORITY RULE = LOWSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:   MEAN=1000.000    STD DEV=    0.000
  DOWN TIME: MEAN=    0.000    STD DEV=    0.000

DATA ACCEPTED FOR WORK STATION  2
  QUEUING PRIORITY RULE = LOWSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:   MEAN=1000.000    STD DEV=    0.000
  DOWN TIME: MEAN=    0.000    STD DEV=    0.000

DATA ACCEPTED FOR WORK STATION  3
  QUEUING PRIORITY RULE = LOWSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =      1
  UP TIME:   MEAN=1000.000    STD DEV=    0.000
  DOWN TIME: MEAN=    0.000    STD DEV=    0.000

DATA ACCEPTED FOR WORK STATION  4
  QUEUING PRIORITY RULE = LOWSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
```

```
  MAXIMUM LOAD =       1
  UP TIME:    MEAN=1000.000     STD DEV=    0.000
  DOWN TIME: MEAN=    0.000     STD DEV=    0.000

DATA ACCEPTED FOR WORK STATION  5
  QUEUING PRIORITY RULE = LOWSTEP
  # OF PARALLEL MACHINES = 1
  SET UP TIME =     0.000
  MAXIMUM LOAD =       1
  UP TIME:    MEAN=1000.000     STD DEV=    0.000
  DOWN TIME: MEAN=    0.000     STD DEV=    0.000

***   SYSTEM INTERVENTION INFORMATION   ***

DATA ACCEPTED:
  NUMBER OF INTERVENTIONS =    9
  TYPE OF INTERVENTION     = TIME
```

```
                                   S L A M   I I   S U M M A R Y   R E P O R T

                              SIMULATION PROJECT SLAM WITH FRONTEND        BY YIMIN

                              DATE 17/ 5/1989                              RUN NUMBER    1 OF    1

                              CURRENT TIME   0.1000E+04
                              STATISTICAL ARRAYS CLEARED AT TIME  0.0000E+00


                              **STATISTICS FOR VARIABLES BASED ON OBSERVATION**

                        MEAN         STANDARD      COEFF. OF     MINIMUM       MAXIMUM      NUMBER OF
                        VALUE        DEVIATION     VARIATION     VALUE         VALUE        OBSERVATIONS

CYCLE TIME PRD 1   0.3009E+03     0.1324E+03    0.4401E+00    0.8500E+02    0.5168E+03         25
PROC TIME PRD 1    0.8243E+03     0.2654E+03    0.3220E+00    0.2910E+03    0.1175E+04         25
CYCLE TIME PRD 2                       NO VALUES RECORDED
PROC TIME PRD 2                        NO VALUES RECORDED
CYCLE TIME PRD 3                       NO VALUES RECORDED
PROC TIME PRD 3                        NO VALUES RECORDED
CYCLE TIME PRD 4                       NO VALUES RECORDED
PROC TIME PRD 4                        NO VALUES RECORDED
CYCLE TIME PRD 5                       NO VALUES RECORDED
PROC TIME PRD 5                        NO VALUES RECORDED
CYCLE TIME         0.3009E+03     0.1324E+03    0.4401E+00    0.8500E+02    0.5168E+03         25
```