

AN INVESTIGATION OF THE EFFECTS OF ROUTING
FLEXIBILITY FOR A MULTI-STAGE
JUST-IN-TIME SYSTEM

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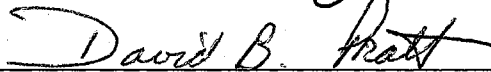
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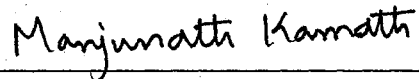
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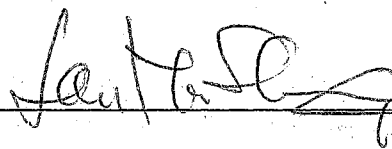


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CHAPTER I

INTRODUCTION

Routing Flexibility in Manufacturing Systems

Customer satisfaction has become the most important issue in today's global market. As customers favor more diversified products and services, companies are now trying to manage their production more efficiently in order to meet customers' demands. The high degree of variety in customers' demands outdates mass production that was used in the past to produce the same type of products in large volume. In order to provide low to medium production volume and higher product variety, new manufacturing technologies and philosophies need to be developed. The emergence of new technologies highlight the concept of manufacturing flexibility in the design, operation, and management of manufacturing systems [Sethi and Sethi, 1990]. As a result, manufacturing flexibility has become an important aspect, along with quality, service and cost, in strategic planning [Clark *et al.*, 1988].

Although flexibility has drawn attention from researchers, defining it is not an easy task. According to a survey [Sethi and Sethi, 1990], there are at least 50 different terms for various types of flexibility found in the manufacturing literature. Definitions for these terms are not always appropriate and are sometimes inconsistent with one another. The limited knowledge of flexibility has created a lot of problems for the management of flexibility [Benjaafar and Ramakrishnan, 1993]. Moreover, the lack of appropriate

methodologies for quantifying flexibility enhances the difficulty of justifying the implementation of flexible technologies [Benjaafar and Ramakrishnan, 1993].

Routing flexibility is defined by Sethi and Sethi [1990] as "*the ability to produce a part by alternate routes through the system.*" These alternate routes are created by the use of different machines, different operations, or different sequences of operations. The flexibility of routing can be found in systems implementing general-purpose machines [Sethi and Sethi, 1990], alternative or identical machines [Yao and Pei, 1990], redundant machine tools [Browne *et al.*, 1984], or the versatility of material handling systems [Sethi and Sethi, 1990].

The purposes of routing flexibility can be identified as follows.

1. To schedule parts more efficiently by better balancing machine loads [Sethi and Sethi, 1990].
2. To continue producing a given set of part types when unanticipated events such as machine breakdowns [Browne *et al.*, 1984], late receipt of machine tooling, a preemptive order of parts, or the discovery of defective parts occur [Sethi and Sethi, 1990].
3. To improve the productivity of a machine shop [Nasr and Elsayed, 1990].

A substantial amount of literature dealing with routing flexibility has primarily been devoted to Flexible Manufacturing Systems (FMS). A flexible manufacturing system is an advanced manufacturing system that consists of automated machines linked by a material handling system which are all under central computer control [Buzacott and Shanthikumar, 1980]. FMSs possess characteristics of both flow shops and job shops. Fixed sequence flow shops are capable of performing large volume production, and usually result in higher machine utilization and shorter lead times [Ro and Kim, 1990]. On the other hand, job shops are utilized to manufacture a variety of products in small volumes. As a result, job shops are likely to incur lower machine utilization, longer lead

times and higher in-process inventories [Ro and Kim, 1990]. Integrated FMSs are designed to combine the efficiency of flow shops with the flexibility of job shops.

Operational measures of routing flexibility have been developed by a number of researchers. The most used measure is based on the number of available routes through which a part type can be processed in a given manufacturing system [Chung and Chen, 1989] [Bernardo and Mohamed, 1992]. Nevertheless, these measures always focus on counting the total number of routes while ignoring the effect of overloading some machines. As a result, systems that have bottleneck machines are as flexible as those not having a bottleneck as long as the numbers of available routes are identical. Therefore, the term “flexibility” becomes self-contradicted.

Entropy types of measures are also used to measure the uncertainty of alternative routings in a number of studies [Kumar, 1987] [Yao and Pei, 1990]. Entropy is a measure used to measure the uncertainty or disorder of a system. The entropy measure can determine the routing flexibility of a system at any point of time during the operation. However, the calculation of an entropy measure is very tedious and currently can only be used in systems that produce single part types.

Routing flexibility can exist in any kind of manufacturing system that can provide alternate routings, yet it has mainly been related to push-type systems such as FMSs, flexible transfer lines, and job shops [Buzacott and Shanthikumar, 1980] [Sethi and Sethi, 1990] [Basnet and Mize, 1994]. For pull-type production systems such as Just-In-Time systems, research on routing flexibility has remained untouched despite its existence in this type of system.

Just-In-Time Production Systems

As Japanese manufacturers continue prospering in the global market, the Just-In-Time production system, which primarily originated at the Toyota Motor Company and was adopted by many Japanese companies in the early 1970's, has earned more and more respect. The Just-In-Time (JIT) system is aimed at flexible adaptation to fluctuations in demand mix and quantity in the market through the use of pull mechanisms [Monden, 1993]. The "pull" mechanism allows upstream production stations to produce in response to the demand's pulling force at the downstream stations. In that sense, the system will produce the necessary amount of products only at the necessary time. Therefore, unnecessary waste can be eliminated and inventory levels can be lowered. Toyota Motor Company, which initially conceived the JIT system, has shown the entire world how a successful JIT system can help produce quality products in minimum time at low cost. Following Toyota's success, increasing numbers of companies around the world have adopted the JIT approach in order to stay competitive in the competitive global market.

The pull mechanism in JIT systems is called Kanban (meaning "card" in Japanese). A typical Kanban contains production information such as store number, part name, part number, and container capacity. Kanbans are regarded as the media that transport production information along the production line. The production-ordering Kanban and the withdrawal Kanban are the two most recognized Kanbans in the literature [Huang *et al.*, 1983] [Monden, 1993]. A production-ordering Kanban specifies the kind and quantity of product that the preceding process must produce. A withdrawal Kanban enlists the kind and quantity of product that the subsequent process must withdraw from the preceding process [Monden, 1993].

Production-ordering and withdrawal Kanbans are manipulated between two processes to trigger the production and withdrawal of required products when necessary. As a result, just in time production can be realized through the practice of Kanban

systems. The directions of part and Kanban flows are illustrated in Figure 1-1.

Withdrawal Kanbans flow back and forth between processes to withdraw necessary parts. The subsequent process sends out a withdrawal Kanban, usually attached to a container, to the preceding process whenever parts are needed for processing. The preceding process will then issue the appropriate production-ordering Kanban in order to produce the required parts whenever possible. When completed, the withdrawal Kanban along with a filled container will return to the subsequent process. Huang *et al.* [1983] described the Kanban flows in the dual-Kanban JIT system and indicated that the production-ordering Kanban never leaves its home stage while the withdrawal Kanban moves between stages.

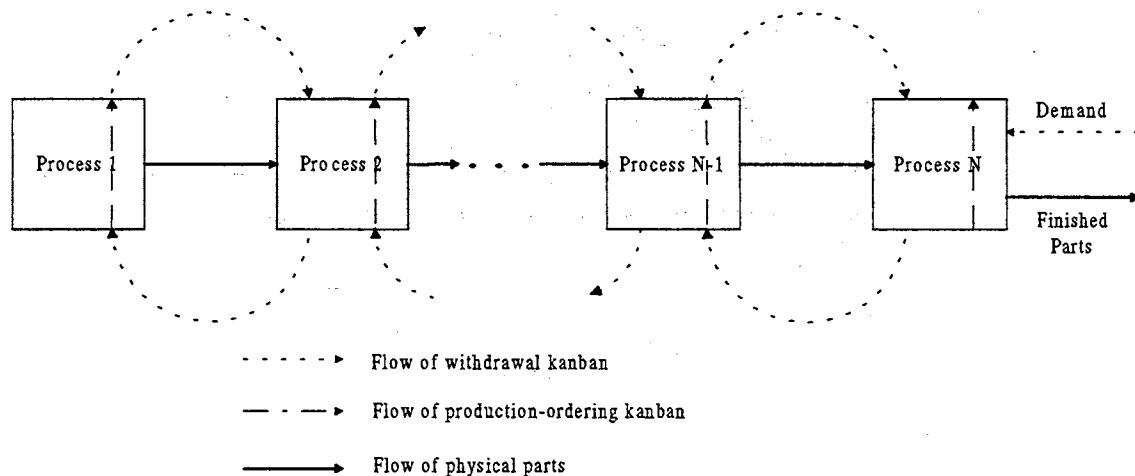


FIGURE 1-1 Directions of Kanbans and Physical Parts

According to a survey conducted by Crawford *et al.* [1988], inventory reduction and lead time reduction are the two leading benefits of implementing JIT for the surveyed companies. Excess inventory causes extra manpower, equipment, and floor space that all contribute to high manufacturing costs. Reducing inventory levels not only can lower manufacturing costs but also can eliminate problems that create excess inventory. Shorter lead times enhance the company's ability to react quickly to changes in demand in the

middle of a planning period. The capability of swift reaction can compensate for the discrepancies between monthly predetermined production plans and daily dispatched quantities. The ability to accommodate these discrepancies can then greatly reduce the level of inventory, work force, and waste.

The part-flow control in a typical JIT system is simple and straightforward. On the other hand, part flows in systems with alternate routings require dedicated control methods such as scheduling rules and machine selection rules to make routing decisions. However, both JIT systems and the systems with alternate routings are capable of reducing inventory level and production lead time. In this research, a pull-type Kanban-controlled JIT system that allows alternate routings will be studied so that the effects of routing flexibility on the JIT systems can be identified.

Statement of Problem

Routing flexibility can be found in any kind of manufacturing system that can provide alternate routings. However, it has mostly been related to FMSs, flexible transfer lines, and job shops [Buzacott and Shanthikumar, 1980] [Sethi and Sethi, 1990] [Basnet and Mize, 1994]. Some of the existing literature focuses on investigating the relationships between routing flexibility and system performance [Chen and Chung, 1991] [Das and Nagendra, 1993] [Benjaafar and Ramakrishnan, 1993]. Others studied the performance of various scheduling rules under the environment of alternate routings [Stecke and Solberg, 1981] [Denzler and Boe, 1987] [Piplani and Talavage, 1995].

For both of the research categories identified above, the types of manufacturing systems being studied are mainly FMSs and job shops that have always been recognized as "flexible" systems. In these research works, systems are composed of a number of automated machines (i.e., NC, DNC/CNC) which are linked by material handling systems.

Parts are created by the assigned probability distribution and are processed from the first needed operation to the last via either fixed or varying routes.

Part movements in these types of systems are called push-type flows in which parts are "pushed" through a series of required operations in order to be completed on time. Due dates are explicitly addressed in operation control to avoid customer complaints. Hence due-date related system performance such as tardiness and the number of tardy jobs are frequently used to measure push-type systems. Most manufacturing systems in western industry still operate with push-type mechanisms.

Unlike push-type production systems, a pull-type system developed by Japan's Toyota Motor Company in the 1960's operates differently. The demand of a pull-type system is created at the end of the production line such that the products are pulled through the last station.

The increasing use of general purpose machines has enabled the JIT systems to become more flexible in order to respond to a fluctuating market [Monden, 1993]. Unlike the exclusive-purpose machine, a general-purpose or multi-function machine is capable of processing different types of parts in a manufacturing facility. In other words, a specific operation of a part can be carried out by more than one machine. For JIT systems, operating in a pull-system manner, the effects of routing flexibility have not been evaluated in order to provide information for system design or system control.

In short, the problem statement for this research can be summarized as:

There is a need to determine the effects of routing flexibility on system design and performance of a Kanban-controlled, pull-type multi-stage JIT system.

Overview of the Dissertation

The remainder of this dissertation is presented in five chapters. Chapter II reviews the relevant literature on (1) routing flexibility in manufacturing systems and (2) multi-stage JIT production systems. Chapter III presents the statement of the research that includes the goal, objectives, scope and limitations of the research. Chapter IV presents the research methodology developed for achieving the research objectives. The results of the simulation experiment are presented, statistically analyzed and interpreted in Chapter V. Finally, Chapter VI summarizes this research by presenting the summary, the research contributions and the research areas for future study.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

This chapter describes and reviews in detail existing literature that is related to the research problem. Research on the issues of routing flexibility in manufacturing systems is reviewed first. Three research areas were identified and studied: (1) operational measures of routing flexibility in manufacturing systems, (2) research on identifying effects of routing flexibility on various system performance measures, and (3) research on measuring various control methods under flexible routing environments. Secondly, literature on JIT systems is reviewed to provide a foundation of past work that is related to this research.

Research on Routing Flexibility in Manufacturing Systems

A study conducted by Gere [1966], found that production systems equipped with machines capable of performing alternate operations could reduce total lateness for a job shop. Scheduling heuristics result in better performance if alternate operations are allowed in the systems.

Routing flexibility is the product of alternate routings which are composed of using alternate machines and alternate sequences [Carter, 1986] [Bobrowski and Mabert, 1988] [Sethi and Sethi, 1990]. "Alternate machines" is the instance when one or more machines can be used to substitute for the intended machine to perform identical operations.

"Alternate sequences", on the other hand, is defined as the instance when a part can be performed by different process sequences [Bobrowski and Mabert, 1988]. Research on routing flexibility has mainly focused on the alternate routings incurred by "alternate machines" [Bobrowski and Mabert, 1988].

Buzacott and Shanthikumar [1980] identified alternate routings as an inherent characteristic in FMSs. They indicated that a fair degree of routing flexibility can better balance the utilization of machines and hence bottlenecks can be avoided. They also suggested that alternate routings can help prevent disturbances caused by machine breakdowns and variability in part processing times.

To gain better control of FMSs, Buzacott and Shanthikumar [1980] constructed a three-level control hierarchy to lessen the complexity of routing options. *Pre-release planning*, which is the highest level of the three, is responsible for: determining which parts are to be manufactured; identifying the constraints on the operation sequence; and estimating operation durations. *Input control* determines the order and timing of releasing parts to the system. The *operational control* level monitors the part movements between machines. This level is also responsible for resolving the conflict between alternate routings when the same machines are scheduled to be used at the same time.

Most research on alternate routings has mainly focused on the operational control level [Bobrowski and Mabert, 1988]. However, Buzacott and Shanthikumar [1980] recommended that some of the routings may be determined at the pre-release planning phase in order to reduce the complexity of routing decisions encountered at the operational control level.

Wilhelm and Shin [1985] focused the benefit of alternate routings on off loading bottleneck machines. However, they implied that time penalties may be incurred for these alternate routings when the primary routings are not available.

Bobrowski and Mabert [1988] developed several alternate routing strategies that can be used for making routing decisions at higher control levels (i.e., pre-release

planning). These strategies were applied to a nine-machine job shop to study the effects on the system performance. Results of this simulation study show that even the smallest introduction of routing flexibility can improve system performance. However, the improvement of system performance seems to increase at a diminishing rate.

Bobrowski and Mabert [1988] also concluded that the benefits incurred from routing flexibility require some efforts. To increase the level of routing flexibility, the company must invest in flexible machines, extra tooling and fixtures, and the upgrade of worker skill levels.

During the past two decades, manufacturing flexibility has been a major research target. Research on how routing flexibility can affect the manufacturing systems is one of the more heavily studied areas. The literature on routing flexibility for manufacturing systems can be categorized into the following three groups:

1. Operational measures of routing flexibility in manufacturing systems.
2. Effects of routing flexibility on system performances.
3. Performance of control methods under flexible routing environment.

Operational Measures of Routing Flexibility

Quantitative measurement of routing flexibility has been developed by a number of authors. The various measures of routing flexibility can be grouped into two categories. The first category includes the majority of the existing measures that were developed based on the number of alternate ways to process a part type. The other category measures routing flexibility in terms of *routing entropy*, a measure of routing uncertainty in a manufacturing system.

Chatterjee *et al.* [1984] proposed a routing flexibility measure which is simply the number of available routes. Chung and Chen [1989] developed a similar measure that

measures the routing flexibility of a manufacturing system by calculating the average number of available routes for each part type. The value of routing flexibility will range from 0 (i.e., fixed routed) to any positive value if alternate routings are allowed. Bernardo and Mohamed [1992] utilized the inverse of the number of available routes as a term of the routing flexibility measure. As a result, the values of routing flexibility range from 0, if no alternate routings are allowed, to approximately 1, if a very large number of alternate routes are allowed. These measures assumed that each available route has identical value of flexibility so that only the number of available routes is considered.

A measure elaborated by Das and Nagendra [1993] takes into account the difference between various routes. The difference between two routes is expressed by a function of the difference in processing time for each machine. The routing flexibility is the sum of the average differences between each route and all the other routes.

The above measures are primarily a function of the number of available routes and/or the machine information of each route. The parameters utilized in the calculation of routing flexibility must be identified and determined in advance. Therefore, measures in this category are recognized as deterministic measure of routing flexibility because they can be determined before system starts operating.

Entropy has been used to measure the uncertainty or disorder of a system. Kumar [1987] and Yao and Pei [1990] applied the entropy theory to measure the routing flexibility of a manufacturing system. However, their studies have only focused on the system of producing a single part type.

For a manufacturing system, the entropy (i.e., routing flexibility) is determined for every operation based on the number and the availability of processing machines. The equation of the entropy measure is a function of the probability that an operation can be completed on a specific machine. The total routing flexibility of a system is the summation over the entropy measures of all operations. The entropy measure of routing flexibility

can be reviewed and calculated at any time during the operation. Therefore, it can be viewed as a dynamic measure of routing flexibility.

Routing Flexibility and System Performance

Several researchers have investigated the effects of routing flexibility on specific system performances in order to realize their benefits. A number of performance measures are utilized for evaluating the impacts due to routing flexibility. Definitions of the widely used performance measures are presented in Table 2-1.

TABLE 2-1 Definitions of Common Performance Measures

Performance Measure	Definition
Flow Time	The time span between the time at which a part is available for processing and the time at which it is completed. [Bedworth and Bailey, 1987]
Makespan	The time between the time at which a part is available for processing and the completion time of the last part. [Pinedo, 1995]
Lateness	The difference between a part's completion time and its due date. [Bedworth and Bailey, 1987]
Tardiness	The measure of positive lateness. [Bedworth and Bailey, 1987]
Work-in-process (WIP)	The amount of semi-finished product currently located on the shop floor. [Viswanadham and Narahari, 1992]
Utilization	The amount of actual output of a machine (or a production system) relative to its capacity. [Groover, 1987]
Throughput	The number of parts or jobs produced per time unit. [Viswanadham and Narahari, 1992]

Wilhelm and Shin [1985] studied the effects of alternate machines on system performance in a flexible manufacturing system. Each part has a primary machine to perform a specific operation. An alternate machine will become available when the primary machine is busy. Three approaches for implementing alternate machines were evaluated and their performance measures are compared to the scheme with no alternate machines allowed.

The differences among three control approaches are based on the various levels of control hierarchy that are similar to the three-level control hierarchy in Buzacott and Shanthikumar [1980]. The most straightforward approach is operated at the shop floor. Parts will proceed to a known alternate machine when the primary machine is busy. A planned approach operated during the planning period manages to balance workloads among machines. This approach is implemented by linear programming with the objective of minimizing the total operating time for all machines. Solutions from the LP model determine the planned number of specific parts to be produced on designated machines. The third approach is a combination of the other two approaches. Alternate machines are planned initially to balance machine workloads and are dynamically directed at the operational level.

It is noted that Wilhelm and Shin's [1985] study assumes that no machine breakdowns occur in the FMS, and all data elements are deterministic. The FMS model was simulated for only one replication because of the deterministic data assumption. The six performance measures tested in the simulation model were makespan, system utilization, individual machine utilization, flow time, maximum spaces needed in common storage, and maximum number of vehicles needed. The results indicate that the approach which allows alternate machines at all levels of control hierarchy outperforms other approaches on most performance measures except maximum storage spaces. They concluded that alternate machines should be planned long-term but managed short-term on the shop floor. The results are similar to Buzacott and Shanthikumar [1980].

Bobrowski and Mabert [1988] studied the impact of both alternate machines and alternate sequences on cost related performance measures in a job shop. The routing decisions in this study occur during the *pre-release planning* [Buzacott and Shanthikumar, 1980]. The components of measured cost performance include:

1. cost of work in process (WIP),
2. cost of finished parts inventory,
3. penalty costs for failing to meet due dates.

In addition to the cost measures, flow time, lateness, tardiness and system utilization were also measured and compared in the simulation study. The results indicate that the implementation of alternate routings can result in substantial reduction in cost as well as the improvement of other performance measures. Therefore, the authors suggest it is worthwhile to invest in the machines and extra tools capable of enhancing routing flexibility.

Chen and Chung [1991] conducted a study similar to Wilhelm and Shin's [1985] to investigate the effects of routing flexibility on total makespan and system utilization. Three loading models were included in this research with the objective to maximizing the number of operation assignments to machines. The output of the loading models was then examined by a routing decision model to find the optimal routes that can minimize total makespan. System utilization was calculated based on the optimal routes.

In addition to the loading and routing policies, the tool duplication levels and the variation of processing times were also utilized as experimental factors in Chen and Chung's research. The number of duplicate tools for each tool type constrains the operation-machine assignment assuming that the machines are capable of processing an operation if the needed tool is available.

Variation of processing times is the result of the different lengths of processing times among different part types and machines. To determine the degree of variation of

processing times, a Group Technology (GT) concept was considered. GT is defined as a manufacturing philosophy in which similar parts are identified and grouped into part families based on their similarities in manufacturing and design attributes [Groover, 1987]. Consequently, parts in the same part family tend to have a low variation in processing times and vice versa.

Chen and Chung [1991] utilized discrete uniform distributions to simulate processing times and determine the variation of processing times by controlling the ranges of the distributions.

The effects of four experimental factors on the system performance in Chen and Chung's study are summarized as follows:

1. A loading model that considers both the processing times and the number of operation assignments in the objective function performs better than the ones that focus only on maximizing the number of operation assignments.
2. Systems equipped with an alternate routing policy outperform those with a fixed routing policy in both system utilization and total makespan.
3. Low processing time variation, although it results in statistically significant lower total makespan, does not provide the significant advantage of system utilization when alternate routings are available.
4. The introduction of a small degree of tooling duplication from a scenario of no duplication can greatly improve both system utilization and total makespan.

However, as the level of tooling duplication becomes higher, the introduction of tooling duplication does not show much improvement on the system performance. This supports the law of diminishing returns on routing flexibility observed by Wilhelm and Shin [1985] and Bobrowski and Mabert [1988].

An economic evaluation of routing flexibility was conducted by Ghosh and Gaimon [1992]. The results justified the benefits of routing flexibility based on a reduction of total manufacturing costs, WIP inventory, number of bottleneck machines, and system utilization. The only drawback is the increase in the number of setups, but that is considered insignificant when compared to the benefits.

Ghosh and Gaimon limited their research to FMSs. Das and Nagendra [1993] extended the system domain to a combination of a job shop, an FMS, and an assembly line in a real automobile engine plant. Although the simulation study concluded that routing flexibility can significantly reduce the flow time and WIP inventory, the routing flexibility does have limits. With a high degree of processing time imbalance, there is a range of routing flexibility that will deteriorate the system performance. This so-called zone of avoidance must be identified and eliminated when designing the system.

Benjaafar and Ramakrishnan [1993] utilized queuing models to evaluate the effects of routing flexibility for an FMS. The results show that performance measures such as mean and variance of flow time, waiting time, and WIP decrease when routing flexibility is increased. A *diminishing rate of returns* relationship is held between the performance measures and the degree of routing flexibility. Their research also indicated that routing flexibility has a significant effect on the system performance when the system is operated in a highly variable environment or under conditions of high system loading.

Routing Flexibility and Control Methods

Two types of control decisions are used to direct part flows in a production system having routing flexibility. The first type of decision is when one machine becomes available with more than one part awaiting its service, a specific part must be selected.

Scheduling rules (i.e., part selection rules) are utilized for choosing the candidate part that is located at the storage area between two serial stages.

The second type of decision is needed due to the alternate routings when more than one machine is available for processing the part. Machine selection rules are employed for selecting an appropriate machine for processing between multiple available machines. The two types of routing decisions are illustrated as Figure 2-1 and 2-2.

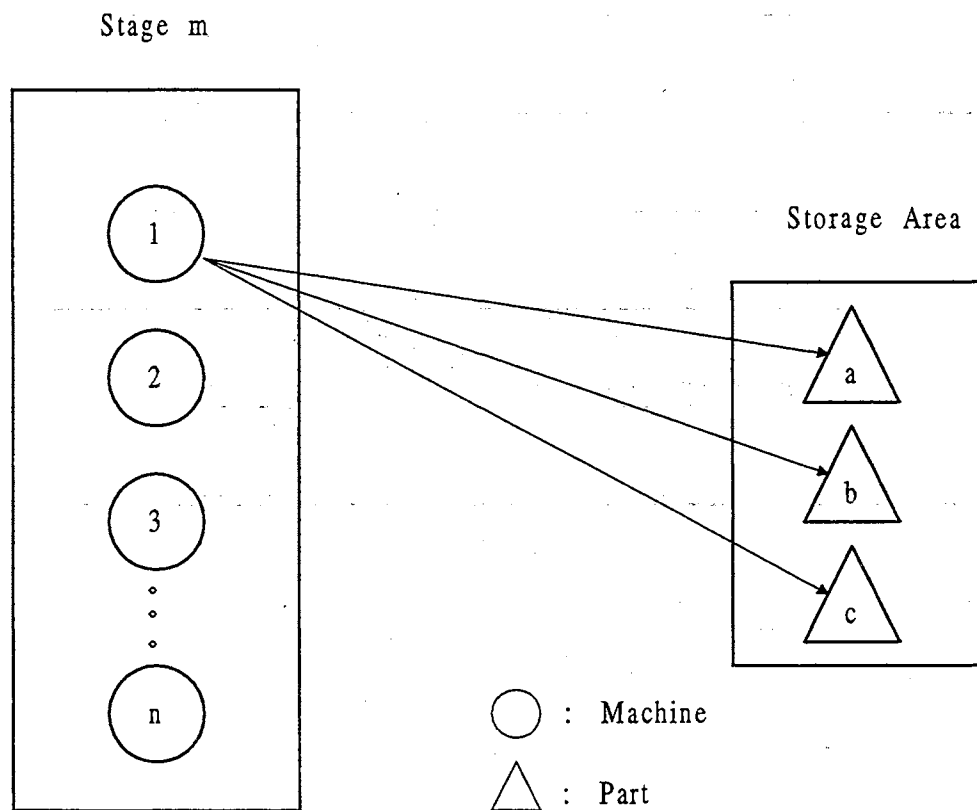


FIGURE 2-1 One Machine Selects between Multiple Parts

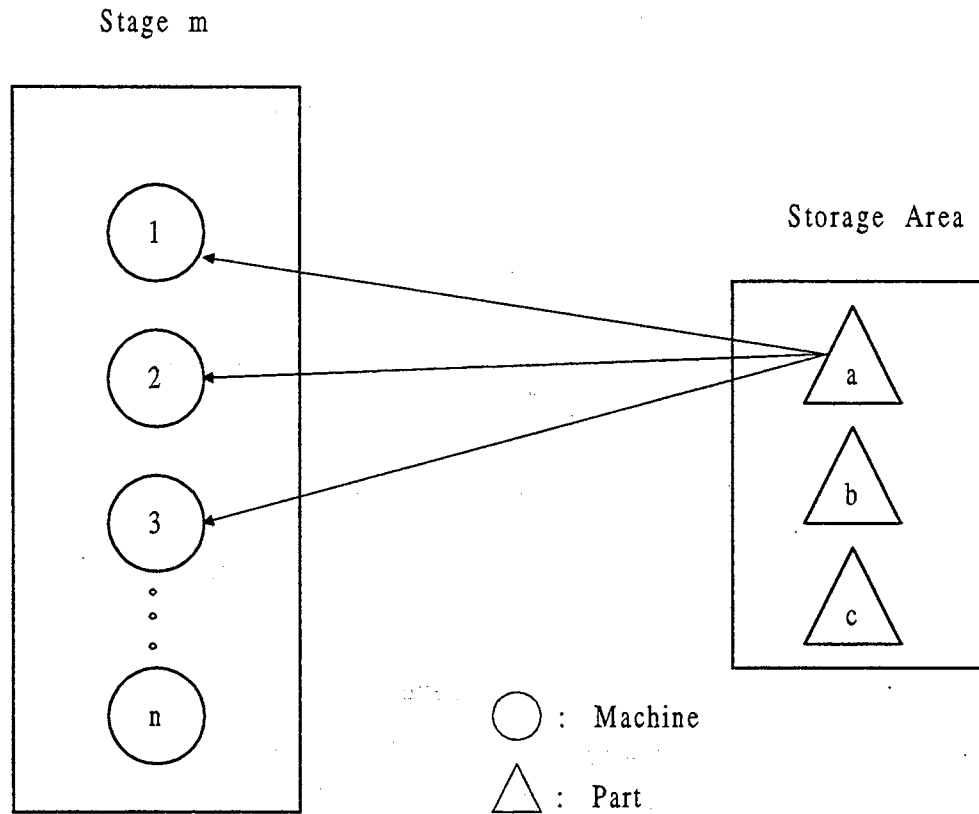


FIGURE 2-2 One Part Selects between Multiple Machines

Scheduling Rules Scheduling rules are the disciplines used to select the next part to be processed from those awaiting service [Montazeri and Van Wassenhove, 1990]. These rules mediate the selection of parts by evaluating specific characteristics of waiting parts such as processing times, due dates, and other quantifiable measures. Analyzing the performance of scheduling rules has been a heavily studied research area. However, one must note that the performance measures chosen and the configuration of the production system, which vary between studies, are two important factors that greatly affect the application and usefulness of various scheduling rules.

Conway [1965] pioneered studies on scheduling rules for job shops. Most of the scheduling rules studied by Conway have been utilized and studied under various system configurations by later researchers. Panwalkar and Iskander [1977] surveyed over 100

scheduling rules. These rules are classified based on the characteristics considered in the scheduling of parts.

Blackstone *et al.* [1982] conducted an extensive survey on the then state-of-the-art of scheduling rules that are used in job shop environments. Methodologies for studying scheduling rules, such as analytical methods and simulation, are described and reviewed. It was concluded that no single scheduling rule can be identified as the best for all systems and instances.

All the above studies have assumed fixed routings for the parts within the system. Steckel and Solberg [1981] and Shanker and Tzen [1985] reported on the experimental investigation of loading policies and scheduling rules in an FMS where alternate routings are allowed. They concluded that the combination of specific loading policies and scheduling rules would provide better performance.

Montazeri and Van Wassenhove [1990] evaluated 14 scheduling rules for an FMS by using a modular simulator. The results show that some scheduling rules have a large impact on specific system performance measures. Scheduling rules should be selected according to the preferred performance measures.

Hutchison *et al.* [1991] addressed the problems of scheduling in an FMS where a large number of part types with low demand were manufactured. The study assumed at most one alternate machine for each operation and no machine breakdowns. It was concluded that routing flexibility affects the system performance (i.e., average flow time) in spite of the scheduling approaches employed.

Benjaafar and Ramakrishnan [1993] studied the effects of routing flexibility in FMSs. They concluded that although some scheduling rules provide better system performance than others, the significance of scheduling rules decreases as the routing flexibility increases.

In Table 2-2, the descriptions of some of the most studied scheduling rules are presented. Their names and descriptions follow closely Montazeri and Van Wassenhove's [1990] and O'Keefe and Kasirajan's [1992] research.

TABLE 2-2 Descriptions of Scheduling Rules

Name	Description
FCFS (First come first served)	Select the part that first entered the system
SPT or SIO (Shortest imminent operation)	Select the part with the shortest imminent processing time
LPT or LIO (Longest imminent operation)	Select the part with the longest imminent processing time
FRO (Fewest remaining operations)	Select the part with the fewest number of remaining operations
MRO (Most remaining operations)	Select the part with the most number of remaining operations
SRPT (Shortest remaining processing time)	Select the part with the shortest remaining processing time
LRPT (Longest remaining processing time)	Select the part with the longest remaining processing time
SLACK (Minimum slack)	Select the part with the least amount of slack (i.e., due date - present time - remaining processing time)
SPT/TOT or SIO/TOT (Shortest imminent ratio)	Select the smallest ratio obtained by dividing the imminent processing time by the total processing time
LPT/TOT or LIO/TOT (Largest imminent ratio)	Select the largest ratio obtained by dividing the imminent processing time by the total processing time

Machine Selection Rules Machine selection rules are rules that can be used for a waiting part to select an appropriate machine when multiple machines are capable of and available to process that part [O'Keefe and Kasirajan, 1992]. Machine selection rules have received less attention in the past since traditional job shops apply fixed routings in which every machine is only capable of performing a specific operation. With the use of flexible machines or general-purpose machines, however, an operation can be performed by a number of "process identical" or "functionally similar" machines and hence the need to select a machine is inevitable.

Choi and Malstrom [1988] utilized a physical simulator to evaluate seven scheduling rules and four machine selection rules in an FMS. The FMS under investigation was composed of seven workstations where each had a local buffer. The four machine selection rules examined are described in Table 2-3. Choi and Malstrom observed that the combination of SPT and NINQ results in the best production rate, while SPT and WINQ produce the most total output.

TABLE 2-3 Descriptions of Machine Selection Rules

Name	Description
RANDOM	Select the station randomly
FMFS (First machine first served)	Select the station that is closest to the part
WINQ (Work in queue)	Select the station whose local buffer has the smallest total processing times for all parts
NINQ (Number in queue)	Select the station whose local buffer has the fewest number of parts

The simulation study conducted by Choi and Malstrom [1988] utilized only one replication and the results remain skeptical. To overcome the limitation, O'Keefe and Kasirajan [1992] performed a steady-state analysis in order to obtain a more convincing conclusion. It was concluded that when WINQ is chosen as the machine selection rule, the choice of scheduling rules is insignificant. In terms of system performance, WINQ outperforms the other machine selection rules for flow time and machine utilization.

Ro and Kim's [1990] study added three new machine selection rules for an FMS with local buffers to compare with WINQ. The simulation results found that *Alternative Routings directed Dynamically* (ARD) outperforms the other machine selection rules for the selected system performance measures that include makespan, average flow time, average tardiness, and maximum tardiness. ARD is a rule that directs the part to the machine that has the shortest travel, queuing and operation times combined.

Summary

After the published research on routing flexibility and related control topics was reviewed, the following conclusions were drawn:

1. There is no universally recognized definition and measure of routing flexibility.
2. Existing research on routing flexibility utilized only push-type production systems, and no pull-type systems have been studied on the issues of routing flexibility.
3. Alternate routings can be either planned during the planning period, operated at the shop floor, or a combination of both can be used [Buzacott and Shanthikumar, 1980] [Wilhelm and Shin, 1985] [Chen and Chung, 1991].

4. A number of studies [Browne, 1984] [Carter, 1986] [Yao and Pei, 1986] presumed that routing flexibility is primarily dedicated to continuous production when machine breakdowns occur.
5. Most research concludes that there is a diminishing rate of return between routing flexibility and system performance measures, i.e., as the degree of routing flexibility increases the effects on the system performance measures decrease [Wilhelm and Shin, 1985] [Bobrowski and Mabert, 1988] [Chen and Chung, 1991] [Benjaafar and Kamakrishnan, 1993].
6. Two types of routing decisions are needed to direct part flows in manufacturing systems that allow flexible routings. Most research has only focused on the one dealing with the selection between multiple parts while ignores the selection between multiple machines for a waiting part.
7. Rules for scheduling parts and selection of next machine were mostly studied by utilizing simulation methods [Choi and Malstrom, 1988] [Ro and Kim, 1990] [Montazeri and Van Wassenhove, 1990] [O'Keefe and Kasirajan, 1992].

Research on Multi-stage Just-In-Time Systems

In the first article published in the United States on the Just-In-Time system, Sugimori *et al.* [1977] introduced this Japanese production system and its basic concepts to western industry. A Kanban-controlled pull-type system implemented in Toyota Motor Company was physically described, and its benefits were presented. It is reported that four requirements are needed for operating a JIT system:

1. *Withdrawal by subsequent processes*: Final assembly line determines the necessary timing and quantity of parts to be produced based on customers' demands.

2. *One piece production and conveyance*: Each process must aim at producing and conveying only one part, which is the ideal lot size.
3. *Leveling of production*: The daily production quantity for each product type must be leveled in order to avoid holding excessive inventory for certain types of parts and finished products.
4. *Elimination of waste from over-producing*: Waste, especially inventory, is considered as a source of troubles and problems that cause bad quality, excess capacity, excess work forces, high production costs, and customer dissatisfaction for a production system.

The Kanban-controlled JIT systems are considered as multi-stage flow shops in most studies [Huang *et al.*, 1983] [Sarker and Harris, 1988] [Sarker, 1989] [Sarker and Fitzsimmons, 1989] [Berkley and Kiran, 1991] [Berkley, 1992] [Gunasekaran *et al.*, 1993]. Each stage of these JIT flow shops consists of only one machine that is capable of performing the specific production function. Some authors, for example, Lee [1987], Gravel and Price [1988], and Price and *et al.* [1995], have adopted the JIT concept into the job shop environment.

The Kanban-controlled JIT systems are often perceived as straightforward in terms of part-flow control due to the use of a Kanban mechanism. Therefore, the issue of manufacturing flexibility for JIT systems has not drawn much attention from the previous researchers even though the general-purpose machines have been heavily implemented in these systems. Gunasekaran *et al.* [1993] developed a mathematical model for determining the number of identical machines in a multi-stage JIT system. Unlike the flow shop, every stage of this JIT system can have multiple machines to perform the same type of operations so that routing flexibility is allowed.

Simulation Studies of Pull-type JIT Systems

Simulation has been widely used as a tool to study and model the operational problems existing in JIT systems [Chu and Shih, 1992]. The reason for using simulation is mainly due to its ability to model complex systems and test various system conditions.

The pull-type JIT system was first modeled by Kimura and Terada [1981]. A multi-stage JIT system was simulated to compare it with a traditional push-type system regarding amplification of inventory and production fluctuation. It was concluded that the forecast error will eventually amplify inventory and production fluctuation for the push-type system. A pull-type system, on the other hand, is affected by the size of order. Large order sizes will amplify both the inventory and production fluctuations.

Huang *et al.* [1983] conducted a simulation study for a multi-stage, multi-line JIT system. A three-line, four-stage, single-Kanban JIT system was used for analyzing the behavior of JIT systems. Variation of processing times, variation of demand rate, and bottlenecks were modeled to observe their effects on the JIT system that has either one or two Kanbans at each Kanban post. Performance measures for this study were overtime, inventory at the final assembly stage before and after production, and the total production at the end of a normal work day prior to overtime.

Four different distributions of processing times were tested in the research of Huang *et al.*, each with both one and two Kanbans. These distributions have a mean processing time of 48 minutes per container, which include a constant, an exponential, a normal with a small standard deviation ($\sigma=4.8$), and a normal with a large standard deviation ($\sigma=24$). The experimental results indicate that as the variation of processing times increased, the required overtime and post-production inventory are also increased. However, the average normal daily throughput is decreased. As the number of Kanbans is increased from one to two, the mean and standard deviation of the required overtime decrease for all four different distributions of processing times. An extra experiment was

conducted to examine the effect of the number of Kanbans. The results show that extra Kanban capacity reduces overtime, but only up to a limited number of Kanbans.

The impact of variability in the demand rate was investigated by a method similar to that used to study the processing time variation. Four distributions of demand each having a mean of 1,000 units per day were considered in this experiment. It was concluded that the variability of required overtime and normal daily throughput will increase significantly as the variability of demand rate increased. The relation explains why the master production schedule of a JIT system must be nearly frozen during the length of that schedule.

Another experiment was conducted to evaluate the effect of bottlenecks at different stages. In this experiment, it was assumed that the processing time per container is a constant of 48 minutes initially. Two levels of bottleneck, low (72 minutes) and high (96 minutes) at each stage, were tested respectively. The results indicate that an extra Kanban will not bring down the required overtime on the bottlenecks. Huang *et al.* suggested that the bottleneck problems can only be resolved by reducing bottlenecks themselves, such as reducing setup times and operation times through technology breakthroughs and skilled workers.

The combined effects of the variability of processing time and demand rate were also investigated under a similar experiment that utilized the same distributions. The results further showed that variability in processing times and demand rates affects required additional overtime and decreased daily throughput in a JIT system.

Without conducting statistical analysis of the results of their simulation study, Huang *et al.* concluded that companies who have experienced significant variability in demand and processing times are not suitable for implementing JIT systems. It was also recommended that American companies need a transition period to prepare themselves for refining their production environment to fit JIT systems. During the transition period, the companies have to train workers to do multiple functions.

The impact of the variability of processing time studied by Huang *et al.* [1983] has also been investigated by others. Sarker and Harris [1988] focused on the effect of imbalance between the stages in the JIT flow shop. The simulation results concluded that different combinations of processing time variations affect the system performance. Sarker and Fitzsimmons [1989] and Sarker [1989] studied the effect of the coefficient of variation (C_v) of the processing times on the system efficiency where the mean processing time for every machine on the line is assumed to be identical. The results show that an increase in the variability of the processing times will reduce the system efficiency and daily throughput dramatically.

Scheduling Rules of Pull-type JIT Systems

The existence of queues that accumulate inventory as a buffer storage necessitates the implementation of scheduling rules for selecting parts awaiting processing. Although scheduling rules of push-type systems have been a research area well explored, the scheduling rules of JIT systems have been basically ignored by researchers. Only a small number of studies can be found that investigated the performance of scheduling rules for pull-type JIT production systems.

Scheduling in pull-type Kanban-controlled systems is different from the scheduling in push-type systems because of different objectives. The objective of scheduling in conventional push-type systems is primarily meeting the expected due dates. JIT systems, however, are more interested in minimizing WIP levels and flow times.

Lee [1987] investigated the effects of scheduling rules in a JIT job shop. The study found that the SPT/LATE rule performs significantly better in minimizing mean tardiness and waiting time than FCFS. The SPT/LATE rule selects a part by applying the SPT rule as long as the part is not "late". The term "late" is defined as the incident when a

part in the subsequent stage is unable to be processed due to the inability to pull from the current stage. The priority will be based on the amount of part "lateness" if at least one part is late.

As for the SPT and FCFS rules, Lee found that the SPT rule results in greater throughput and higher machine utilization than the FCFS rule. However, significantly higher WIP is also incurred by the SPT rule.

Berkley and Kiran [1991] conducted a simulation study on scheduling rules in a dual-Kanban-controlled flow shop where Kanbans are moved in constant periods. In this study, the FCFS/SPT rule results in shorter average waiting time than the SPT/LATE rule recommended by Lee [1987]. The FCFS/SPT rule is a two-phase priority selection process that applies FCFS for selecting the part types and then employs SPT to select parts within the same part type. When compared between SPT and FCFS, it is concluded that the FCFS rule is favored because it incurs lower average WIP than the SPT rule.

In a separate study conducted by Berkley [1993], the performance of the FCFS and SPT rules was examined in a six-station, dual-Kanban JIT flow shop. A Kanban blocking mechanism was utilized to control the parts' movement between two adjacent stations. Under this blocking by part-type mechanism, a specific part type is not allowed to move from the preceding station to the subsequent station if the subsequent station's input buffer contains a designated number of that same type of part. The simulation results show that the SPT rule is favored under the part-type blocking mechanism since it has a greater throughput and smaller WIP than FCFS.

Summary

Several conclusions can be drawn after reviewing the published research on multi-stage JIT systems. These conclusions are described as follows.

1. Most research has considered the Kanban-controlled JIT system as a multi-stage flow shop [Huang *et al.*, 1983] [Sarker and Harris, 1988] [Sarker, 1989] [Sarker and Fitzsimmons, 1989] [Berkley and Kiran, 1991] [Berkley, 1992] [Gunasekaran *et al.*, 1993].
2. Variability of processing times and demand rate are concluded to have a great effect on the throughput of a JIT system than that of a push-type system [Sarker and Fitzsimmons, 1989]. The coefficient of variation (C_v) of processing time and demand rate has, hence, been frequently utilized as an experimental factor when the throughput of the JIT system is measured [Huang *et al.*, 1983] [Sarker and Fitzsimmons, 1989].
3. It was concluded in some studies [Huang *et al.*, 1983] [Sarker and Fitzsimmons, 1989] that as the C_v of processing times increases, the throughput decreases and the total WIP increases.
4. Scheduling rules for JIT systems have not been fully studied and only a limited number of studies can be found. Unlike the due-date related objectives in push-type systems, the objectives of the scheduling rules in JIT systems are the maximization of throughput and machine utilization, and the minimization of WIP. First Come First Served (FCFS) and Shortest Processing Time (SPT) are the two rules that are most frequently employed and studied [Lee, 1987] [Berkley and Kiran, 1991] [Berkley, 1993].
5. Unlike the push-type system, research of pull-type JIT systems utilized non due-date related performance measures. The most frequently used performance measures are throughput, WIP and machine utilization [Chu and Shih, 1992]. Table 2-4 summarizes the three performance measures and their users.

TABLE 2-4 Summary of Frequently Used Performance Measures in JIT Research

Performance Measures	References
Throughput	<p>[Schroer <i>et al.</i>, 1985] [Lee, 1987] [Changchit and Kung, 1988] [Sarker and Harris, 1988] [Villeda, 1988] [Sarker and Fitzsimmons, 1989] [Chaturvedi and Golhar, 1992] [Berkley, 1993]</p>
WIP	<p>[Huang <i>et al.</i>, 1983] [Schroer <i>et al.</i>, 1985] [Lee, 1987] [Gupta and Gupta, 1989] [Sarker and Fitzsimmons, 1989] [Berkley and Kiran, 1991] [Chaturvedi and Golhar, 1992] [Berkley, 1993]</p>
Machine Utilization	<p>[Schroer <i>et al.</i>, 1985] [Lee, 1987] [Gupta and Gupta, 1989] [Sarker and Fitzsimmons, 1989] [Chaturvedi and Golhar, 1992] [Berkley, 1993]</p>

CHAPTER III

STATEMENT OF THE RESEARCH

Research Goal

The overall goal of this research is to investigate the effects that routing flexibility has on system performance in multi-stage, Just-In-Time systems where multiple machines and hence alternate routings are allowed at each processing stage. Two subgoals are included for investigating the effects of routing flexibility. The first subgoal is to examine the effects of routing flexibility and other experimental factors on the selected performance measures. The second subgoal is to develop control methods that can better control part flows in the JIT system that allows alternate routes.

Understanding these effects will lead to the realization of routing flexibility for the design of a multi-stage JIT system. System designers can utilize this information to determine the operational configurations so that a specific system performance can be significantly improved.

In order to achieve these research goals, the following research objectives have been identified.

Research Objectives

Objective 1 Created a measure of routing flexibility for the multi-stage JIT system.

Routing flexibility and the system for this research must be clearly defined so that confusion with other types of manufacturing flexibility and systems can be avoided. Quantitative measures of routing flexibility were developed for measuring various degrees of routing flexibility. Descriptions of the system which include system configuration, operational characteristics, and necessary assumptions were done.

Objective 2 Identified system performance measures.

The system performance measures that were used to examine the effects of routing flexibility in a JIT flow shop were identified and clearly defined. Selected performance measures are mainly time and inventory based measures. These measures were evaluated under various degrees of routing flexibility and other experimental factors.

Objective 3 Developed system control methods.

The system control methods were developed so that they can be applied in a pull type JIT flow shop where alternate routings exist. The control methods typically are combinations of scheduling and machine selection rules. These methods were utilized to direct part flows when control decisions must be made.

Objective 4 Identified experimental factors.

The independent variables that may have an effect on the system performance measures were identified and defined. Selected variables that served as experimental factors were utilized to compare the system performance under various scenarios and levels of routing flexibility.

Objective 5 Created and utilized an experimental model.

An experimental model was developed and then utilized. The experimental model for the research determined the type of design, analysis methodology, and statistical analysis procedures.

Objective 6 Generalized results from the experimental model that can be applied to a wide-range of JIT systems.

The experimental results were analyzed and then generalized. Statistical analysis procedures were utilized for analyzing the experimental results. The results of the analysis were used to describe how routing flexibility can affect the selected performance measures and the system control approaches.

Research Scope and Limitations

The scope of the research is limited to a 4-stage Kanban-controlled pull-type flow shop due to time and economic constraints. This JIT flow shop was treated as a generalized system that can represent similar production facilities of all sizes. Therefore, the findings from studying this simplified system are presumed to be consistent with, and generalizable to, those from larger systems and hence can be applied to systems with similar configurations.

This research assumes that quantitative performance measures such as WIP inventory, system throughput, and shortage of finished products are major concerns of the production facility. Economical or cost related performance measures were not considered in this study.

CHAPTER IV

RESEARCH METHODOLOGY

Introduction

This chapter discusses the research methodology employed in this research. First of all, the definition of routing flexibility and the development of equations for measuring the defined routing flexibility are presented. Secondly, the configurations and the operational characteristics of the multi-stage JIT system are described. The necessary assumptions concerning this system are also made. Thirdly, the system performance measures are identified based on the related literature. Their operational definitions are also specified.

Fourthly, the basic routing control methods were determined. The control methods are the combinations of scheduling rules (i.e., part type selection rules) and machine selection rules. Five scheduling rules and three machine selection rules are studied in this research. The definitions of these rules and how each rule works are presented.

The experimental factors studied in this research were determined based on the literature and the goal of the research. The experimental models are presented in order to describe how the experiments for this research were conducted. Finally, the development of the simulation model for the experiment is discussed. The verification and validation of this simulation model is also presented.

Routing Flexibility

Numerous definitions have been given for routing flexibility in the literature. To avoid confusion, the routing flexibility studied in this research has adopted the definition presented by Sethi and Sethi [1992] and Das and Nagendra [1993]:

The ability of a manufacturing system to produce parts continuously by alternate routes through the system, where a route is a series of machines visited in order to accomplish a part.

The alternate routes are accomplished by using alternate machines and alternate sequences in the system [Carter, 1986] [Bobrowski and Mabert, 1988] [Sethi and Sethi, 1990]. Alternate machines can perform similar or identical operations on a waiting part when the primary machine is unavailable. In a flow shop where each stage contains only one machine, no alternate machine is allowed. If a flow shop has n machines capable of performing a specific operation at a specific stage, it is said that there are $n-1$ alternate machines available in that stage. In the JIT system studied in this research, the alternate machines are located at the same stage capable of performing identical machining processes as the primary machine but with less efficiency.

The sequence of manufacturing is the order of operations in which a part is processed through the machines [French, 1982]. An alternate sequence becomes available when this part can be completed by a swapped order of processes. In this research, the order of machines for processing a part can only be changed within the same stage since the order of processes is fixed due to its flow shop configuration. Therefore the impact of alternate sequences is ignored in this research.

Measurement of Routing Flexibility

The most obvious measure of routing flexibility (RF) is related to the number of alternate ways a part can be processed in a system [Sethi and Sethi, 1990]. However, the measures developed by Chung and Chen [1989] and Bernardo and Mohamed [1992] fail to recognize that a system will become less flexible if the majority of parts can only be processed by a small number of machines.

For the purpose of this research, a quantitative measure was developed for finding the appropriate level of routing flexibility for flow shops that have multiple machines at each stage. Instead of simply counting the number of available routes, this measure takes into account the loading balance between machines and across stages. Therefore, a manufacturing system with overloaded machines will have less routing flexibility than the one without when both have the same number of available routes.

Notation:

- k = Stage number ($k = 1, 2, 3, \dots, K$).
- K = The total number of stages in the flow shop.
- i = Part type.
- TI = The total number of part types processed by the system.
- I_k = The number of part types processed at stage k .
- SU_i = The number of standard units for part type i .
- j = Machine number.
- J_k = The number of machines at stage k .
- R_{jk} = For machine j at stage k , the number of part types (in terms of standard units) that it can process.

- TR_k = The total number of part types (in terms of standard units) that all the machines at stage k can process. $TR_k = \sum_{j=1}^{J_k} R_{jk}$. Effectively, TR_k is the stage's capability to process parts.
- U_{ijk} = A zero-one indicator whether or not part type i at stage k can be processed by machine j . The value of U_{ijk} can be either 1 (yes) or 0 (no).
- S_{ik} = For part type i , the number of machines that can process part type i at stage k .
- WV_i = The weight of the volume of part type i relative to the other part types.
- P_k = The average number of part types a machine can process at stage k .
- PT_{ik} = The processing time for part type i at stage k .
- M_k = The number of machines being used effectively at stage k . Effectively is related to the workload balance between machines at a specific stage.
- $D_k \langle TR_k \rangle$ = The quantitative distance between the current routing combination and the most flexible routing when the machines' capability at stage k is TR_k .
- WS_k = The weight of stage k relative to the other stages in the system.
- RF_k = The routing flexibility of stage k .
- SRF = The system routing flexibility.

The routing flexibility of a specific stage in a flow shop is a function of the number of routes and the number of part types each machine can process. A route at a stage is a combination of the part type and a machine that can process that part type. Therefore, the routing flexibility of stage k (RF_k) is defined as a ratio of the product of the average number of part types a machine can process (P_k) and the number of machines being effectively used (M_k) to the maximum possible number of routes which can be quantified as the number of parts multiplied by the number of machines:

$$RF_k = \frac{P_k \times M_k}{I_k \times J_k} \dots\dots\dots (1)$$

The average number of part types each machine can process at stage k (P_k) can be obtained by dividing the total number of parts (in terms of standard units) that can be processed by all machines at stage k (TR_k) by the number of machines at stage k.

$$P_k = \frac{TR_k}{J_k} \dots\dots\dots (2)$$

TR_k , the summation of R_{jk} for all j machines at stage k, represents the total number of part types in terms of standard units that can be processed by all the machines at stage k. R_{jk} can be obtained by summing up the number of standard units of the part types that can be processed by machine j (see equation 3). The number of standard units for part type i (SU_i) is determined by the number of part types processed by this system times the weight of volume for that part type (see equation 4). The weight of volume for part type i (WV_i) is determined by the percentage of production volume for part type i.

$$R_{jk} = \sum_{i=1}^{\pi} (SU_i \times U_{ijk}) \dots\dots\dots (3)$$

$$SU_i = \pi \times WV_i \dots\dots\dots (4)$$

The number of machines being effectively used at stage k (M_k) is a relative measure of the number of machines being used as if each machine can process all part types. It is computed by taking the smallest possible number of machines needed (i.e.,

$$\frac{\sum_{i=1}^{\pi} S_{ik}}{I_k}) \text{ and then adding up the extra number of machines (i.e., } J_k - \frac{\sum_{i=1}^{\pi} S_{ik}}{I_k}) \text{ times the}$$

relative distance from the current to the point of the smallest number of machines (i.e.,

$$\frac{\text{Max } D_k \langle TR_k \rangle - D_k \langle TR_k \rangle}{\text{Max } D_k \langle TR_k \rangle}).$$

$$M_k = \frac{\sum_{i=1}^{\Pi} S_{ik}}{I_k} + \left[\frac{\text{Max } D_k \langle \text{TR}_k \rangle - D_k \langle \text{TR}_k \rangle}{\text{Max } D_k \langle \text{TR}_k \rangle} \right] \times \left[J_k - \frac{\sum_{i=1}^{\Pi} S_{ik}}{I_k} \right] \dots\dots\dots (5)$$

$D_k \langle \text{TR}_k \rangle$ is used to measure the difference between the current routing and the balanced routing under the same number of routes where a route is a combination of a part type and machine. The balanced routing is a set of routes where each machine is able to process the same number of part types. Therefore, the difference between each machine's processing capability under the current routing (i.e., R_{jk}) and under the balanced routing (i.e., $\frac{\text{TR}_k}{J_k}$) is computed and the difference is squared to avoid a negative value. Since the average number of part types a machine can process may not be integer, the balanced routing is simply virtually balanced.

The summation of all the squares of the differences is then computed to represent the overall differences. The square root of the summation is taken to portray the distance between the current routing and the balanced routing for a specific number of routes. The balanced routing for a specific number of routes is the routing where each machine is capable of processing equal number of part types.

$$D_k \langle \text{TR}_k \rangle = \sqrt{\sum_{j=1}^{J_k} \left[R_{jk} - \left(\frac{\text{TR}_k}{J_k} \right) \right]^2} \dots\dots\dots (6)$$

After the routing flexibility of every stage is computed, the routing flexibility of the entire system can then be obtained by summing the weighted routing flexibility of each stage. The weight allocated to each stage (WS_k) is the relative importance of that stage. The relative importance may be the degree of preference and/or relative operational measures among all stages.

$$\text{SRF} = \sum_{k=1}^K (\text{WS}_k \times \text{RF}_k) \dots\dots\dots (7)$$

In this research, the weight of a stage k (WS_k) is the average processing time of that stage relative to the other stages. For stages with higher average processing times, higher routing flexibility can help speed up part flows and hence reduce the effect due to bottleneck stages. Therefore, the systems having higher routing flexibility on stages with higher average processing times are considered to be more flexible than those that do not.

WS_k can be obtained by dividing the average processing time of stage k by the summation of average processing times of all stages. The average processing time of stage k is the average of mean processing times for all part types at stage k .

$$AP_k = \frac{\sum_{i=1}^{\pi} PT_{ik}}{I_k} \dots\dots\dots (8)$$

$$WS_k = \frac{AP_k}{\sum_{k=1}^K AP_k} \dots\dots\dots (9)$$

A simple example is given in order to illustrate how the above measures are implemented.

Example

Consider a 2-stage flow shop where each stage contains three machines. A total of three part types can be produced by this flow shop. During a typical period, the percentage of demanded volumes (WV_i) among the three part types at all stages is 50%, 25%, and 25% respectively. The average processing time that each part type spends at the two stages is listed in Table 4-1. The routings of each stage are displayed in Figure 4-1.

TABLE 4-1 The Average Processing Times for Each Part Type in the Example

Part type	Stage 1 Average Processing Time	Stage 2 Average Processing Time
A	8	13
B	10	15
C	12	17

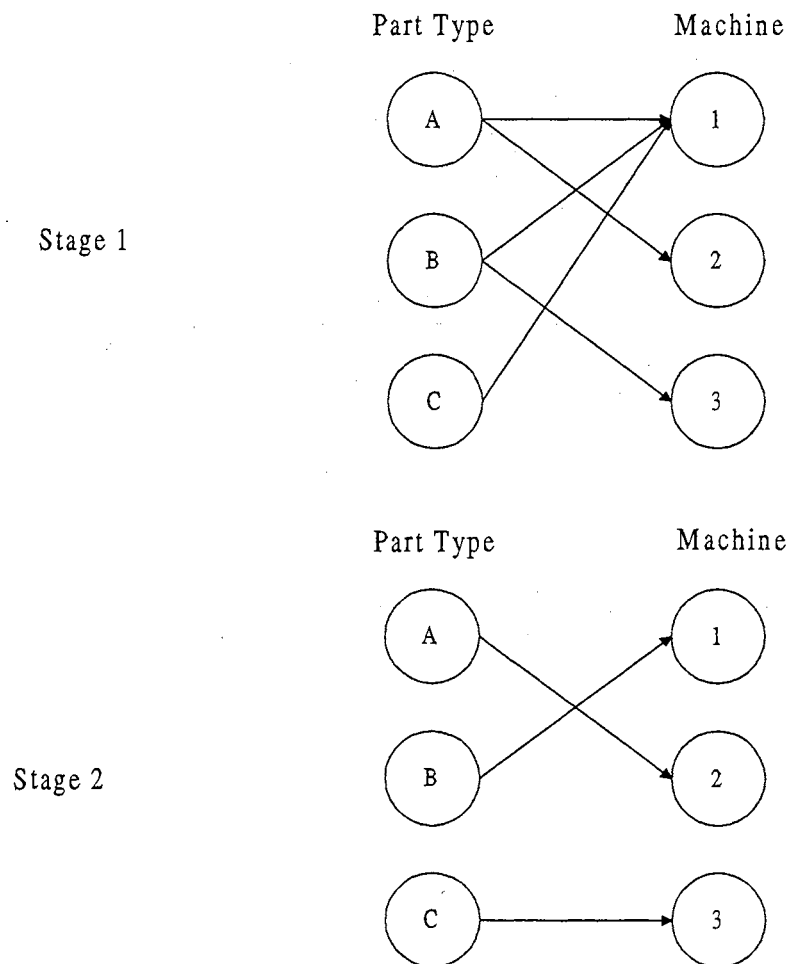


FIGURE 4-1 The Routings for a Two-stage Flow Shop

Based on the system configurations described above, the values of the following variables can be obtained:

$$TI = 3,$$

$$I_1 = I_2 = 3,$$

$$J_1 = J_2 = 3,$$

$$WV_A = 0.5, \quad WV_B = WV_C = 0.25.$$

For each part type, the number of standard units (SU_i) can be calculated by applying equation 4. Therefore, $SU_A = 3 \times 0.5 = 1.5$, $SU_B = SU_C = 3 \times 0.25 = 0.75$.

At stage 1, part type A can be processed by machines 1 and 2 (see Figure 4-1). Therefore, the number of machines that can process part type A at stage 1 (i.e., S_{A1}) is equal to two. Similarly, $S_{B1} = 2$, $S_{C1} = 1$, $S_{A2} = 1$, $S_{B2} = 1$, and $S_{C2} = 1$.

U_{A11} is 1 since machine 1 is capable of processing part type A at stage 1. Likewise, $U_{B11} = 1$, $U_{C11} = 1$, $U_{A21} = 1$, $U_{B21} = 0$, $U_{C21} = 0$, $U_{A31} = 0$, $U_{B31} = 1$, $U_{C31} = 0$, $U_{A12} = 0$, $U_{B12} = 1$, $U_{C12} = 0$, $U_{A22} = 1$, $U_{B22} = 0$, $U_{C22} = 0$, $U_{A32} = 0$, $U_{B32} = 0$, and $U_{C32} = 1$.

For stage 1, R_{11} , R_{21} , and R_{31} are calculated by using equation 3. The result shows that machine 1 is capable of processing $1.5 + 0.75 + 0.75 = 3$ standard units of part types, while machines 2 and 3 can process 1.5 and 0.75 standard units respectively. As a result, TR_1 is 5.25 ($3 + 1.5 + 0.75$). It is said that stage 1 is capable of processing a total of 5.25 standard units of part types.

To process 5.25 standard units of part types at stage 1, the least flexible (i.e., the smallest number of machines utilized) routing combination is (3, 2.25, 0). One of the three machines will process 3 standard units, another processes 2.25 standard units, and the other remains idle. The balanced routing is when each of the three machines can process equal number of standard units of part types (i.e., $\frac{5.25}{3} = 1.75$ standard units).

Therefore, the balanced routing is (1.75, 1.75, 1.75).

Similarly, $(R_{12}, R_{22}, R_{32}) = (0.75, 1.5, 0.75)$ and $TR_2 = 3$. The best and worst combinations for stage 2 can be identified as:

(3, 0, 0) --- the least flexible routing

(1, 1, 1) --- the balanced routing

The routing flexibility of each stage as well as the entire system can then be calculated by utilizing the developed formula. The detailed calculations of the measure are carried out as follows.

Stage 1:

$$P_1 = \frac{5.25}{3}$$

$$= 1.75$$

(i.e., each machine at stage 1 can process an average of 1.75 part types)

$$D_1 \langle TR_1 = 5.25 \rangle = \sqrt{(3-1.75)^2 + (1.5-1.75)^2 + (0.75-1.75)^2}$$

$$= 1.62$$

(i.e., the distance between the current routing and the balanced routing is 1.62 when the capability of stage 1 is 5.25 standard units of parts)

$$\text{Max } D_1 \langle TR_1 = 5.25 \rangle = \sqrt{(3-1.75)^2 + (2.25-1.75)^2 + (0-1.75)^2}$$

$$= 2.21$$

(i.e., the distance between the least flexible routing and the balanced routing is 2.21 when the capability of stage 1 is 5.25 standard units of parts)

$$M_1 = \frac{(2+2+1)}{3} + \left(\frac{2.21-1.62}{2.21} \right) \times \left[3 - \frac{(2+2+1)}{3} \right]$$

$$= 2.0828$$

(i.e., a total of 2.0828 machines is being effectively used at stage 1)

$$RF_1 = \frac{1.75 \times 2.0828}{3 \times 3} = 0.405$$

(i.e., the routing flexibility of stage 1 is 0.405)

Stage 2:

$$P_2 = \frac{3}{3} \\ = 1$$

(i.e., each machine of stage 2 can process an average of 1 part types)

$$D_2 \langle TR_2 = 3 \rangle = \sqrt{(0.75-1)^2 + (1.5-1)^2 + (0.75-1)^2} \\ = 0.61$$

(i.e., the distance between the current routing and the balanced routing is 0.61 when the capability of stage 2 is 3 standard units of parts)

$$\text{Max } D_2 \langle TR_2 = 3 \rangle = \sqrt{(3-1)^2 + (0-1)^2 + (0-1)^2} \\ = 2.449$$

(i.e., the distance between the least flexible routing and the balanced routing is 2.449 when the capability of stage 2 is 3 standard units of parts)

$$M_2 = \frac{(1+1+1)}{3} + \left(\frac{2.449 - 0.61}{2.449} \right) \times \left[3 - \frac{(1+1+1)}{3} \right] \\ = 2.5$$

(i.e., a total of 3 machines is being effectively used at stage 2)

$$RF_2 = \frac{1 \times 2.5}{3 \times 3} = 0.2778$$

(i.e., the routing flexibility of stage 2 is 0.2778)

To compute the routing flexibility of the system, the weight of the two stages must be determined. The average processing time based weight can be obtained by applying equations 8 and 9.

$$AP_1 = \frac{(8+10+12)}{3} = 10$$

$$AP_2 = \frac{(13+15+17)}{3} = 15$$

$$WS_1 = \frac{10}{(10+15)} = 0.4$$

$$WS_2 = \frac{15}{(10+15)} = 0.6$$

Using equation 7, the routing flexibility of the system (SRF) can then be obtained by averaging the weighted routing flexibility of the two stages:

$$\begin{aligned} SRF &= (0.4 \times 0.405 + 0.6 \times 0.2778) \\ &= 0.3287 \end{aligned}$$

This example shows that a two-stage JIT system has a routing flexibility of 0.3287 when the developed measure is applied. A different set of routings is given to illustrate how this measure can compare the routing flexibility between different systems. In Figure 4-2, part type B, instead of being processed by machine 1 and 2 as in the original routings, is now processed by machine 2 and 3 so that machine 1 can be off loaded. As a result, the routing flexibility of the system with the new routings is slightly increased to 0.3425.

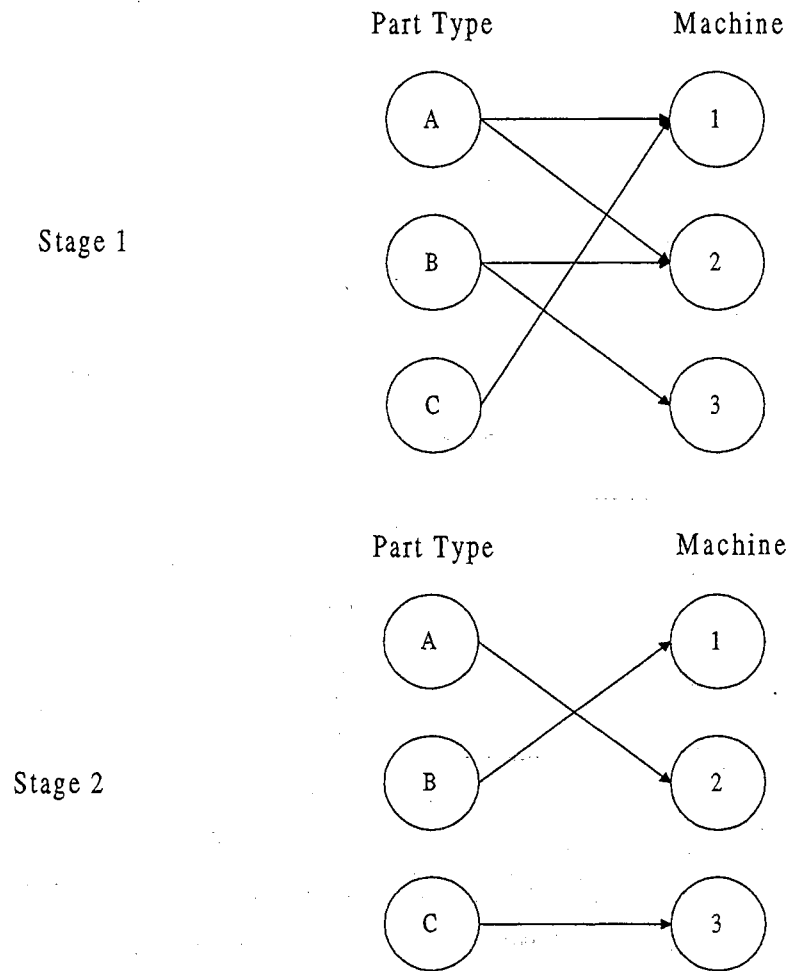


FIGURE 4-2 The Alternate Routings for a Two-stage Flow Shop

The developed measure is a relative measure that can compare the routing flexibility between systems that have identical number of stages and the number of available machines at each stage. The measure should not be applied to a standard flow line that has only one machine at each stage since there is no flexibility for this type of system. For the systems that have at least some routing flexibility, the values of routing flexibility measured by this method range from approximately 0 to 1.

In sum, the developed measure of routing flexibility has many advantages:

1. It is capable of dealing with multiple part types.
2. Production volumes for each part type are considered.

3. Overloading on specific machines is discouraged since it will result in a smaller value of routing flexibility.
4. The stages with higher average processing times (i.e., bottleneck stages) are given higher weights for their routing flexibility in order to encourage higher flexibility on these stages.

The JIT System

A multi-stage JIT system that allows multiple machines at each stage was utilized for studying the effects of routing flexibility in this research. This JIT system, as illustrated in Figure 4-3, is composed of four stages. Each stage consists of three machines capable of performing similar operations. The detailed physical configuration and operational characteristics of the system are described as follows.

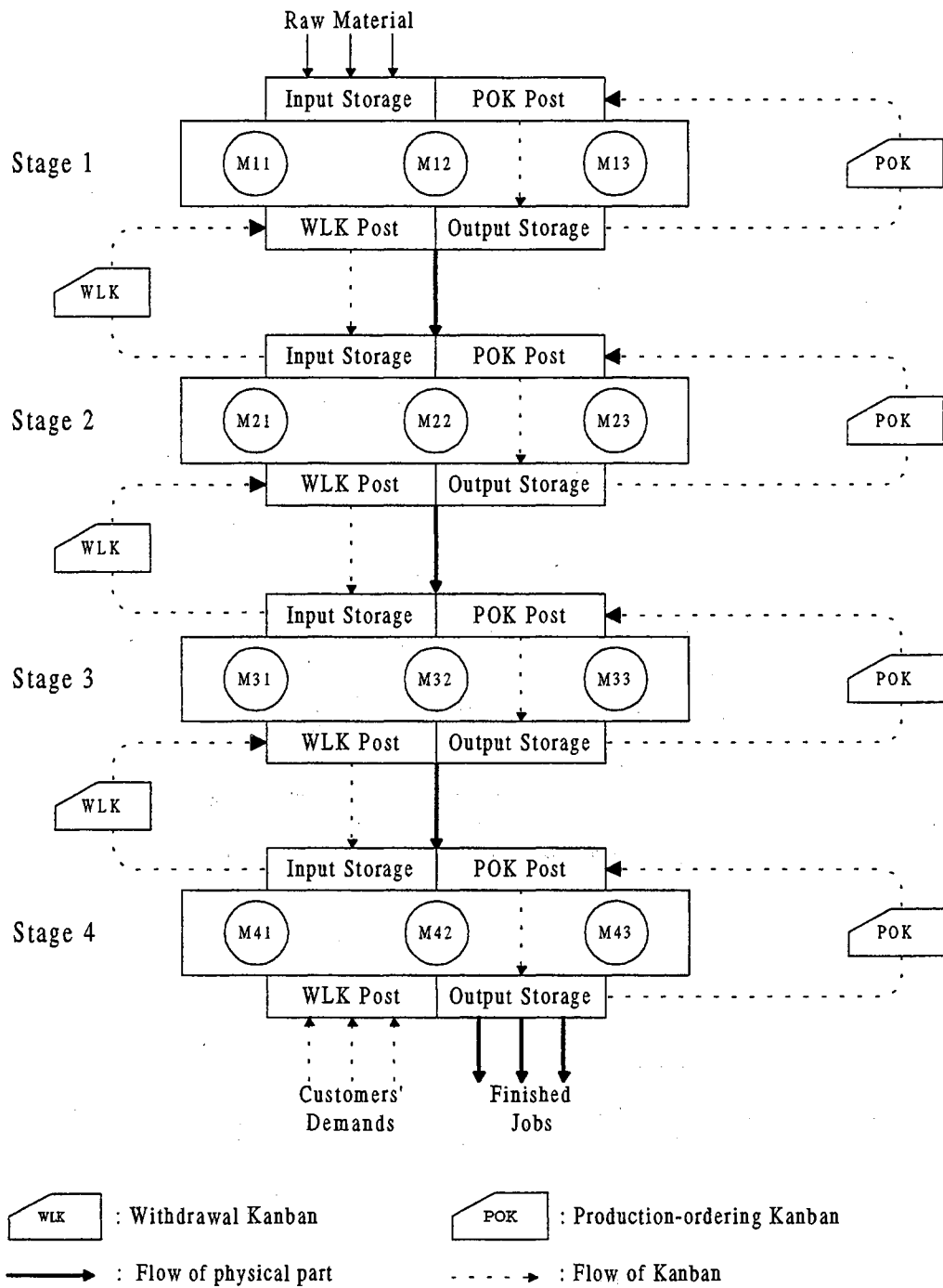


FIGURE 4-3 Physical Distribution of the 4-stage JIT System

Physical Configuration

The JIT system consists of four stages and operates similar to a flow shop. Nine different part types can be produced in this system. Each stage is responsible for performing a specific production operation that is required for every part that enters the system. Every part must be processed by each of the four stages starting from stage 1 to stage 4 in a fixed sequence. The daily demand rate follows a normal distribution. The average demand rates for each part type are given in Table 4-2. The standard deviations of these normally distributed demand rates are determined by the coefficient of variation which is served as one of the experimental factors.

TABLE 4-2 The Average Daily Demand Rate for Each Part Type

Part Type	1	2	3	4	5	6	7	8	9
Average Demand Rate	15	15	15	15	15	15	15	15	15

Dual Kanbans are utilized in this JIT system. A Production-Ordering Kanban (POK) specifies the information of the parts that the preceding stage must produce. A Withdrawal Kanban (WLK) specifies the part type and the quantity that the subsequent stage needs to withdraw.

Each stage contains an input buffer that is immediately before the stage and an output buffer that immediately follows. The input buffer includes an input storage area and a POK post while the output buffer is composed of an output storage area and a WLK post. The POK post collects the production-ordering Kanbans that are transported from the output buffer after the production in that stage is completed. The input storage area,

on the other hand, stores the required parts that are withdrawn from the preceding stage by the authorization of withdrawal Kanbans. The input storage area of the first stage (i.e., stage 1), however, is used to store incoming raw material.

The output storage area of a stage stores the parts that are produced at that stage. The WLK post of that stage is utilized to collect the withdrawal Kanbans transported from the input buffer of the subsequent stage. The WLK post of the last stage (i.e., stage 4) is responsible for receiving customers' orders rather than collecting withdrawal Kanbans.

Parts are stored in containers when they are moved between stages. The containers must be accompanied by either POKs or WLKs based on the Kanban mechanism described in the *operation characteristics*.

As illustrated in Figure 4, each stage consists of 3 machines. M_{kj} denotes the j th machine of stage k . For example, M_{32} represents the second machine in stage 3. The machines at the same stage are capable of performing similar but not identical operations.

A given part type can only be processed by a number of selected machines where required tools are available. If an alternate machine is made available for processing a specific part type, required tooling must be prepared and hence longer time is needed. As a result, extra processing time is incurred for an alternate machine to process this part type.

In this research, a part type can be processed by a primary machine, a first alternate or a second alternate machine, if they are available. Both the primary machine and alternate machines are assumed to be 100 percent efficient so that the effect of routing flexibility can be maximized. The processing times for each part type follow a normal distribution. The average processing times each part type consumes at each of the four stages are given in Table 4-3. The standard deviations of the normally distributed processing times are determined by the coefficient of variation which serves as the experimental factor.

TABLE 4-3 The Average Processing Times for Each Part Type

Part Type	1	2	3	4	5	6	7	8	9
Stage 1	8	10	12	8	10	12	8	10	12
Stage 2	8	10	12	8	10	12	8	10	12
Stage 3	8	10	12	8	10	12	8	10	12
Stage 4	8	10	12	8	10	12	8	10	12

Operational Characteristics

The operational characteristics of the system determine how physical parts and Kanbans move. The movement of parts and Kanbans between stages are regulated by the Kanban mechanism. Since multiple machines are available in each stage, routing decisions must be made to direct parts to appropriate machines for processing. The Kanban mechanism and routing decisions are discussed in the following sections.

Kanban Mechanism The two types of Kanbans utilized in the system are utilized to direct the parts' movement. The withdrawal Kanbans control the movement of parts from a stage's output storage to the input storage of the subsequent stage. The production-ordering Kanbans, on the other hand, authorize the production of parts and the parts' movement within a specific stage.

Customers' demands for specific part types arrive at the output buffer of stage 4. These demands are reviewed at the storage area so that available finished parts in the area can be shipped immediately. If no matched final products are found, the unfulfilled demands wait at the WLK post until the demanded parts become available. After the

demanded parts are withdrawn, the POKs attached to the containers are removed and are returned to the input kanban post of stage 4.

The detailed flow of Kanbans between adjacent stages is illustrated in Figure 4-4. For a container of a specific part type to be produced at stage n , both a POK and a container of the needed parts, that is accompanied by a WLK, must be present at the input buffer. The WLK is then replaced by the POK and is returned to the WLK post of stage $(n - 1)$ (i.e., the preceding stage). When the production activity of this stage is completed, the container of parts attached with the POK is stored in the output storage area until it is withdrawn to stage $(n + 1)$ (i.e., the subsequent stage) by a matched WLK.

To withdraw a container of a specific part type at stage n , a matched WLK at the WLK post and a container of that part type accompanied by the POK must be present at the output buffer. The POK is then detached from the container and is returned to the POK post of stage n awaiting the next production activity. The withdrawn container of parts along with the WLK is moved to the input storage area of stage $(n + 1)$.

The continuous swaps of WLK and POK pull the necessary parts through the stages "just in time" in order to meet customers' demands. The POKs always stay in the same stage and act as the intra-stage control apparatus. On the contrary, the WLKs move between stages and serve as the inter-stage control apparatus [Huang *et al.*, 1983].

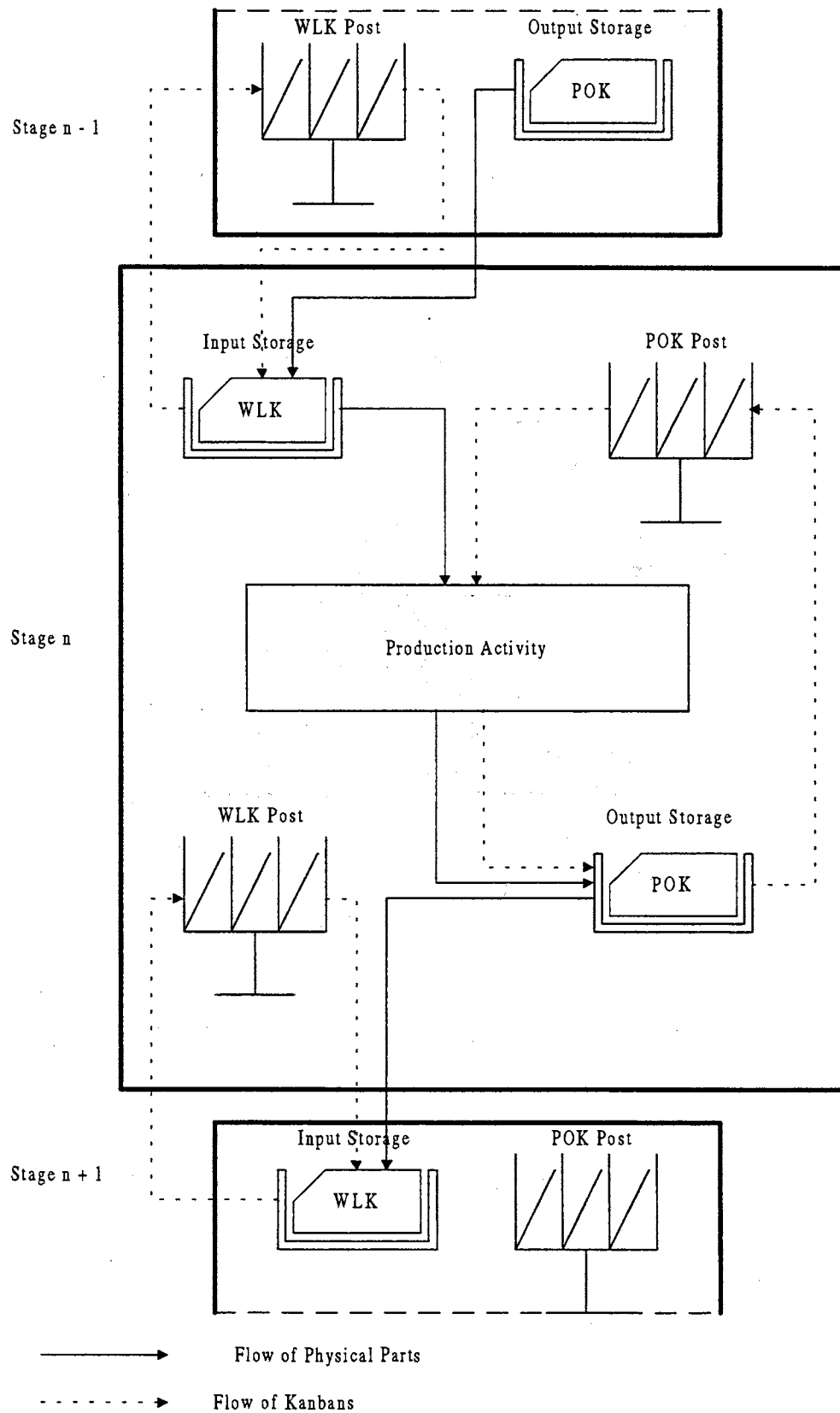


FIGURE 4-4 Flow of Kanbans between Adjacent Stages

Routing Decisions The routings of the nine different part types are determined in two hierarchical control levels. The higher control level determines primary and alternate machines for each part type before the system starts operation. The processing times for any part type being processed on the alternate machines are assumed to be identical to those being processed on the primary machine. The number of alternate machine for a part type is determined by the level of routing flexibility.

The lower control level determines the routings at the shop floor. The predetermined routes for a specific part type may not be upheld in two occasions:

1. The preferred machine is occupied by other parts,
2. The preferred machine has other part types waiting for it.

For each of the two occasions, the scheduling rules and the machine selection rules are utilized to direct the parts to appropriate alternate machines within that stage. The scheduling rules and machine selection rules used in this research will be presented in a separate section.

Assumptions for the System

A number of assumptions are made for this multi-stage JIT system. These assumptions are summarized as follows.

1. There is an infinite supply of raw material. The first stage can never be starved by waiting for raw material.
2. The transportation time for moving parts from one location to another is assumed to be zero.
3. The machines' setup times are negligible.
4. The processing times of the primary machines and alternate machines for a part type are identical.

5. Each part type has one production-ordering Kanban and one withdrawal Kanban at each stage.
6. The containers used for different part types have the same size. A container carries only one unit of part.
7. The batch size for each part type is one.
8. There are no scrapped or reworked parts.
9. There is no limit on the backorder size.
10. Production is started immediately as long as the required parts, a production-ordering Kanban, and an available machine are all ready. Withdrawal of part is instantly carried out if both a withdrawal Kanban, and the part waiting to be withdrawn are available.
11. Demands is recognized only at the beginning of each day.
12. Each production day consists of 480 minutes.
13. Preventive maintenance is well implemented. All machines are breakdown free.

Identification of Performance Measures

In this research, average work-in-process, throughput and the shortage of final products were chosen as the performance measures. Average WIP and throughput were selected because they are recognized as the most important and the most widely used performance measures in JIT related studies [Monden, 1993] [Chu and Shih, 1992]. The shortage of final products, on the other hand, aims at measuring the system's capability of meeting customers' variable demands. The three selected measures are described as follows.

1. Average work-in-process:

The average WIP was measured by calculating the average number of Kanbans at all Kanban posts. The customers' demands are assumed to arrive daily at the withdrawal Kanban post of stage 4. Therefore, the amount of backorder size incurred due to insufficient inventory at stage 4 is also considered as part of the WIP. Initially at system start up, withdrawal Kanbans and production-ordering Kanbans are attached to the containers that carry corresponding part types at the input storage and output storage areas respectively. WIP at this time is the customers' demands that arrive at the withdrawal Kanban post of stage 4. As the system starts operating, withdrawal Kanbans and production-ordering Kanbans are detached from the containers and are delivered to the appropriate Kanban posts for withdrawal or production of associated part types. It is noted that parts being processed are not regarded as WIP in this research since machines are busy for most of the time due to high system loading. Therefore, the average WIP in this research is more similar to the average number of requested parts. The average WIP is a collected statistic that was computed by the summation of the average length of eight queues (i.e., Kanban posts).

2. Throughput:

Throughput is the number of parts completed per unit of time. It was measured by dividing the total number of completed parts by the total units of time observed. The throughput hence can be expressed as:

$$\text{Throughput} = \frac{TP}{T}$$

where TP = the total number of parts produced,

T = the number of time units observed.

3. Shortage of final products (Backorder):

Shortage of final products is a measure of the unsatisfied demands for a period of time. It is defined as the lag between the total demands for that period and the number of finished parts at the end of that period. It is assumed that the unsatisfied demands for a day will become part of the demands for the next day.

$$\text{Backorder} = \sum_{i=1}^{TI} (PD_i - PP_i)$$

where i = part type

TI = the total number of part type

PD_i = the demand for part type i

PP_i = the number of produced parts for part type i

Scheduling Rules and Machine Selection Rules

The scheduling rules and the machine selection rules were utilized in this research to direct part flows throughout the system. The rules were either selected based on the literature or were developed based on the characteristics of the system used in this research.

Operation of the Control Methods

When a production-ordering Kanban of a specific part type is detached from the accompanied container, it is immediately transported to the production-ordering Kanban (POK) post located at the front area of that stage. This POK will match its corresponding part type with the parts in the input storage. If there is a match, that part type is said to be

qualified for production, otherwise, that POK must queue in the POK post and wait for a matched part type.

Figure 4-5 illustrates the part and machine selection rules within stage 1. The qualified part will be put into a queue of its part type. In this research, nine queues (P1, P2, ..., P9) were formed to accommodate the 9 part types.

The control method is a two-step control mechanism. The scheduling rules are activated when there is a need to select a part type for processing among a number of part types. On the other hand, the machine selection rules are activated when more than one machine is idle.

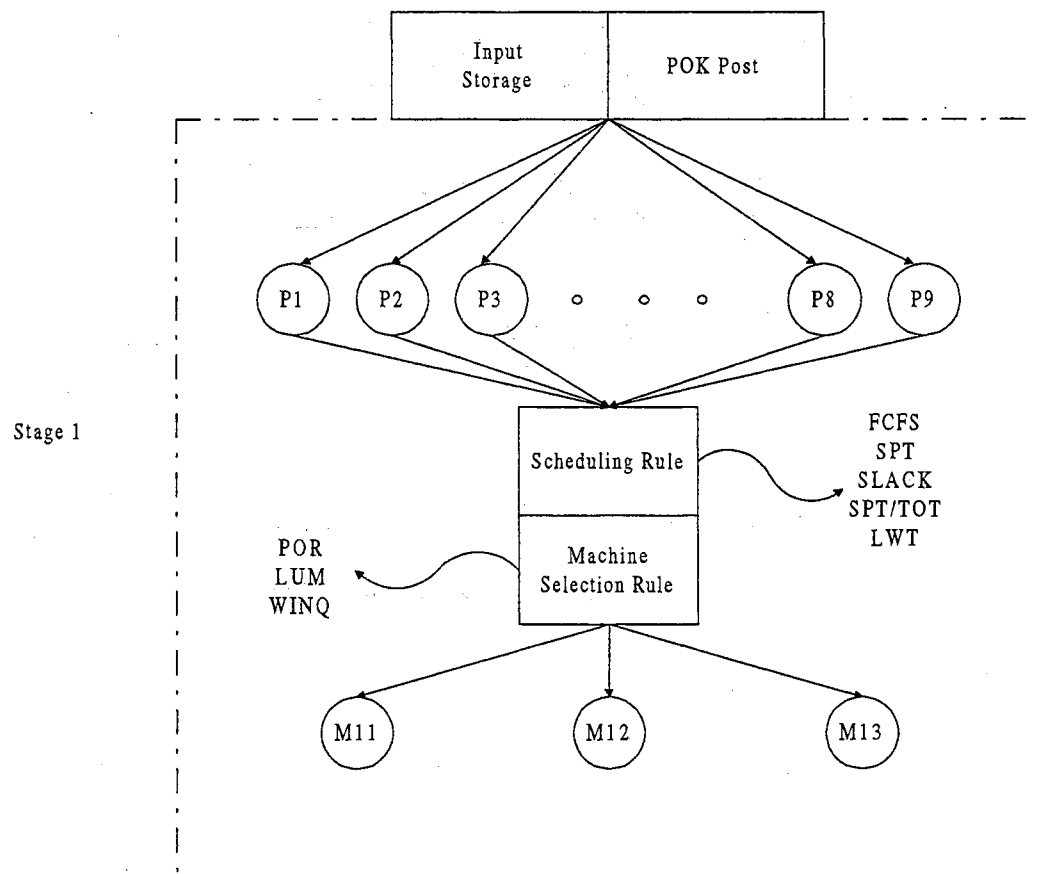


FIGURE 4-5 The Control Methods within a Stage

Initially, when the first part arrives at any one of the queues, no part type selection is needed. However, the machine selection rule is activated since all three machines are idle. Eventually, more part types arrive at the queues after they are qualified for production so that most machines will become busy. If all machines become busy, the arriving part type stays in its corresponding queue until one of the machines becomes idle.

When a machine becomes idle after it has completed a part, the scheduling rule is activated to select a part type for processing. If a corresponding part type (i.e., a part type that can be processed by this machine based on the planned routing) can be found, this machine starts processing that part, otherwise, it remains idle until an appropriate corresponding part type arrives.

It is noted that the scheduling rule is used to select among the first arrived part in each queue. In other words, a First Come First Served (FCFS) rule was applied to rank the parts in each queue if more than one part was accumulated. In this research, however, since only one withdrawal Kanban and one production-ordering Kanban was utilized for each part type, the number of parts in a queue was no more than one.

The following sections present the descriptions of these two types of rules.

Scheduling Rules

First Come First Served (FCFS), Shortest Processing Time (SPT), Shortest Imminent Ratio (SPT/TOT), Longest Waiting Time (LWT) and SLACK* rules were utilized in this research as the basic scheduling rules. The asterisk mark * for the SLACK* rule is used to differentiate it from the conventional SLACK rule.

For the conventional SLACK rule, slack is defined as the difference between the due date and the current time. For the SLACK* rule used in this research, slack is defined as the difference between the actual demand, which is considered as the target production

quantity, and the actually finished parts for a specific part type. In other words, the amount of slack is the number of to-be-produced parts for meeting the actual demand. SLACK* rule selects a part type that has the largest slack. The SLACK* rule can avoid producing a large proportion of a specific part type beyond what is demanded and hence help smooth the production quantity, which is one of the effective tools to incorporate demand changes for JIT systems.

SPT and FCFS are the two most studied scheduling rules in JIT related research [Lee, 1987] [Berkley and Kiran, 1991] [Berkley, 1993]. It is also noted that the majority of JIT systems in industry utilize FCFS to select from awaiting parts [Berkley, 1993].

The SPT/TOT rule selects a part type with the smallest ratio obtained by dividing the processing time of the imminent operation by the total processing time for that part [O'Keefe and Kasirajan, 1992]. It was selected because it can result in high throughput [Stecke and Solberg, 1981] and low makespan [Montazeri and Van Wassenhove, 1990]. The LWT rule selects a part type that has the longest waiting time for processing, i.e., has been waiting the longest as compared to other jobs in the queue. This rule aims at reducing the total waiting time in the system.

The five scheduling rules used in this research are described as follows. It is noted that the parts mentioned in these descriptions are for parts that are qualified for production (i.e., both corresponding POK and required parts are available).

FCFS Rule: The time when a part is qualified for production is marked as the time that the part arrives at the stage. These marked times are compared and the part type that has the earliest marked time is selected as the next to-be-processed part.

SPT Rule: The actual processing times for qualified part types at a specific stage are compared. The part type that has the shortest mean processing time is selected for processing.

SPT/TOT Rule: The ratios of SPT/TOT for qualified part types at a specific stage are compared. The part type that has the smallest SPT/TOT ratio is selected for processing.

LWT Rule: The waiting times for processing at a specific stage among part types are compared. The part type that has the largest waiting time is selected for processing.

SLACK* Rule: The slacks for qualified part types are compared. Here, slack is defined as the difference between the actual demand and the actually finished parts for a specific part type. The part type that has the largest slack is selected for processing.

Machine Selection Rules

The machine selection rules direct a part to an appropriate machine when multiple machines are available. In this JIT system, a part awaiting operation in the input storage area must select an appropriate machine among multiple qualified machines. The qualified machines are those that have been assigned in the routing table as either primary or alternate machines for that specific part type.

Three machine selection rules are utilized based on the system characteristics in this research. The Priority (PRIOR) rule selects a machine based on the order of primary machine, first alternate machine, and second alternate machine. The Least Utilized Machine (LUM) rule assumes the benefits of pursuing a balanced system and hence favors the machines with lower utilization. The LUM rule has been studied by O'Keefe and Kasirajan [1992].

The Modified Work IN Queue (MWINQ) rule modifies the WINQ (i.e., least work in queue in terms of processing time) rule in order to fit in a system having a central buffer

at each stage. A machine is selected if it has the least work in the current input storage in terms of processing time.

The three machine selection rules used in this research are described as follows:

PRIOR Rule: The awaiting to-be-processed part selects the machine based on the preferred order of primary machine, first alternate machine, and second alternate machine. In other words, the primary machine will be selected if it is idle, otherwise, the first alternate machine will be selected if it is available, and so on.

The reason of adopting the PRIOR rule is to have the processing time as short as possible since the processing time on the primary machine is assumed to be the shortest compared to the alternate machines.

LUM Rule: The awaiting to-be-processed part selects the machine that has the lowest utilization. The utilization rate for each machine at the same stage is reviewed when the LUM rule is to be utilized.

MWINQ Rule: The awaiting to-be-processed part selects the machine that has the least possible work (i.e., capable of processing) in the stage's input storage in terms of processing time.

Identification of Experimental Factors

The experimental factors are the independent variables that should have the greatest impact on the selected performance measures (i.e., average WIP, throughput, and backorder). The determination of these independent variables relies on the literature and the system characteristics. The identified experimental factors include: (1) routing

flexibility, (2) control method, (3) variability of processing time, and (4) variability of demand rate.

The following text discusses how these factors may have an effect on the system performance measures and the reasons. The levels of each experimental factor are also defined.

Routing Flexibility

Numerous studies have investigated the effects of routing flexibility on the performance of push-type FMSs. The results of these studies suggested that routing flexibility may affect utilization [Wilhelm and Shin, 1985] [Chen and Chung, 1991] [Ghosh and Gaimon, 1992], and WIP [Wilhelm and Shin, 1985] [Ghosh and Gaimon, 1992] [Benjaafar and Ramakrishnan, 1993].

Since the ultimate objective of this research is to investigate the effects of routing flexibility on a pull-type Kanban-controlled system, routing flexibility is a must-have experimental factor. The various degrees of routing flexibility will result from the different number of routings a part type is allowed.

In this research, three levels (i.e., low, medium, and high) of routing flexibility were selected for the experiment. The scenarios of the different levels of routing flexibility are illustrated by fixing the system with different number of combinations between part types and machines. Figures 4-6, 4-7, and 4-8 illustrate the scenarios of the three levels of routing flexibility.

A total of nine part types (1, 2, 3, ..., 9) that belong to three part families can be produced by the system. Part family 1 comprises part types 1, 2, and 3, while part family 2 consists of part types 4, 5, 6, and part family 3 includes part types 7, 8, 9. Machine

Mk1, Mk2, and Mk3 are the three machines at stage k. It should be noted that each scenario is applied to all four stages for this JIT system.

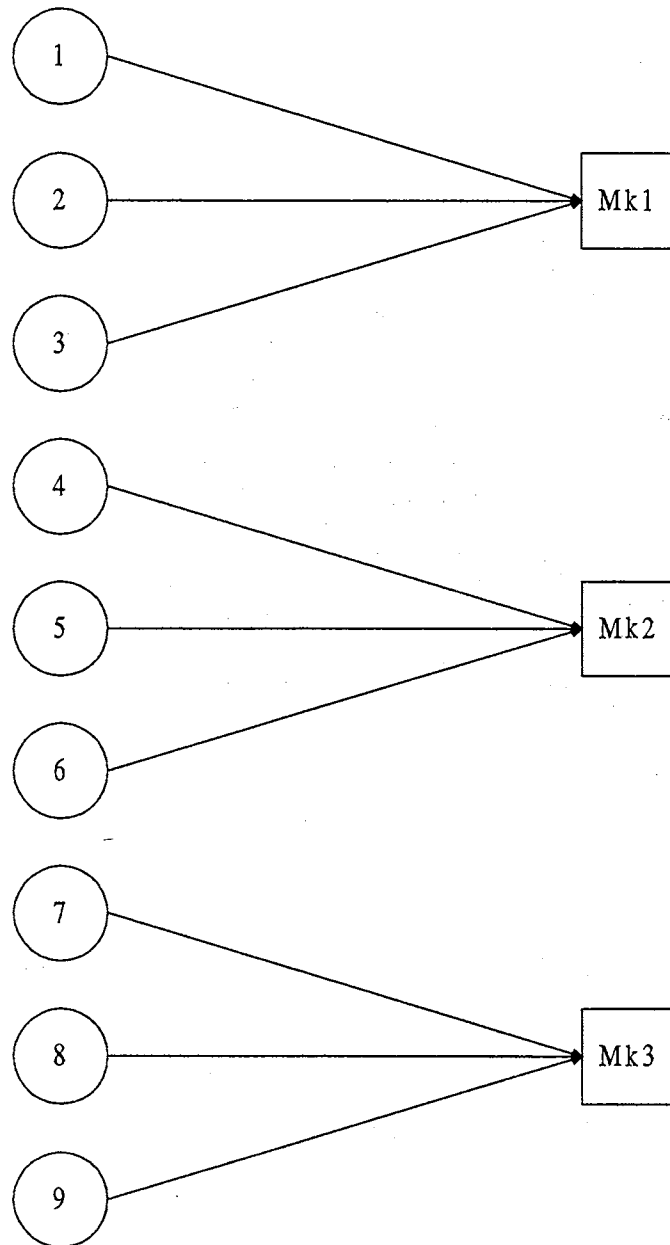


FIGURE 4-6 The Scenario of the Low Routing Flexibility

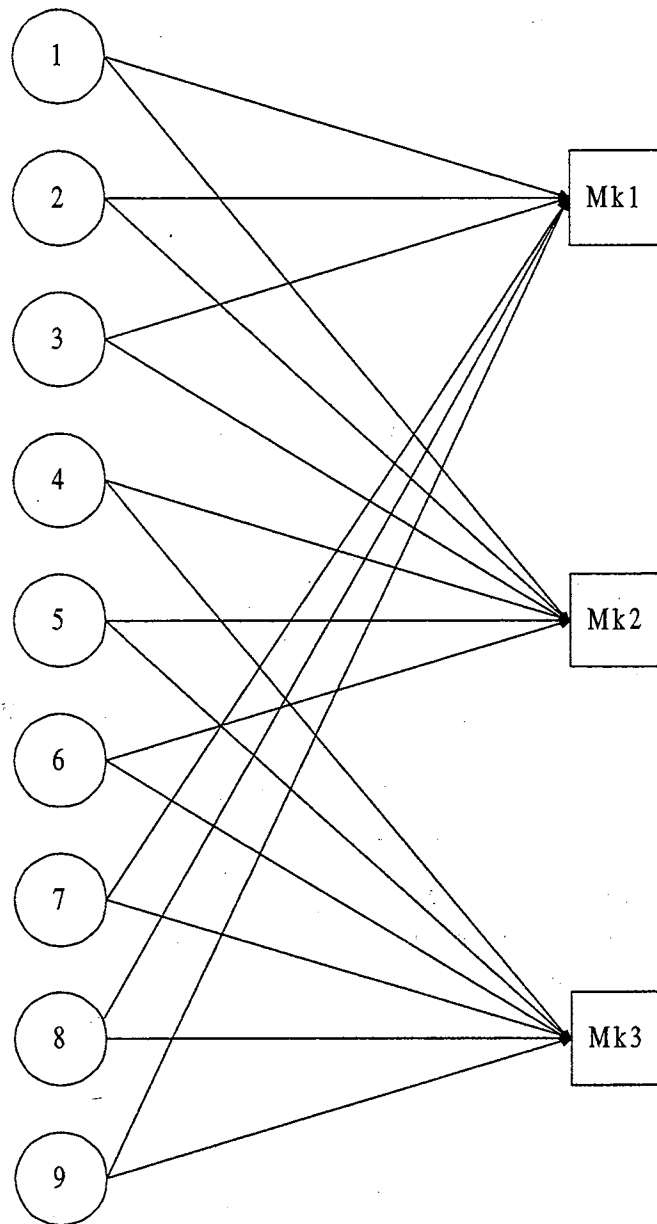


FIGURE 4-7 The Scenario of the Medium Routing Flexibility

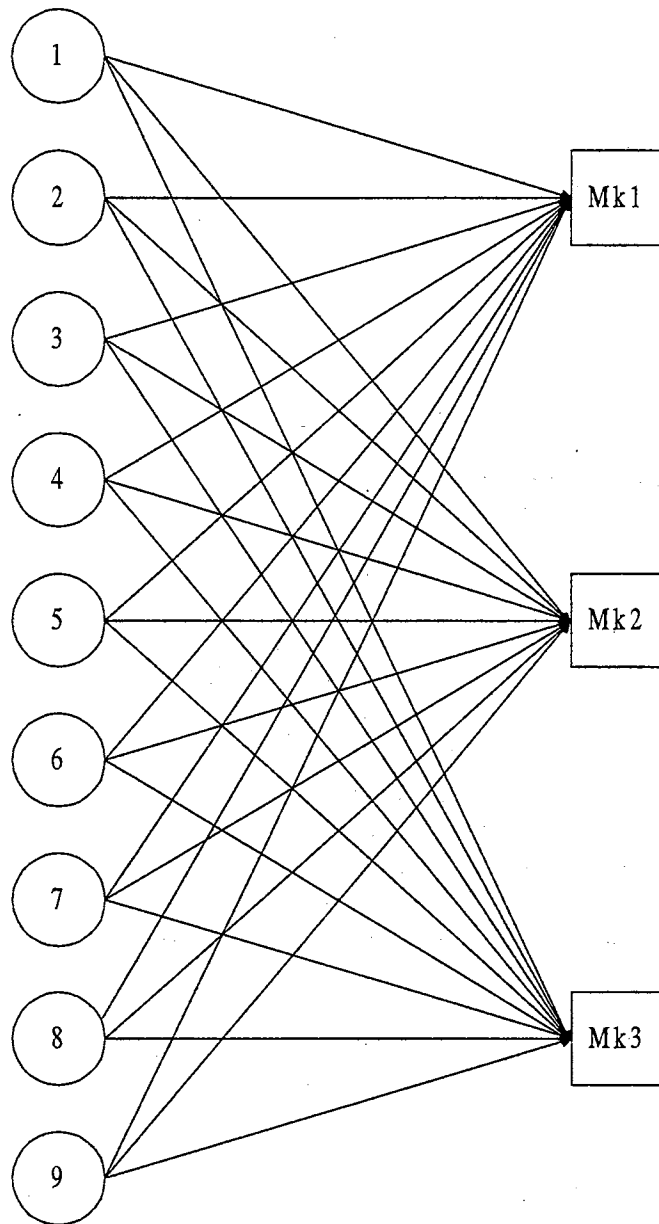


FIGURE 4-8 The Scenario of the High Routing Flexibility

For the low routing flexibility, each of the nine part types can only be processed by one primary machine at all stages. For the medium level of routing flexibility, each part type can be processed by one primary machine and a first alternate machine. For the highest level of routing flexibility, each part type can be processed by one primary machine, a first alternate machine, and a second alternate machine. The machine information for each part type is described in Table 4-4.

The routing flexibility for the three levels was measured by applying the equations developed in the section of "measurement of routing flexibility". As a result, the values of the three levels of routing flexibility are 0.3333, 0.6667, and 1.0000 respectively.

TABLE 4-4 Machine Information for Each Part type

Part type 1, 2, 3:	Primary machine: M11, M21, M31, M41
	First alternate machine: M12, M22, M32, M42
	Second alternate machine: M13, M23, M33, M43
Part type 4, 5, 6:	Primary machine: M12, M22, M32, M42
	First alternate machine: M13, M23, M33, M43
	Second alternate machine: M11, M21, M31, M41
Part type 7, 8, 9:	Primary machine: M13, M23, M33, M43
	First alternate machine: M11, M21, M31, M41
	Second alternate machine: M12, M22, M32, M42

Control Method

The control method is the tool to resolve conflicts between machine selection and part selection in order to direct parts through the system. In this research, the control methods include the scheduling rules and machine selection rules. Both types of rules

were utilized in the studies of routing flexibility so that the selection conflict due to multiple routes could be resolved. Therefore, the control method is an experimental factor.

The scheduling rules and machine selection rules are used to control part flows at the operational level of system control. The results of numerous studies concluded that these rules can improve selected system performance measures which include the three measures employed in this research [Montazeri and Van Wassenhove, 1990]. However, no single rule has been found to outperform the other rules for each of the three performance measures.

In this research, five control methods were selected through the phase 1 experiment (discussed later in the section on the experimental model). The selected five control methods were investigated in the second experiment.

Variability of Processing Time

A perfectly balanced production system has identical processing times at different stages so that parts can flow through the system without being idle at the storage area. However, in reality, the processing times at the machines of each stage vary due to constraints such as different machine and tool setup, or different operations required.

An ideal Kanban-controlled pull-type system should be perfectly balanced in order to achieve the goal of inventory minimization. The variability of processing time will imbalance the Kanban system and hence should affect the system performance. Alternate routing that can direct part types through alternate machines with various processing times appears to be a solution to reduce the effect of the variability of processing times. Therefore, the variability of processing time is included as one of the experimental factors to portray a more realistic system.

Past research [Huang *et al.*, 1983] [Sarker and Harris, 1988] [Villeda *et al.*, 1988] has suggested that variable processing times at different stages of a pull-type JIT flow shop is responsible for increases in WIP, and decreases in throughput and system utilization. The variability of processing time in this research is represented by the coefficient of variation of the processing time (C_{pv}) which is measured by the proportion of the standard deviation to the mean value.

In this research, two levels of the variability of processing time were studied. The low level of variability is represented by $C_{pv} = 0.1$, while the high level of variability is $C_{pv} = 0.3$.

Variability of Demand Rate

For an ideal JIT production system, the monthly master production schedule must be frozen or nearly frozen in order to avoid fluctuating production. As a result, scheduled daily production quantities (i.e., daily demand rate) must also be kept as constant as possible. Huang *et al.* [1983] concluded that the firms which experience large demand fluctuations are not suitable for the implementation of a JIT system.

The variability of the demand rate has been used as an experimental factor by several researchers [Huang *et al.*, 1983] [Chaturvedi and Golhar, 1992] to realize its effect on the performance measures of a JIT system. It was concluded that the throughput of the JIT flow shop is decreased when the variability of the demand rate increases.

The variability of demand rate is represented by the coefficient of variation of the demand rate (C_{dv}). In this research, two levels of the variability of demand rate were studied. The low level of variability is represented by $C_{dv} = 0.1$, while the high level of variability by $C_{dv} = 0.3$.

Experimental Model

Four experimental factors were identified for this research. The purposes of using these factors is discussed in the section on "identification of experimental factors". The four experimental factors identified are routing flexibility, control methods, variability of demand rate, and variability of processing time.

In this research, a two-phase experiment was designed to fulfill the research objectives. The first-phase experiment aims at finding the control methods that have good performance for the multi-stage flexible JIT system. These "good" control methods serve as the various treatments for the second-phase experiment which was conducted for examining the effects of routing flexibility and the selected experimental factors on the performance of this multi-stage JIT system.

Phase 1

In this phase, 15 control methods were evaluated with respect to the selected performance measures. The best 5 methods were identified and served as the treatments for an experimental factor for phase 2.

To conduct the experiment in this phase, the other three experimental factors were held constant at:

Routing flexibility = 0.6667, $C_{dv} = 0.3$, and $C_{pv} = 0.3$.

The routing flexibility for this experiment is set at the medium level (i.e., 0.6667). The reason for selecting a medium routing flexibility is that the difference between the effects of control methods diminishes as the degree of routing flexibility increases [Benjaafar and Ramakrishnan, 1993]. Therefore, the highest level of routing flexibility (i.e., 1.000) was neglected because of the less significance between the effects of the

control methods. The lowest level of routing flexibility (i.e., 0.3333) was ignored because the machine selection rules could not be applied.

The higher levels of variation on both demand rate and processing time (C_{dv} and C_{pv}) were selected so that the system is more imbalanced. The selection was made because the effects between control methods are more likely to show significant differences in an imbalanced system than a balanced one.

Phase 2

In this phase, the four identified experimental factors were included and tested in order to examine the effects of these factors with respect to the selected performance measures. The various levels for each experimental factor are listed in Table 4-5. A full factorial design was conducted for this research utilizing all levels of each experimental factor. Table 4-6 shows the list of experiments that were conducted and the treatment combinations among the four experimental factors.

TABLE 4-5 Levels of Experimental Factors

Experimental Factor	Level	Description
Routing Flexibility	Low	0.3333
	Medium	0.6667
	High	1.0000
Control Method	1	Control Method 1
	2	Control Method 2
	3	Control Method 3
	4	Control Method 4
	5	Control Method 5
Variability of Demand Rate	Low	$C_{dv} = 0.1$
	High	$C_{dv} = 0.3$
Variability of Processing Time	Low	$C_{pv} = 0.1$
	High	$C_{pv} = 0.3$

TABLE 4-6 Experiments to Be Conducted

Routing Flexibility	Control Method 1			
	$C_{dv} = 0.1$		$C_{dv} = 0.3$	
	$C_{pv} = 0.1$	$C_{pv} = 0.3$	$C_{pv} = 0.1$	$C_{pv} = 0.3$
RF = 0.3333	Exp. 1	Exp. 2	Exp. 3	Exp. 4
RF = 0.6667	Exp. 5	Exp. 6	Exp. 7	Exp. 8
RF = 1.0000	Exp. 9	Exp. 10	Exp. 11	Exp. 12

Routing Flexibility	Control Method 2			
	$C_{dv} = 0.1$		$C_{dv} = 0.3$	
	$C_{pv} = 0.1$	$C_{pv} = 0.3$	$C_{pv} = 0.1$	$C_{pv} = 0.3$
RF = 0.3333	Exp. 13	Exp. 14	Exp. 15	Exp. 16
RF = 0.6667	Exp. 17	Exp. 18	Exp. 19	Exp. 20
RF = 1.0000	Exp. 21	Exp. 22	Exp. 23	Exp. 24

Routing Flexibility	Control Method 3			
	$C_{dv} = 0.1$		$C_{dv} = 0.3$	
	$C_{pv} = 0.1$	$C_{pv} = 0.3$	$C_{pv} = 0.1$	$C_{pv} = 0.3$
RF = 0.3333	Exp. 25	Exp. 26	Exp. 27	Exp. 28
RF = 0.6667	Exp. 29	Exp. 30	Exp. 31	Exp. 32
RF = 1.0000	Exp. 33	Exp. 34	Exp. 35	Exp. 36

Routing Flexibility	Control Method 4			
	$C_{dv} = 0.1$		$C_{dv} = 0.3$	
	$C_{pv} = 0.1$	$C_{pv} = 0.3$	$C_{pv} = 0.1$	$C_{pv} = 0.3$
RF = 0.3333	Exp. 37	Exp. 38	Exp. 39	Exp. 40
RF = 0.6667	Exp. 41	Exp. 42	Exp. 43	Exp. 44
RF = 1.0000	Exp. 45	Exp. 46	Exp. 47	Exp. 48

TABLE 4-6 (Continued)

Routing Flexibility	Control Method 5			
	$C_{dv} = 0.1$		$C_{dv} = 0.3$	
	$C_{pv} = 0.1$	$C_{pv} = 0.3$	$C_{pv} = 0.1$	$C_{pv} = 0.3$
RF = 0.3333	Exp. 49	Exp. 50	Exp. 51	Exp. 52
RF = 0.6667	Exp. 53	Exp. 54	Exp. 55	Exp. 56
RF = 1.0000	Exp. 57	Exp. 58	Exp. 59	Exp. 60

Statistical Analysis Procedures

The procedures of statistical analysis depend on how the experiment was designed. Each of the two phases in the experiment required different types of comparisons so that the objectives of these experiments could be achieved. The results of the two experiments were analyzed by the following two statistical tests.

1. F-test and Duncan's test for phase 1 to select five control methods:

The performance measures from different scheduling rules and machine selection rules were examined by a two-way analysis of variance (ANOVA). An F-test at 0.10 significance level was used to see if there are significant differences between different scheduling rules and different machine selection rules with respect to three performance measures. Duncan's new multiple-range test was then utilized to compare the performance of these rules if there are significant differences between these rules.

A total of five control methods was selected based on the results of statistical analysis. These selected control methods later served as the different treatments for the experiment that examined the routing flexibility and other experimental factors.

A total of five control methods was selected based on the results of the statistical analysis. These selected control methods later served as the different treatments for the experiment that examined the routing flexibility and other experimental factors.

2. Analysis of variance (ANOVA) for phase 2 to examine the effects of routing flexibility and the experimental factors with respect to the three performance measures:

For the experiment that examined experimental factors with respect to each of the three performance measures, the ANOVA was conducted to obtain the variances between and within the experimental factors. An F-test was then utilized to decide whether there is a significant difference between the means of a specific performance measure incurred by the experimental factors and the interaction among the four experimental factors. This F-test was performed at a significance level of 0.10.

Simulation Model

Selection of a Simulation Language

Simulation was utilized in this research as a tool to model the multi-stage JIT system because of simulation's ability to model complex systems. The conversion of a conceptual model into a simulation model can be carried out by employing either *general-purpose computer languages* or *simulation languages* [Law and Kelton, 1991].

Simulation languages are computer packages that are written by general-purpose language featuring certain types of simulation capability. SIMAN, SLAM II, SIMSCRIPT II.5 and GPSS are the most widely used simulation languages in the United States [Law and Kelton, 1991]. SIMAN and SLAM II are the two mostly employed in academic research

[Chu and Shih, 1992]. In this research, SLAM II [Pritsker, 1986], a FORTRAN-based language, was selected for simulating the conceptual JIT model because it is available on the mainframe computer at Oklahoma State University.

SLAM II provides a natural framework for simulation modeling so that the users can easily build simulation models and edit them when needed. The framework is a network structure consisting of specialized nodes and branches that can be used to model resources, queues, activities, and part flow decisions [Pritsker, 1986]. In addition, users can develop customized FORTRAN subroutines to model complicated activities and processes. The additive user-written subprograms greatly enhance the modeling flexibility for simulation studies.

The Simulation Model

The SLAM II model is made up of two major parts: the SLAM II network and the FORTRAN subprograms. The SLAM II network is the backbone of the simulation model which provides the framework of the JIT model. The FORTRAN subprograms support the SLAM II network to deal with complicated tasks such as file manipulations, dedicated calculations, and the selection of queues and servers. The SLAM II network and statements are presented in Appendixes A and B respectively. The FORTRAN subprograms are not presented in this dissertation but are available from the author upon request.

1. SLAM II Network

The SLAM II network (see Appendix A) is a group of nodes and branches capable of modeling queues, processing activities, and the flow of parts. In this research, three SLAM II networks were constructed to represent three levels of routing flexibility. In each network, CREATE nodes are utilized to initiate the network and control the duration

of the simulation. EVENT nodes (1, 2, ..., 9) are then used to assign attributes to each part type. These attributes include part identity, processing times at each stage, and the daily demand rate for that part type. Demands for each of the nine part types are created by the ENTER nodes (DEM1, DEM2, ..., DEM9).

These demands are placed in the queue for the withdrawal Kanban post at stage 4 (WLK4 node) waiting to withdraw available finished parts stored in the output storage (OS4 node). The withdrawal of parts is carried out only when the attribute of part type between WLK4 and OS4 is matched (AW4 node). The unfilled demands wait in WLK4 until the corresponding part types become available in OS4.

After the demanded parts are withdrawn, they proceed to the node SHIP, and terminate after the statistics are collected. Production-ordering Kanbans (POK) are detached from the containers that carry the withdrawn parts. These POKs will be moved to the POK post located at the front area of stage 4 (POK4). Node AP4 reviews the part attributes between the available parts in the queue of input storage (IS4) and the POK in node POK4. If there is a match, the matched part is now ready for production, otherwise, it waits in queue until its counterpart (i.e., a POK or an available part) becomes available.

Two branches are taken from node GI4 after the matching of a POK and its corresponding required part. A WLK is detached from the container that carries the matched part and is hence transported to the WLK post at stage 3 (WLK3 node). Node GP4 assigns the current time (i.e., TNOW) as an attribute to each part that qualifies for production. The following EVENT node is used to manipulate the global variables that will later be utilized as the parameters for the control methods.

The to-be-processed part is then routed to a queue of its part type (PT41, PT42, ..., PT49) before it can be processed. Three different networks were utilized to model the part type and machine selections for the three levels of routing flexibility. For the low routing flexibility ($RF = 0.3333$), since each part type can only be processed by one primary machine at each stage, a part can be routed to either PD41, PD42, or PD43

according to its part type. PD41, PD42, and PD43 are select nodes where each has a user-defined NQS rule that is used to perform the selection of a preferred part type.

For the medium and high level of routing flexibility, each part type can be directed to two or all of the three select nodes (PD41, PD42, and PD43) since each part type can be processed by two and three machines respectively. In these two networks, both user-defined NQS and NSS rules are needed to determine the preferred part type and appropriate machine respectively.

The machine processing time for a part is determined according to the mean processing time specified for this part type and the variation of processing time utilized for the experiment. When a part has finished being processed, it is placed in the output storage at stage 4 (OS4 node), and its part type is reviewed by the demands in WLK4 in order to find a match and hence to be withdrawn.

The networks for stages 3, 2, and 1 are similar to the stage 4 network just presented. The link between each stage of this pull-type Kanban-controlled JIT system is maintained by the intra-stage movement of POKs and the inter-stage movement of WLKs.

2. FORTRAN Subprograms

The FORTRAN subprograms are constructed for more detailed and complicated tasks. These FORTRAN subprograms include a number of subroutines and functions. The names and descriptions of these subprograms are presented as follows.

- SUBROUTINE INTLC:

This subroutine is used to set initial conditions such as the demands for each part type, the initial inventory for each input and output storage area, and the planned routes for every part type. The SLAM II processor calls subroutine INTLC at the beginning of each simulation run.

- **SUBROUTINE OTPUT:**

This subroutine is used to calculate desired performance measures and collect needed statistics. The SLAM II processor calls subroutine OTPUT at the end of each simulation run and the collected statistics are shown in the summary report.

- **SUBROUTINE EVENT:**

This subroutine is used to assign attributes to each of the nine part types and to calculate global variables that will be used as the parameters of control methods.

The subroutine EVENT is called when an entity arrives to an EVENT node in the SLAM II network. The logic for these EVENT nodes is presented in Appendix C.

- **FUNCTION NQS:**

This user-defined function NQS is used to perform the selection of a part type which is waiting for processing through the desired queue selection logic. The call of function NQS will return either the file number of the selected queue , or zero if no selection is made, to the SLAM II network. The first part of the selected part type is hence taken from the queue and tries to find a processing machine through the function NSS. The flowcharts that describe how NQS functions operate are presented in Appendix D.

- **FUNCTION NSS:**

This user-defined function NSS is used to perform the selection of processing machines through the desired service activity selection logic. The call of function NSS will return either the activity number of the selected service activity, or zero if no selection is made, to the SLAM II network. If an appropriate service activity is selected the part selected by the function NQS will be routed to the selected activity for processing. The flowcharts that describe how NSS functions operate are presented in Appendix E.

Verification and Validation

Before a simulation model can be used to generate useful experimental information, it must be verified and validated. *Verification* aims at determining that the simulation program performs as expected. *Validation* is concerned with exploring the accuracy of system representation for the conceptual simulation model. In this research, validation on the representation of a real system was ignored since no real world systems are available for this multi-stage JIT system.

To verify the simulation model developed in this research, the following tests were conducted.

1. The three SLAM II networks, each represents a routing flexibility level, were simulated for 1500 days (i.e., 720,000 minutes) with 10 replications. The total number of finished parts was compared to the mean demand rates for all part types. The average machine utilization was collected and compared to the system loading. The system loading is a measure calculated by dividing the required working hours to the system capacity. In this research, the system loading is 93.75%. Table 4-7 shows that the average system utilization for the three networks is very close to the system loading. The mean total demand (i.e., $9 \times 15 \times 1500 = 202,500$) is then compared with simulated total demand which is the sum of the total output and the backorder. Table 4-8 shows that these two figures are very close.

TABLE 4-7 The Average Utilization for the Three Levels of Routing Flexibility

	Level 1	Level 2	Level 3
Average Utilization	93.742%	93.7525%	93.7543%
Difference with System Loading	-0.0085%	0.0027%	0.0046%

TABLE 4-8 The Average Throughput and Backorder Size
for the Three Levels of Routing Flexibility

	Level 1	Level 2	Level 3
Average Total Output	202454	202475	202480
Average Backorder	21	4.3	2.5
Average Total Demand	202475	202479.3	202482.5

2. Each of the three SLAM II networks was simulated for one day. The control statement "MONTR, TRACE" was utilized to trace the flow of entities and the activity (machine) numbers that have been utilized. The part types of these traced entities were compared with the activity number they encounter to see that if the routings are appropriate according to the flexibility. For example, under the low level routing flexibility (i.e., $RF = 0.3333$), each part family can only be processed by one machine at each stage. Therefore, the activity numbers for the traced entity must always agree with the attribute of the corresponding part family. The results showed that the each part type is only processed by the appropriate machines under each of the three routing flexibility levels.

3. Each of the control methods was tested on each of the three SLAM II networks. The control statement "MONTR, TRACE" was utilized to trace the entities and their associated attributes as well as global variables related to the implementation of the control methods. The trace reports for all control methods were examined with care by tracing the flow of entities and comparing the related variables to make sure these control methods functioning as expected. The results of the trace reports show that appropriate part type is selected based on the criteria of a specific scheduling rule. On the other hand, an appropriate machine is selected according to the criteria of a specific machine selection rule.

Steady-state Behavior

The simulation models were tested to examine their steady-state behavior. The steady-state behavior was observed by plotting each of the performance measures against time. A warm-up period for the simulation study was determined by taking the minimum required time span required to achieve steady-state. In this research, the steady-state for average backorder can not be reached since its size relies heavily on the daily demand. As a result, the measure of average backorder varies from time to time.

The simulation model was tested for the period of 400 days. All of the three SLAM II networks with different control methods were tested. Figure 4-9 shows the steady-state behavior of the average throughput for the three routing flexibility levels. The simulation model achieves steady-state status after about 260 days. Figure 4-10 shows that the average WIP reaches steady-state after about 300 days.

The research model was hence simulated for 400 days with the first 300 days being considered as the warm-up period. The performance measures from the last 100 days were collected as the steady-state statistics of the system. This simulation model was run with 10 independent replications to calculate the central tendency in the performance measures. Different random numbers were used for each replication so that a replication is independent to the others. These random numbers were randomly selected from a random number table.

To justify the number of replications for the simulation model, a 90 percent confidence interval was constructed for the steady-state mean values of the performance measures under all of the 15 control methods. It was found that for both throughput and average WIP obtained by the 15 control methods, the half-length of the 90 percent confidence interval was less than 5 percent of the mean values. In the case of the average backorder, the half-length was mostly between 10 and 20 percent of the mean value. To

avoid very long simulation execution time, it was decided that this level of statistical accuracy was satisfactory for this research.

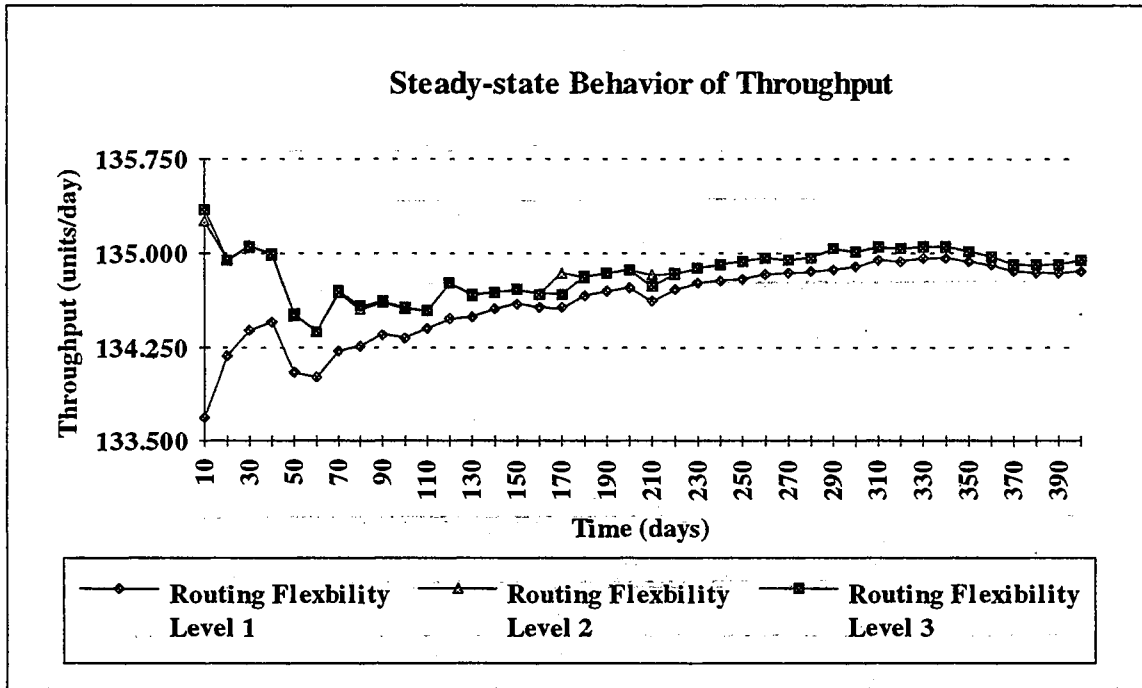
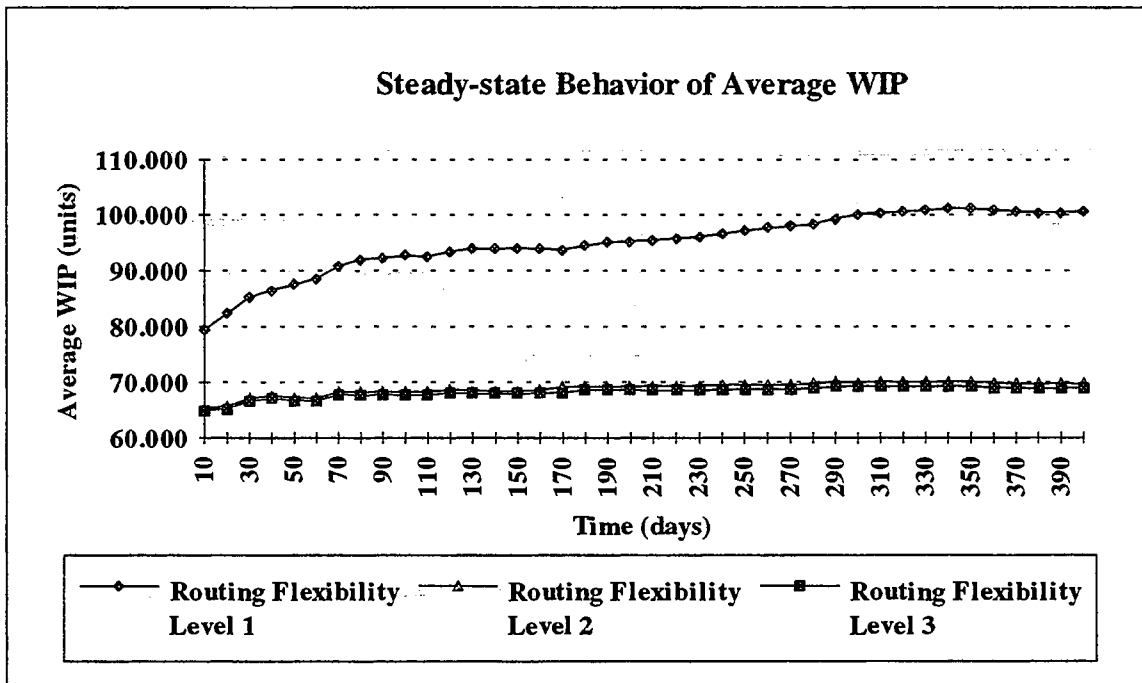


FIGURE 4-9 The Steady-state Behavior of the Throughput



CHAPTER V

STATISTICAL ANALYSIS AND INTERPRETATION OF RESULTS

Introduction

This chapter presents the results, statistical analysis and interpretation of the simulation results for the experiment model. For the phase 1 experiment, a summary of the data resulting from the simulation experiment is presented. The results of a two-way ANOVA tested by an F-test at 0.10 significance level are summarized to show the significance between different scheduling rules and machine selection rules with respect to three performance measures. The performance of these rules analyzed by Duncan's new multiple-range test is then described and the selection of five control methods is made.

For the phase 2 experiment, a summary of the experiment results is presented first. An analysis of variance (ANOVA) tested by an F-test at 0.10 significance level was utilized to analyze the results to examine the effects of the four experimental factors with respect to the performance measures. The interaction among these factors with respect to the performance measures was also studied. Finally, the results of the ANOVA were interpreted and conclusions were drawn.

These results and analysis are only applicable for the specific scenarios studied. Generalizations have been made where appropriate.

Phase 1 Experiment

The purpose of the phase 1 experiment was to determine the control methods that could serve as the various treatments within the experimental factor control method. To model the performance of various control methods, the other three experimental factors (i.e., routing flexibility, the variability of demand rate, and the variability of processing time) were held constant when the control methods were varied. The routing flexibility level was set at 0.6667 (i.e., level 2) while the coefficient of variation for both the demand rate and processing time were 0.3.

Tables 5-1, 5-2, and 5-3 show the average performance measures for each control method over 10 replications. For each replication, there is a 300 day warm-up period and the statistic data was collected for 100 days. A two-way ANOVA tested by an F-test was performed to detect the significant differences between different scheduling rules and different machine selection rules with respect to the three performance measures.

TABLE 5-1 The Average Throughput for Each Control Method
(Parts/day)

		Scheduling Rule				
Machine Selection Rule		FCFS	SPT	SLACK*	SPT/TOT	LWT
	PRIOR	134.75	134.72	134.78	134.75	134.73
	LUM	134.76	134.81	134.78	134.76	134.73
	MWINQ	134.75	134.72	134.76	134.76	134.72

TABLE 5-2 The Average Backorder Size for Each Control Method
(Number of parts)

		Scheduling Rule				
		FCFS	SPT	SLACK*	SPT/TOT	LWT
Machine Selection Rule	PRIOR	18.2	30.9	13.8	20.9	21.0
	LUM	18.0	31.7	13.8	20.8	20.9
	MWINQ	18.4	32.8	15.7	20.8	21.8

TABLE 5-3 The Average WIP for Each Control Method
(Number of parts)

		Scheduling Rule				
		FCFS	SPT	SLACK*	SPT/TOT	LWT
Machine Selection Rule	PRIOR	69.252	77.758	70.048	75.359	70.648
	LUM	69.262	78.262	69.929	75.947	70.800
	MWINQ	69.234	78.299	70.132	75.694	70.832

The results of the F-test are summarized in Table 5-4. It appears that various control methods do not exhibit statistically significant effects on system throughput. The selection of different scheduling rules and machine selection rules do not affect the throughput for this multi-stage JIT system. The system throughput of a JIT system is mainly affected the number of Kanbans and the demand rate. Although some control methods can speed up the part flows and hence reduce the backorder size and average WIP, system throughput is not significantly increased.

The F-test also indicates that machine selection rules appear to have no significant effects on all three performance measures. This is probably because of the high system loading (93.75%) and the use of centralized Kanban posts and storage areas between different stages for this JIT system. Therefore, the performance between different machine selection rules was not studied because of their insignificant effects on performance

measures. Scheduling rules, however, do exhibit significant effects on backorder and average WIP for this JIT system. This result suggests that some scheduling rules have better performance on backorder and average WIP than others.

TABLE 5-4 Summary of the Results of the ANOVA for Phase 1 Experiment

Throughput					
Source	DF	Mean Square	F value	p value	Significance
Model	6	0.009	0.00	1.0000	
Scheduling rule	4	0.010	0.00	1.0000	
Machine selection rule	2	0.007	0.00	0.9972	
Error	143	2.464			
Backorder					
Source	DF	Mean Square	F value	p value	Significance
Model	6	898.293	1.63	0.1427	
Scheduling rule	4	1321.377	2.40	0.0529	*
Machine selection rule	2	52.127	0.09	0.9098	
Error	143	550.762			
Average WIP					
Source	DF	Mean Square	F value	p value	Significance
Model	6	288.029	9.92	0.0001	*
Scheduling rule	4	413.768	14.24	0.0001	*
Machine selection rule	2	36.551	1.26	0.2873	
Error	143	29.048			

In order to compare the performance of different scheduling rules, Duncan's new multiple-range test was conducted at 0.10 significance level. The results of Duncan's test are shown in Table 5-5. In this table, control methods that are grouped before and after "===" have significantly different performance at a significance level of 10%. Throughput is excluded from this table since the F-test indicates that both scheduling rules and machine selection rules have no significant effects on system throughput.

TABLE 5-5 The Performance of the Scheduling Rules

Backorder	Average WIP
SLACK*	FCFS
FCFS	SLACK*
SPT/TOT	LWT
LWT	SPT/TOT
SPT	SPT

The results of Duncan's test on the scheduling rules with respect to backorder and average WIP are discussed below. Notice that the performance measures for these scheduling rules are under a JIT system that has high variation of demand rate, high variation of processing time, and is equipped with medium level of routing flexibility.

Backorder

The results of Duncan's test indicate that SLACK*, FCFS, and SPT/TOT, though having the lowest backorder, exhibit no significant difference on backorder. These three scheduling rules are followed by LWT which has a significantly higher backorder size.

The worst scheduling rule for backorder is SPT, since it has the significantly higher backorder than LWT.

Unlike in the push-type systems, the SPT rule does not have good performance in pull-type JIT systems. When the SPT rule is applied, the part type with the shortest processing time is quickly completed and waits in the output storage until a corresponding withdrawal Kanban from the subsequent stage arrives. However, the release of the corresponding withdrawal Kanban at the subsequent stage depends on the initiation of production for the same part type. If the processing time for this part type at the subsequent stage is relatively long, it takes a longer time before the part can be processed. The release of the withdrawal Kanban is late and the part type will spend a longer time in the output storage at the preceding stage. Therefore, unless a part type has short processing time for all the stages it goes through, it does not appear that the backorder will be helped by the SPT rule.

Average WIP

The results of Duncan's test shows that FCFS and SLACK*, though having the lowest average WIP, appear to have no significant difference on average WIP. From the ranking shown in Table 5-4, FCFS and SLACK* are followed by LWT which has significantly higher average WIP. The third best scheduling rule for average WIP is SPT/TOT and the worst is the SPT rule.

The poor performance on average WIP for SPT again suggests that the SPT rule is not suitable for pull-type systems. The inconsistent priority between different stages due to high variation of processing time can deteriorate the performance of the SPT rule. The reason was discussed in the previous section (backorder).

Summary of the Results of Phase 1 Experiment

In phase 1 experiment, a two-way ANOVA was conducted and tested by an F-test in order to see if there are statistically significant effects for the scheduling rules and machine selection rules with respect to three performance measures. Duncan's test was then utilized to compare the performance of different rules. The findings from the results of the statistical analysis are summarized as follows:

1. The results of the F-test found that the effect of control methods appears to have no significant effect on the throughput of a multi-stage JIT system. The reason for the insignificance on throughput is that in this JIT system there was no limit on the number of backorders. Therefore, the customers' demands will be eventually satisfied since they can not be turned away. Philipoom *et al.* [1987] conclude that the throughput of a pull-type JIT system relies mainly on the demand rate and the number of Kanbans since parts are produced only when they are required. In that sense, throughput is not really a dependent variable that can be used to measure the system performance. Therefore, throughput was eliminated from the phase 2 experiment as a performance measure.
2. Machine selection rules appear to have no significant effects on the performance measures for this JIT system. The reason for the insignificant improvement for machine selection rules appears to be that a common queue is utilized at each stage for this JIT system.

The use of common storage and a common Kanban post is very common for a real-world Kanban-controlled JIT systems. Unlike the use of local storage, the use of a common storage area minimizes the idle time before the machines find an appropriate waiting part for processing after a machine finishes a part. Therefore, the

machines remain busy most of the time until all parts are completed and hence there is no need for the system to apply the machine selection rules.

Previous research [Choi and Malstrom, 1988] [O'Keefe and Kasirajan, 1992] that implemented local storage for push-type systems have concluded that machine selection rules contribute to the improvement of the system performance. It may be the case where there are independent queues in a JIT system where each machine has its own Kanban post and storage area. Further research is required in order to examine the effects of machine selection rules on this type of JIT systems.

3. Among the scheduling rules tested, SLACK*, FCFS, and SPT/TOT are the best at reducing the backorder size over the range of systems analyzed. However, there are no significant differences between the three scheduling rules on backorder. The next best scheduling rule on backorder is LWT and the worst is SPT.

The good performance of the SLACK* rule is mainly because it selects part types based on the measure of the unsatisfied demand. The priority of selection goes to the part type that has the largest amount of parts to be produced in order to meet the demand. As a result, the chance of creating a backorder can be reduced.

4. FCFS and SLACK*, though do not exhibit significant difference on average WIP between each other, do appear to have the best performance in reducing the average WIP. The LWT rule ranks third in average WIP followed by SPT/TOT. The SPT rule has the worst performance for both backorder and average WIP.

This finding is also consistent with Berkley and Kiran's finding [1991]. Berkley and Kiran found that unlike the conventional push-type production system, FCFS outperforms SPT in reducing average WIP in a fixed-routing, dual-Kanban JIT system. The FCFS rule selects the part type that enters the common queue first. The overall waiting time in the queue can be then reduced.

5. For both the backorder size and average WIP, the SPT rule ranks last in this pull-type JIT system. The result is opposite to the conventional push-type systems where the SPT rule outperforms most of the other scheduling rules [O'Keefe and Kasirajan, 1992]. Unlike the conventional systems, in order to produce or withdraw a certain part type requires the appearance of both the raw material and the corresponding Kanban. If priorities of part type selection between stages are not consistent, it is often that only either the raw material or the production-ordering Kanban, but not both, shows up at a stage [Berkley and Kiran, 1991]. As a result, production can not be initiated as expected.

The reason for the inconsistency of priorities between stages is that processing times for a part type vary by stages, therefore, a specific part type may not have the same priority at all stages. Moreover, dual-Kanban systems require a part to be withdrawn by a corresponding withdrawal Kanban and produced when presented with a corresponding production-ordering Kanban.

When the SPT rule is applied, the part type with the shortest processing time is quickly completed and waits in the output storage until a corresponding withdrawal Kanban from the subsequent stage arrives. However the release of the corresponding withdrawal Kanban at the subsequent stage depends on the initiation of production for the same part type. If the processing time for this part type at the subsequent stage is relatively long, it takes a longer time before the part can be processed. Therefore, the release of the withdrawal Kanban is late and the part type will spend a longer time in the output storage at the preceding stage.

For a pull-type JIT system that has imbalance of processing times, the SPT rule appear to increase the backorder and average WIP. Therefore, the SPT rule should not be applied in an imbalanced JIT system.

6. The five scheduling rules FCFS, SPT, SLACK*, SPT/TOT and LWT were selected as the five levels within the experimental factor control method. The PRIOR rule was selected arbitrarily as the machine selection rule that works with the five scheduling rules since the machine selection rules appear to have no significant effect on the performance measures. The number of control methods was reduced from 15 to five. These five control methods were used as the treatments in phase 2 experiment.

Phase 2 Experiment

Phase 2 experiment, a full-factorial experiment, was conducted to investigate the effects of the four experimental factors on the system performance. The control methods selected in the phase 1 experiment were utilized as the levels within experimental factor control methods. Along with the other three experimental factors (i.e., routing flexibility, variability of demand rate, and variability of processing time), the phase 2 experiment was a $3 \times 5 \times 2 \times 2$ factorial.

In this experiment, throughput was dropped as a performance measure. The reason is that in this JIT system there was no limit on the number of backorders. As a result, customers' orders are not turned away from the system. Hence, all of the customers' demands will be eventually satisfied. In steady, the output rate or the throughput rate will be identical to the input rate or the demand rate for this JIT system. Therefore, throughput cannot be considered as a dependent variable and is excluded from the system performance measures.

Tables 5-6 and 5-7 show the backorder and average WIP obtained from the 10 replications for each combination of experimental factors.

TABLE 5-6 The Average Backorder for Phase 2 Experiment
(Number of parts)

		$C_{dv} = 0.1$	$C_{dv} = 0.1$	$C_{dv} = 0.3$	$C_{dv} = 0.3$
		$C_{pv} = 0.1$	$C_{pv} = 0.3$	$C_{pv} = 0.1$	$C_{pv} = 0.3$
RF = 0.3333	FCFS	1.1	3.6	33.2	49.9
	SPT	1.4	12.1	32.3	72.8
	SLACK*	1.0	5.0	35.8	49.4
	SPT/TOT	1.5	8.2	39.7	60.9
	LWT	1.1	3.6	33.2	49.9
RF = 0.6667	FCFS	0.5	1.3	15.1	18.2
	SPT	2.2	7.1	21.5	30.9
	SLACK*	0.6	1.5	13.1	13.8
	SPT/TOT	3.2	4.1	17.1	20.9
	LWT	1.4	2.6	17.5	21.0
RF = 1.0000	FCFS	0.5	1.2	15.0	17.7
	SPT	3.9	8.2	21.0	32.3
	SLACK*	1.3	0.5	12.4	15.7
	SPT/TOT	3.3	5.5	19.9	24.6
	LWT	0.5	1.2	15.0	17.7

TABLE 5-7 The Average WIP for Phase 2 Experiment
(Number of parts)

		$C_{dv} = 0.1$	$C_{dv} = 0.1$	$C_{dv} = 0.3$	$C_{dv} = 0.3$
		$C_{pv} = 0.1$	$C_{pv} = 0.3$	$C_{pv} = 0.1$	$C_{pv} = 0.3$
RF = 0.3333	FCFS	59.120	65.037	80.018	103.018
	SPT	58.265	68.199	77.771	122.557
	SLACK*	60.200	67.841	81.505	103.758
	SPT/TOT	62.148	69.550	84.419	113.562
	LWT	59.120	65.199	80.018	103.018
RF = 0.6667	FCFS	58.053	59.881	65.003	69.252
	SPT	59.074	64.586	69.128	77.757
	SLACK*	58.716	61.060	66.001	70.048
	SPT/TOT	64.029	66.583	70.637	75.359
	LWT	59.601	61.499	66.752	70.648
RF = 1.0000	FCFS	57.630	59.594	64.252	68.465
	SPT	59.368	64.749	68.579	77.137
	SLACK*	57.703	60.445	64.368	69.124
	SPT/TOT	63.902	66.782	70.713	75.422
	LWT	57.630	59.594	64.252	68.462

These simulation results were analyzed using analysis of variance (ANOVA) so that the effects of the experimental factors with respect to the performance measures could be evaluated. A SAS program was developed to conduct the ANOVA. The ANOVA was carried out at a significance level of 10%. An F-test was utilized in order to determine the significant differences among experimental factors.

Table 5-8 presents the abbreviations of experimental factors that were used in the ANOVA and the corresponding figures. The results of the ANOVA are shown in Table 5-9.

TABLE 5-8 The Abbreviations and Definitions of Experimental Factors

Abbreviation	Definition
RF	Routing Flexibility
LRF	Routing Flexibility Level 1 (0.3333)
MRF	Routing Flexibility Level 2 (0.6667)
HRF	Routing Flexibility Level 3 (1.0000)
C_{dv}	Coefficient of Variation for Demand Rate
LC_{dv}	Low C_{dv} (0.1)
HC_{dv}	High C_{dv} (0.3)
C_{pv}	Coefficient of Variation for Processing Time
LC_{pv}	Low C_{pv} (0.1)
HC_{pv}	High C_{pv} (0.3)
CM	Control Method
FCFS	First Come First Served Rule
SPT	Shortest Processing Time Rule
SLACK*	Largest SLACK Rule
SPT/TOT	Smallest SPT/TOT Rule
LWT	Longest Waiting Time Rule

TABLE 5-9 Summary of the Results of the ANOVA for Phase 2 Experiment

Backorder					
Mean = 15.445					
Source	DF	Mean Square	F value	p value	Significance
Model	59	2795.839	6.56	0.0001	*
RF	2	13087.145	30.71	0.0001	*
CM	4	1385.940	3.25	0.0119	*
C _{dv}	1	93325.482	219.00	0.0001	*
C _{pv}	1	6409.202	15.04	0.0001	*
RF*CM	8	45.451	0.11	0.9990	
RF*C _{dv}	2	10718.872	25.15	0.0001	*
RF*C _{pv}	2	1824.372	4.28	0.0143	*
CM*C _{dv}	4	256.590	0.60	0.6613	
CM*C _{pv}	4	492.677	1.16	0.3293	
C _{dv} *C _{pv}	1	2079.482	4.88	0.0276	*
RF*CM*C _{dv}	8	27.049	0.06	0.9999	
RF*CM*C _{pv}	8	69.440	0.16	0.9954	
RF*C _{dv} *C _{pv}	2	765.832	1.80	0.1668	
CM*C _{dv} *C _{pv}	4	98.557	0.23	0.9208	
RF*CM*C _{dv} *C _{pv}	8	34.663	0.08	0.9996	
Error	540	426.151			

TABLE 5-9 (Continued)

Average WIP					
Mean = 69.936					
Source	DF	Mean Square	F value	p value	Significance
Model	59	1911.807	39.9	0.0001	*
RF	2	12948.295	270.23	0.0001	*
CM	4	935.505	19.52	0.0001	*
C _{dv}	1	39340.167	821.04	0.0001	*
C _{pv}	1	11284.666	235.54	0.0001	*
RF*CM	8	13.816	0.29	0.9698	
RF*C _{dv}	2	8782.603	183.29	0.0001	*
RF*C _{pv}	2	3203.278	66.87	0.0001	*
CM*C _{dv}	4	128.930	2.69	0.0305	*
CM*C _{pv}	4	261.182	5.45	0.0003	*
C _{dv} *C _{pv}	1	2736.041	57.11	0.0001	*
RF*CM*C _{dv}	8	19.734	0.41	0.9142	
RF*CM*C _{pv}	8	49.798	1.04	0.4042	
RF*C _{dv} *C _{pv}	2	1464.826	30.58	0.0001	*
CM*C _{dv} *C _{pv}	4	68.546	1.43	0.2220	
RF*CM*C _{dv} *C _{pv}	8	49.285	1.03	0.4122	
Error	540	47.912			

Main Effects of Experimental Factors

The main effects of the experimental factors on the performance measures provide information of how the experimental factor alone has affected the system performance. As can be seen in Table 5-9, all four experimental factors (i.e., RF, CM, C_{dv}, and C_{pv}) exhibit significant effects on backorder and average WIP at a significance level of 10%. The

following sections discussed the main effect of each experimental factor on each of the performance measures.

Routing Flexibility Table 5-9 shows that the various levels of routing flexibility exhibit significant effects on backorder and average WIP. The performances for the three levels of routing flexibility are illustrated in Figure 5-1. The low level of routing flexibility (LRF) appears to have the highest backorder and average WIP. As the level of routing flexibility increases, backorder and average WIP decrease. The high level of routing flexibility (HRF) outperforms the others and has the lowest backorder and average WIP.

As can be seen from Figure 5-1, the high and medium levels of routing flexibility appear to have similar size of backorders and average WIP. The improvement of backorder and average WIP follows the rule of diminishing rate of returns, i.e., as the routing flexibility increases, the rate of improvement for the performance measures decreases.

The diminishing rate of returns relationship between routing flexibility and system performance indicates that the improvement on the system performance or the economical return may not be justified by the investment spent for enhancing the degree of routing flexibility for a JIT system. A system designer must determine the economically optimal level of routing flexibility for the company before the facility is built and the machines are purchased.

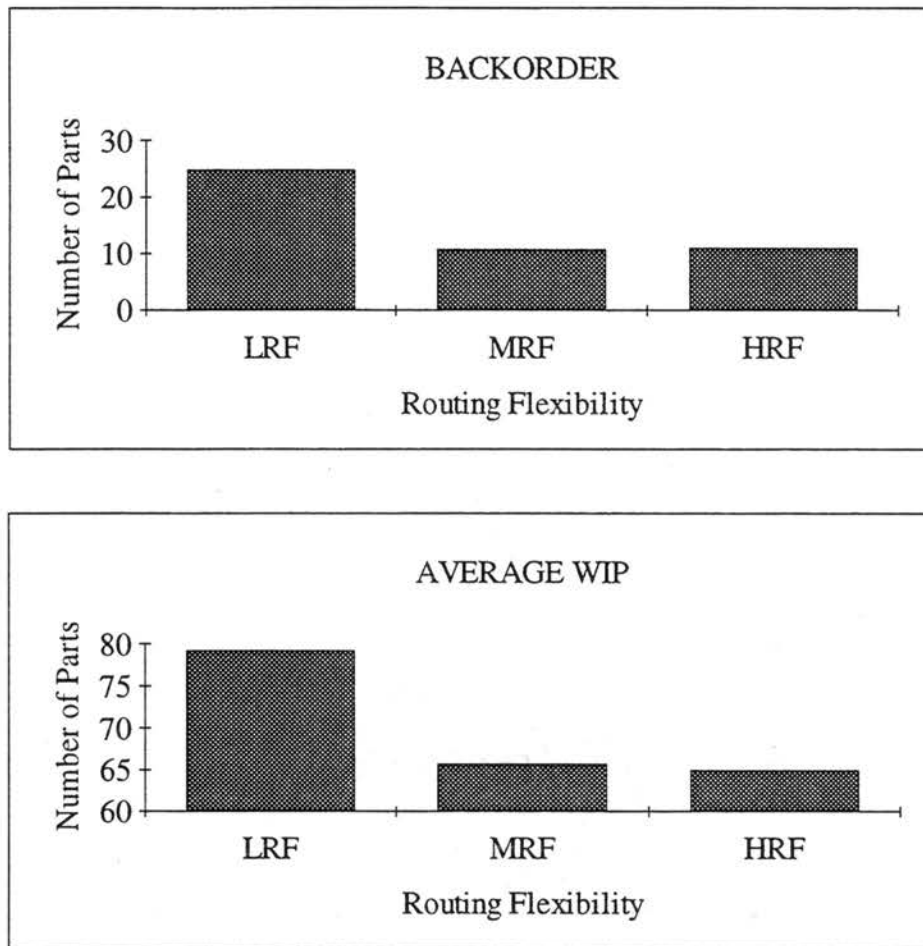


FIGURE 5-1 The Main Effects of Routing Flexibility for System Performance

Variability of Demand Rate The main effects of the variability of demand rate for the performance measures are illustrated in Figure 5-2. As shown in Table 5-9, the variability of demand rate exhibits statistically significant effects on backorder and average WIP at a significance level of 0.10. In Figure 5-2, it appears that low C_{dv} (LC_{dv}) can result in lower backorder and lower average WIP.

In a pull-type system, parts are processed only when they are required by the demand from the subsequent stages. A small C_{dv} means a stable demand for a JIT system and vice versa. When the demand rate is stable, the required production quantities for each part type in every stage are about the same size. Therefore, most of the parts

finished by the preceding stages can be utilized by the parts at the subsequent stages so that fewer parts are likely to be blocked or starved.

The similar quantities of parts transferring between stages enable the system to become more balanced. In a perfectly balanced system, each stage processes the same quantity of parts in the same amount of time so that no parts have to wait and no stages are blocked or starved for parts. Therefore, lower C_{dv} can make this JIT system more balanced so that it can have lower backorder, and higher average WIP [Monden, 1993].

Just like a JIT system with fixed routings, a multi-stage JIT system with alternate routings has better performance when the customers' demands are stable. When stable demand is not possible, the JIT system designer must increase the system capacity or the system flexibility, such as routing flexibility, so that the fluctuation of demand can be handled.

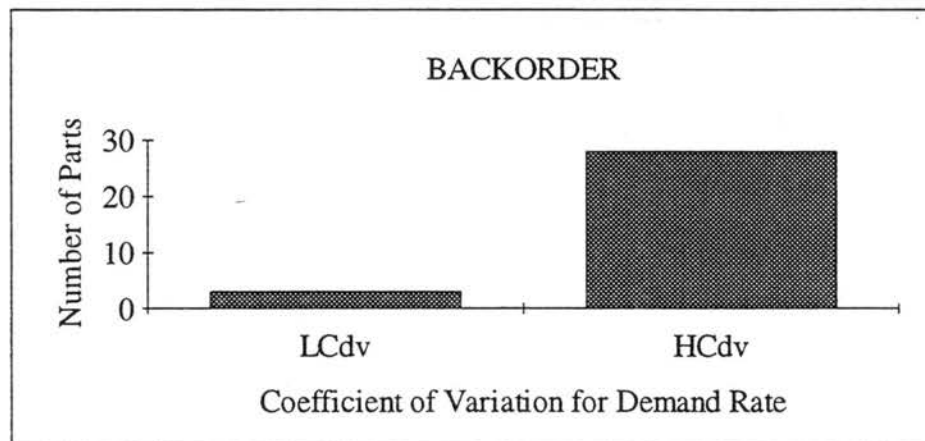


FIGURE 5-2 The Main Effects of C_{dv} for System Performance

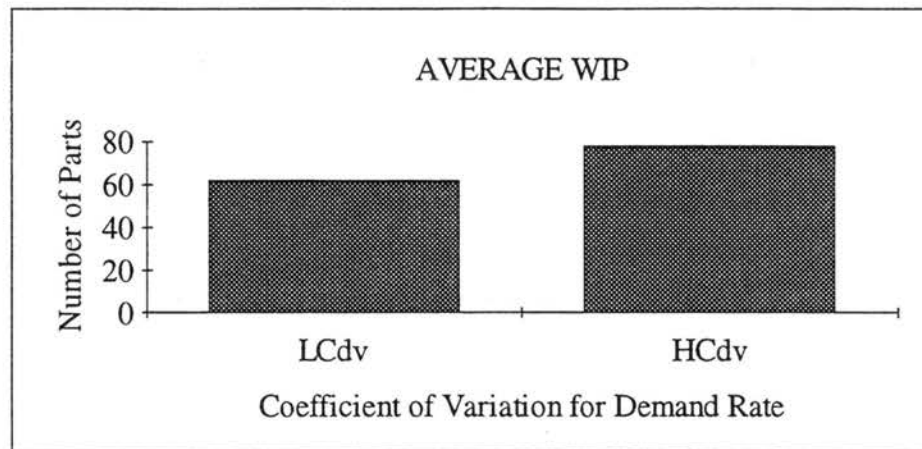


FIGURE 5-2 (Continued)

Variability of Processing Time The main effects of the variability of processing time on the performance measures are exhibited in Figure 5-3. The levels of C_{pv} show a statistically significant effect on backorder and average WIP (Table 5-9). The low C_{pv} (LC_{pv}) can result in lower backorder and lower average WIP for this JIT system.

A multi-stage JIT system must be designed to have lower variation of processing time via the implementation of flexible machines that require short setup time and have low variation of processing time for the same type of operation. The investment in these machines may be justified by the reduction of backorder size and average WIP.

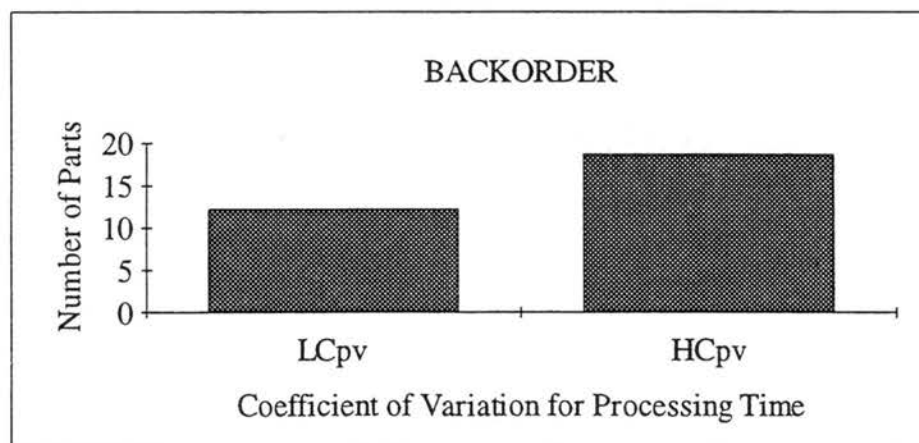


FIGURE 5-3 The Main Effects of C_{pv} for System Performance

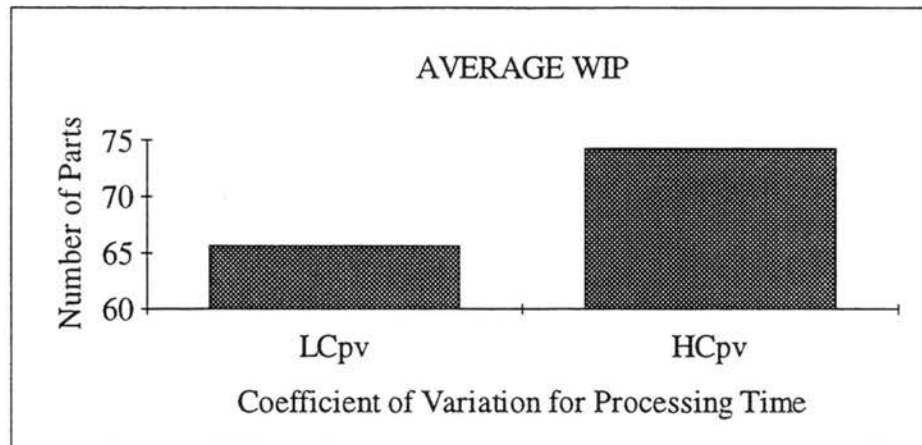


FIGURE 5-3 (Continued)

Control Method Table 5-9 shows that control methods demonstrate a statistically significant effect on the backorder and average WIP. The different scheduling rules, as illustrated in Figure 5-4, appear to result in different backorder sizes and average WIPs. SLACK* has the lowest backorder while FCFS has the smallest amount of average WIP. SPT and SPT/TOT appear to be the worst rules since they incur the highest backorder and average WIP respectively.

The control issues of the multi-stage JIT system must be taken into account since the alternate routings complicate the part flows because more routing decisions need to be made. The system designer must decide which control methods are to be installed in order to have better system measures. It is also suggested that since no universally optimal control method can be found, the control method to be installed is determined by the preference of performance measures for the system.

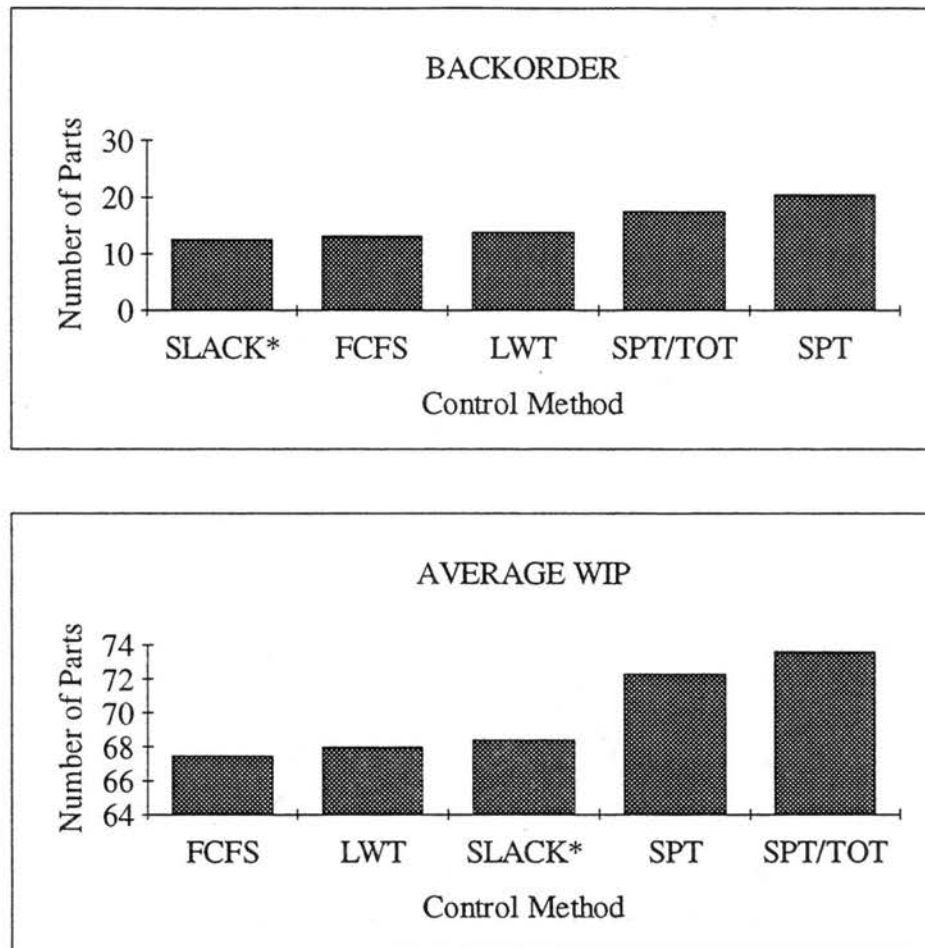


FIGURE 5-4 The Main Effects of Control Methods for System Performance

Two-factor Interactions

The two-factor interaction is used to measure the relationship between two experimental factors. If a two-factor interaction is significant, this indicates that the two experimental factors are not independent of each other. In other words, there are differences between the simple effects of one experimental factor. The simple effects of an experimental factor are defined as the effects of this factor under various levels of the other factor [Steel and Torrie, 1980]. The following sections discuss the two-factor interactions that were found statistically significant, shown previously in Table 5-9, at the 10% level. For the figures shown in these sections, it is noted that the straight lines

connecting two data points show only a visual increase, decrease, or constant rather than indicating linearity between two points.

Interactions between Routing Flexibility and the Variability of Demand Rate

The interactions between routing flexibility (RF) and the variability of demand rate with respect to backorder and average WIP is illustrated in Figure 5-5. The significant interactions indicates that the rate of change for backorder and average WIP by the various levels of routing flexibility varies when C_{dv} is changed from low to high. At the low C_{dv} level, the backorder sizes for the three routing flexibilities are very close. As the C_{dv} increases to the high level, the backorder as well as average WIP for low routing flexibility (LRF) increases dramatically while the performance for medium and high routing flexibilities (MRF and HRF) degenerates at a more moderate rate.

The main effect of the variability of demand rate for a JIT system indicates that high C_{dv} will result in larger backorder size and greater average WIP. In order to offset the effect of high C_{dv} on the backorder and average WIP, system designers can opt to increase the level of routing flexibility because of the statistically significant interaction between the variability of demand rate and the routing flexibility. However, the investment on the routing flexibility remains to be economically justified before the system is installed.

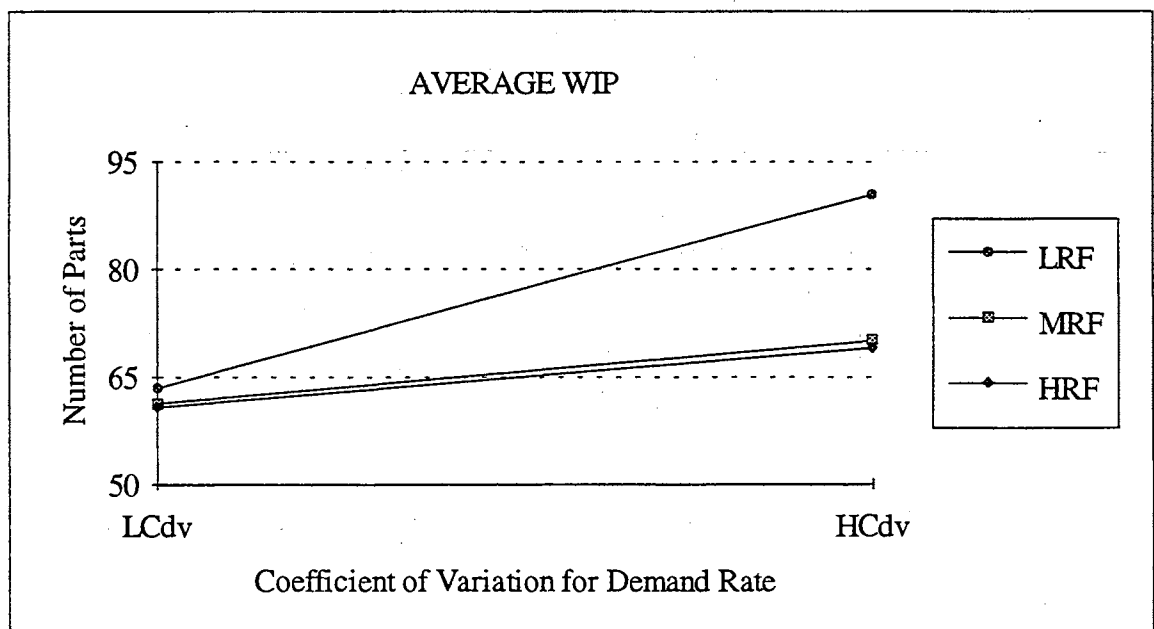
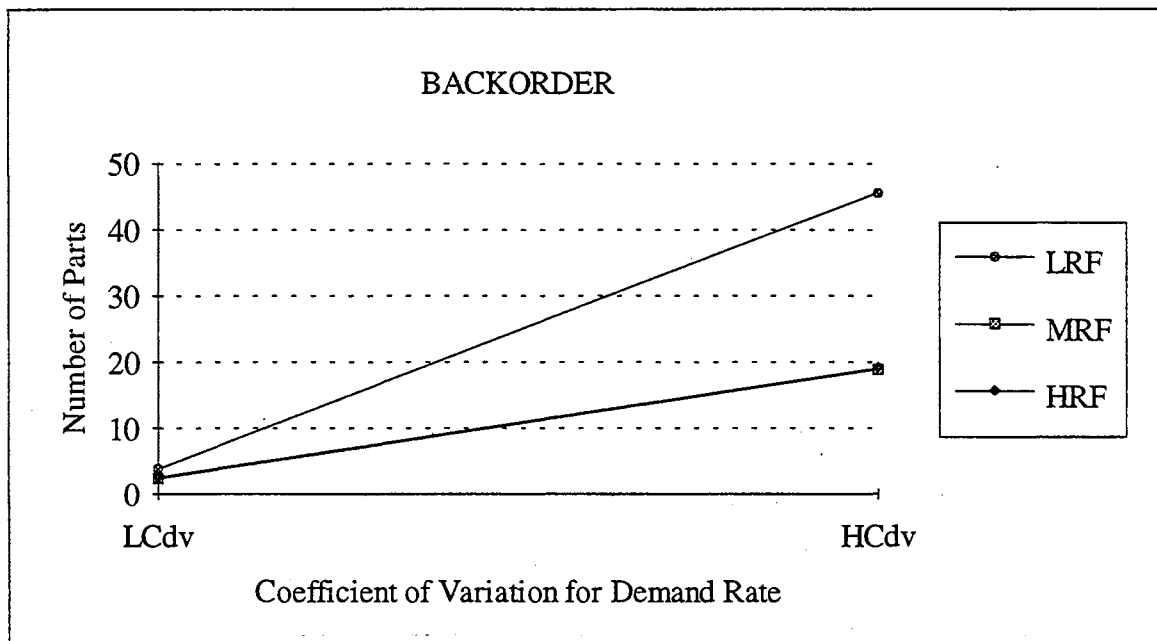


FIGURE 5-5 The Interactions between Routing Flexibility and C_{dv}

Interactions between Routing Flexibility and the Variability of Processing

Time The interactions between routing flexibility (RF) and the variability of processing time with respect to backorder and average WIP are illustrated in Figure 5-6. The rate of change for low routing flexibility (LRF) for backorder and average WIP increases

dramatically when C_{pv} is changed from the low to high level. As for medium and high level of routing flexibility, the incurred backorder and average WIP are very similar. The rate of change for medium and high routing flexibility with respect to backorder and average WIP is relatively moderate.

The main effect of the variability of processing time indicates that a high level of C_{pv} can result in a larger backorder size and greater amount of average WIP. For a JIT system with higher C_{pv} , the system performance in backorder and average WIP can be improved by the increase of routing flexibility since the variability of processing time has a statistically significant interaction with the routing flexibility.

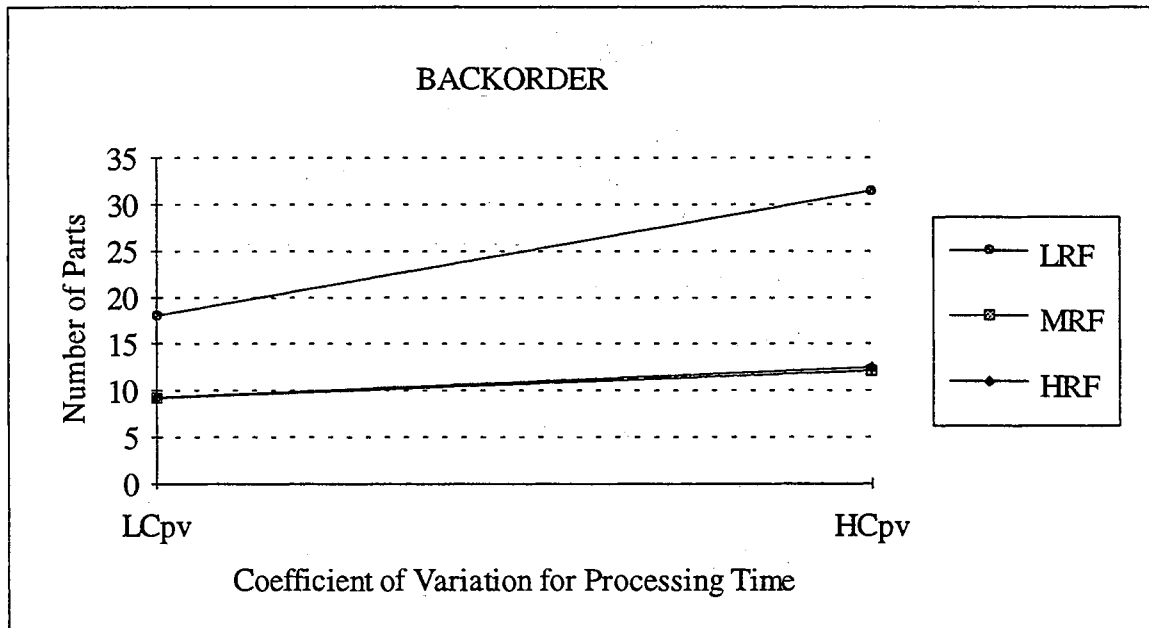


FIGURE 5-6 The Interactions between Routing Flexibility and C_{pv}

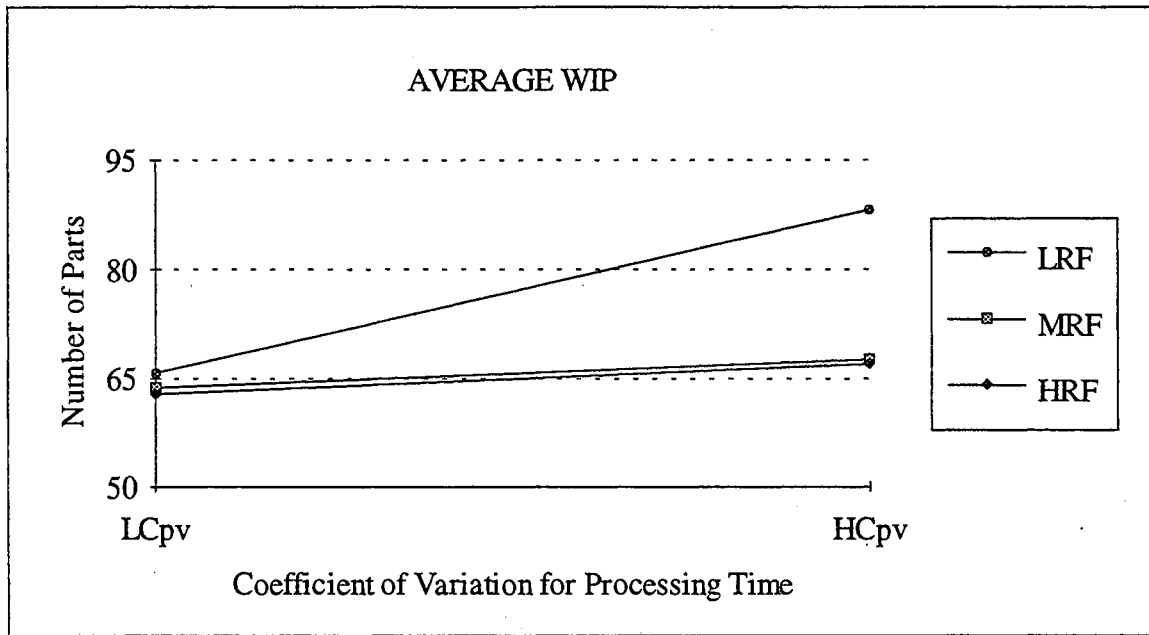


FIGURE 5-6 (Continued)

Interactions between Control Method and the Variability of Demand Rate

The interaction between various control methods (CM) and the variability of demand rate with respect to average WIP is illustrated in Figure 5-7. The rate of change for average WIP by various control methods increases substantially when C_{dv} is changed from low from high.

It is interesting to find that control methods perform differently under different levels of C_{dv} . Figure 5-7 shows that the SPT/TOT rule has the greatest average WIP when the C_{dv} is low while it has the lowest average WIP under the high C_{dv} . This finding suggests that the selection of control methods must take into account the variation of demand rate. The system designer must fully understand the demand pattern before a control method is selected.

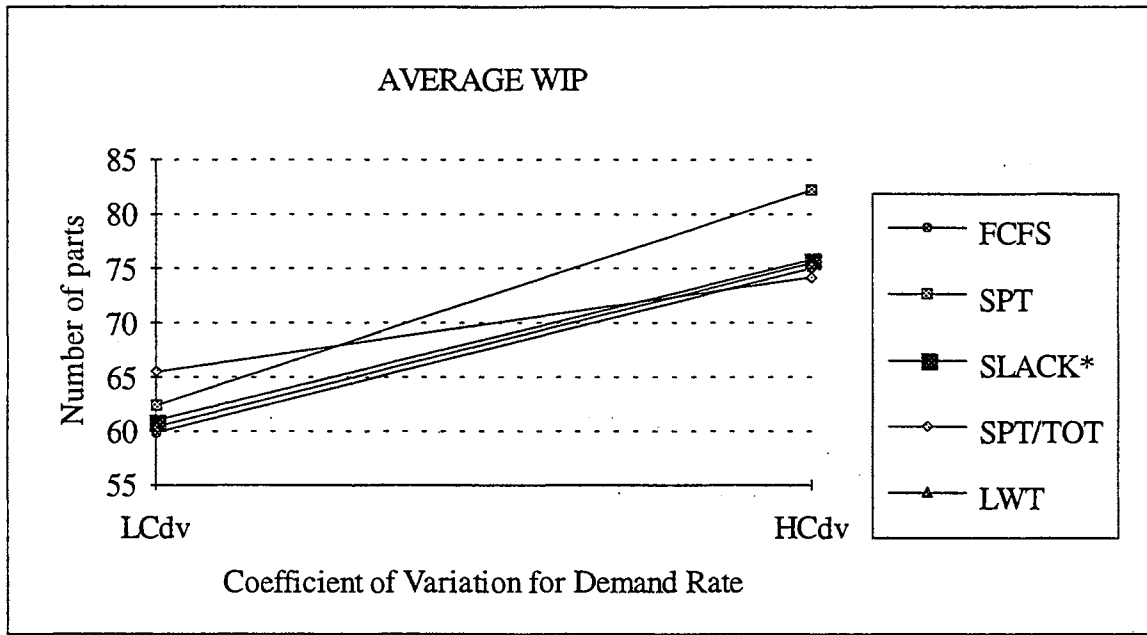


FIGURE 5-7 The Interactions between Control Method and C_{dv}

Interactions between Control Method and the Variability of Processing Time

The interaction between various control methods (CM) and the variability of processing time with respect to average WIP is illustrated in Figure 5-8. The rate of change for average WIP by various control methods increases substantially when C_{pv} is changed from low to high.

The statistically significant interaction between the control methods and the variability of processing time indicates that control methods perform differently under various levels of C_{pv} . Figure 5-8 shows that although various control methods have similar amounts of average WIP under low C_{pv} , they perform differently under high C_{pv} .

The SPT and SPT/TOT rules appear to have a dramatic increase in average WIP when the variation of processing time is changed from low to high. This is probably caused by the highly inconsistent priority for a given part between different stages as a result of high variation of processing time. The part that has shorter processing time in a preceding stage may still have to wait for a long time until the withdrawal Kanban at the

subsequent stage is released because of longer processing time. Therefore, it appears that the selection of control methods implemented in a multi-stage JIT system must take into consideration the variation of processing time.

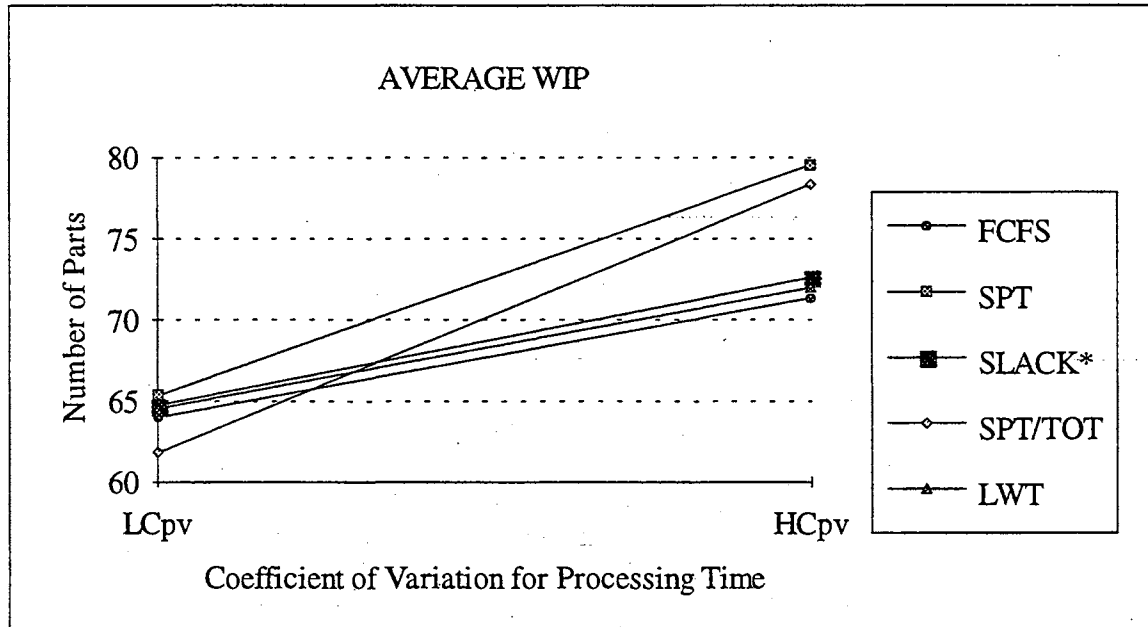


FIGURE 5-8 The Interactions between Control Method and C_{pv}

Interactions between the Variability of Demand Rate and the Variability of Processing Time The interactions between the variability of demand rate and the variability of processing time with respect to backorder and average WIP are illustrated in Figure 5-9. Figure 5-9 shows that high level of C_{pv} (HC_{pv}) has higher backorder and average WIP than for a low level of C_{pv} (LC_{pv}). For both HC_{pv} and LC_{pv} , the backorder size and average WIP increase significantly when C_{dv} is changed from low to high.

The statistically significant interaction between C_{dv} and C_{pv} with respect to the backorder and average WIP offers the system designer an alternate way of improving the system performance. In order to improve system performance for a JIT system with high C_{pv} and high C_{dv} , a system designer can either reduce the variation of processing time or

the variation of demand rate to the low level (i.e., LC_{dv} or LC_{pv}). However, the low variation of demand rate (C_{dv}) appears to have a more significant effect on the improvement of both the backorder and average WIP.

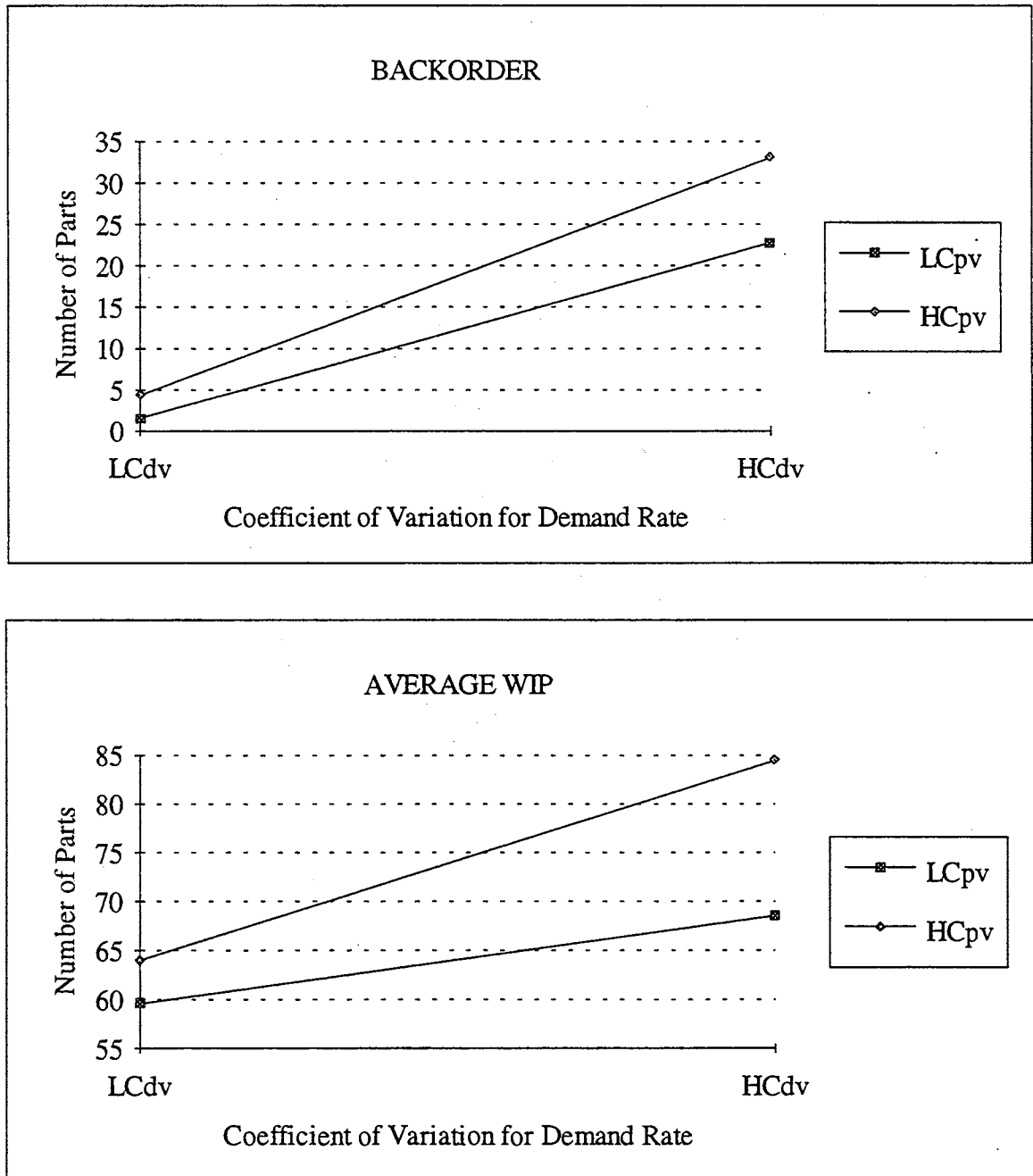


FIGURE 5-9 The Interactions between C_{dv} and C_{pv}

Three-factor Interactions

The three-factor interaction is used to determine the relationship between the effects of any combination of three experimental factors. As can be seen in Table 5-9, only the routing flexibility (RF), the variability of demand rate, and the variability of processing time exhibit a significant three-factor interaction for average WIP.

Interactions among Routing Flexibility, the Variability of Demand Rate, and the Variability of Processing Time The interaction between routing flexibility (RF), the variability of demand rate, and the variability of processing time with respect to average WIP is illustrated in Figure 5-10. Figure 5-10 shows that the average WIP for the three levels of routing flexibility appears to be about the same under the combination of low coefficient of variation for demand rate and processing time (LC_{dv}/LC_{pv}). The average WIP increases for all three levels of routing flexibility when C_{dv} , and C_{pv} are changed from low to high. For low routing flexibility (LRF), the average WIP increases dramatically when the combination of C_{dv} and C_{pv} are changed from HC_{dv}/LC_{pv} to HC_{dv}/HC_{pv} .

A system designer for the multi-stage JIT system must be aware that under high variation of both demand rate and processing time (HC_{dv}/HC_{pv}), a system with low routing flexibility will produce substantially higher average WIP. Therefore, a higher level of routing flexibility must be implemented in order to avoid the consequence of high average WIP.

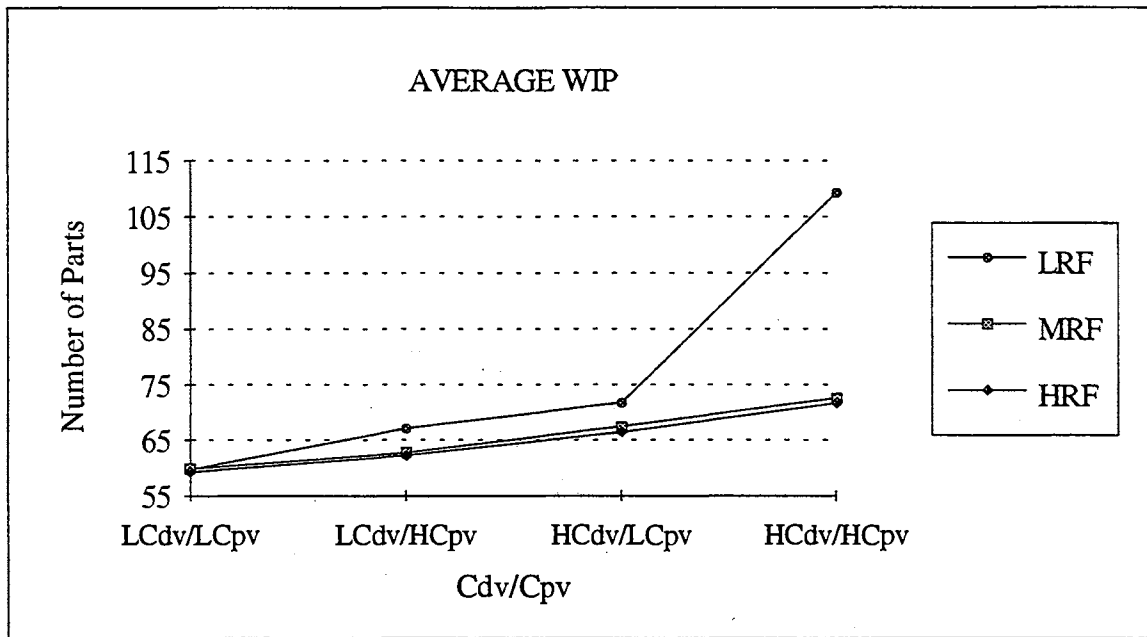


FIGURE 5-10 The Interactions between Routing Flexibility, C_{dv} , and C_{pv}

Summary of the Results of Phase 2 Experiment

The ANOVA conducted for the phase 2 experiment evaluated the major effects as well as the interactions among the four experimental factors. The F-test was utilized to test the significance of the four experimental factors with respect to backorder and average WIP at a significance level of 10%. The results of the ANOVA are summarized below. It is noted that these results are for the range of variables tested. Some generalizations beyond the range of variables tested can be made.

1. The routing flexibility exhibits a statistically significant effect on the backorder size and the average WIP. The low level of routing flexibility appears to have the highest backorder size and average WIP. The medium and high level of routing flexibility have similar amounts of backorder and average WIP. This finding is consistent with the diminishing rate of returns between routing flexibility the performance measures

of push-type systems [Wilhelm and Shin, 1985] [Bobrowski and Mabert, 1988] [Chen and Chung, 1991] [Benjaafar and Kamakrishnan, 1993].

The results suggest that the system designer must carefully evaluate the tradeoff between the investment in an increase of routing flexibility and the improvement made by the increase of routing flexibility. Further economical justification should be conducted before any major investment is spent on the increase of routing flexibility.

2. The variability of demand rate exhibits a statistically significant effect on backorder and average WIP. The results suggest that a pull-type system is very sensitive to the fluctuated demand rates. In order to reduce the sensitivity to demand rate, Toyota has applied the principle of *production smoothing*, which produces the same or similar amount of products for each part type every day in a JIT system [Monden, 1993].
3. The variability of processing time shows a statistical significant effect on the backorder size and the average WIP. A low level of C_{pv} appears to have significant lower backorder size and lower average WIP than a high level of C_{pv} . A multi-stage pull-type system with low C_{pv} is recognized as a more balanced system since each part type requires a similar amount of processing time at each stage. This finding is consistent with Sarker and Harris's [1988], which concluded a more balanced JIT system will have less starvation and blocking between stages and hence should have a smaller average WIP.
4. The various levels of routing flexibility show statistically significant interaction with C_{dv} and C_{pv} for backorder and the average WIP. When C_{dv} and C_{pv} are low, the backorder and the average WIP incurred by various levels of routing flexibility are similar. However, at high C_{dv} and C_{pv} , the low level of routing flexibility has a significantly larger backorder and higher average WIP than have the medium and high

levels of routing flexibility. The result indicates that JIT systems with higher routing flexibility are capable of adapting to changes in demand and processing time. For the low routing flexibility, the limited number of routings restrict the movement of different part types. When C_{dv} and C_{pv} are high, the stages in this less flexible JIT system spend more time to produce the required parts and hence increase the possibility of starvation and blocking between stages. Therefore, the backorder size and the average WIP are dramatically increased.

5. The control methods exhibit statistically significant effects on the backorder size and the average WIP. Some scheduling rules have better performance measures than the others when PRIOR is used as the machine selection rule. However, no universally best control method could be found in this research. Generally, SLACK* and FCFS appear to be the best scheduling rules since they have the lowest amount of backorder and average WIP respectively. On the other hand, SPT and SPT/TOT appear to be the worst scheduling rules because they have the highest backorder and average WIP respectively.
6. The various control methods exhibit statistically significant interactions with C_{dv} and C_{pv} for average WIP. Unlike the other scheduling rules, the SPT rule appears to have a dramatic increase in average WIP at high C_{dv} . Both the SPT and SPT/TOT rules have a dramatic increase in average WIP when C_{pv} is changed from low to high. This finding suggests that the SPT and its related rule (i.e., SPT/TOT) in multi-stage JIT systems should not be utilized to control the part flows under the high variation of processing time. Another interesting finding is that the SPT/TOT rule has the greatest average WIP when the C_{dv} is low while it also has the lowest average WIP under the high C_{dv} .

The results indicate that a system designer must carefully select a control method based on the variability of demand rate and the variability of processing time so that the system performance can be improved.

7. The variability of demand rate shows statistically significant interactions with the variability of processing time on the backorder size and the average WIP. When the C_{dv} is low, both low and high C_{pv} have similar small backorder size and low average WIP. As the C_{dv} changed from low to high, high C_{pv} appears to have dramatically higher backorder and average WIP than the low C_{pv} . This result indicates that the more variability in the JIT system, the higher the backorder and the average WIP of the system.

CHAPTER VI

SUMMARY, CONTRIBUTIONS AND FUTURE RESEARCH AREAS

Summary

This research focused on the investigation of the effects of routing flexibility for a multi-stage Just-In-Time System. A four-stage dual-Kanban-controlled JIT system was utilized to study the effects of routing flexibility. In order to quantify the routing flexibility for this multi-stage JIT system, equations for measuring the routing flexibility were developed. These equations are capable of finding the appropriate level of routing flexibility for flow shops that have multiple machines at each stage.

Unlike the existing measures that focus on the number of available routes, the developed measure takes into account the loading balance between machines. The average production volume for each part type is also considered in this measure so that the work load for each machine can be accurately calculated. As a result, a manufacturing system with more overloaded machines will have less routing flexibility than the one that has fewer overloaded machines when both systems have the same number of available routes.

The measure of routing flexibility for a multi-stage system is developed by summing the weighted routing flexibility of each stage. The routing flexibility of a specific stage is a function of the number of available routes and the number of part types each machine can process. It is assumed that the optimal routing exists when each of the

available machines at a specific stage can process an equal number of weighted part types.

Four advantages can be obtained by using the developed measure of routing flexibility. First, it is capable of dealing with multiple part types. Second, average production volumes for each part type are considered. Third, overloading on specific machines is discouraged since it will result in a lower routing flexibility. Fourth, the stages that have higher average processing times are given higher weights for their routing flexibility to encourage higher routing flexibility on these stages.

On the basis of the developed measure of routing flexibility, three scenarios of routings were used in order to represent low, medium, and high degree of routing flexibility. The low routing flexibility has a scenario where each part type can only be processed by one primary machine. The medium and high level of routing flexibility, however, have scenarios where each part type can be processed by one primary machine plus one or two alternate machines respectively.

In order to investigate the effects of routing flexibility for this 4-stage JIT system, four experimental factors were examined for their effects on the performance measures. The four experimental factors include three levels of routing flexibility (low, medium, and high), control methods (combinations of scheduling rules and machine selection rules), two levels of the variability of demand rate (low and high), and two levels of the variability of processing time (low and high).

Two experiments were conducted in this research. Phase 1 experiment was conducted to identify five control methods that could be used as various treatments for experimental factor control method. In this experiment, routing flexibility was held constant at 0.6667, the variability of demand rate and processing time were held at high level (i.e., $C_{dv} = 0.3$ and $C_{pv} = 0.3$). The results of a two-way ANOVA indicated that machine selection rules do not exhibit significant effects on the three performance measures utilized (i.e., throughput, backorder, and average WIP). It was also found that

both scheduling rules and machine selection rules do not show significant effects on throughput.

The performance of scheduling rules was compared by utilizing Duncan's new multiple-range test at 0.10 significance level. FCFS and SLACK* appear to be the two best scheduling rules that have the lowest backorder and average WIP. On the other hand, SPT is the worst rule that has the highest backorder and average WIP.

Phase 2 experiment is a full-factorial experiment that was used to examine the effects of all four experimental factors on the system performance. In this experiment, throughput was dropped as a performance measure since it does not appear to be a dependent variable due to the assumption of unlimited backorder for this system. An ANOVA was conducted and tested by an F-test at a significance level of 0.10.

The results of the F-test indicated that the various levels of routing flexibility exhibit statistically significant effects on the backorder and average WIP with a diminishing rate of returns. In other words, when the routing flexibility is changed from low to medium, the amount of backorder and average WIP are reduced dramatically. However, when the routing flexibility is changed from medium to high, these two performance measures are only improved slightly.

The study also showed that medium and high levels of routing flexibility can have substantially lower backorder and average WIP under high variation of demand rate and processing time. This finding suggests that a system designer can increase the level of routing flexibility in order to improve the performance of an imbalanced multi-stage JIT system. In order to determine the appropriate level of routing flexibility for a multi-stage JIT system, a preliminary study on the performance of various routing flexibility must be conducted. The selected level of routing flexibility should be justified economically.

The control methods are important since part type selection and machine selection are frequent decisions made by a JIT system with alternate routings. The control methods that were studied are made up by five scheduling rules and three machine selection rules.

The results showed that machine selection rules have no significant effect on the three performance measures. The reason is probably because that this JIT system utilizes a common buffer, i.e., a centralized Kanban post and storage area between stages, so that the machines will remain busy most of the time until all parts are completed and hence the machine selection rules hardly had an effect.

Among the five scheduling rules, no one that is universally best with respect to the performance measures could be found. Generally, SLACK* and FCFS are the two best scheduling rules since they have the lowest backorder and average WIP. On the other hand, SPT and SPT/TOT appear to be the worst rules since they incur the highest backorder and average WIP.

However, this study also found that the control methods perform differently according to the variation of demand rate and processing time. For example, while SPT/TOT has the highest average WIP under the low variation of demand rate, it had the lowest average WIP under the high variation of demand rate. The SPT related rules (i.e., SPT and SPT/TOT) have substantially higher average WIP under high variation of processing time. It is suggested that the control methods must be carefully selected according to the variation of demand rate and processing time.

The variability of demand rate had a statistically significant effect on backorder and average WIP. Low variation of demand rate can substantially lower the backorder and average WIP. The result further expressed the importance of stable demand for a JIT system that has been mentioned by other researchers [Huang *et al.*, 1983] [Monden, 1993].

Research Contributions

The goal and objectives of this research have been achieved via the experiment conducted and the discussion presented in Chapters IV and V. The major contribution of this research is the realization of appropriate operational requirements for a multi-stage JIT flow shop for a system designer. The operational requirements can be attributed into two aspects. The first aspect focuses on the development of control methods that can be utilized to direct part flows in order to improve the selected system performance measures. The second aspect emphasizes the development of guidelines that can be used to determine appropriate levels of routing flexibility and related independent variables with respect to the selected performance measures.

To achieve the major contribution mentioned above, the following sub-contributions are also been made.

1. Development of equations for measuring routing flexibility that can appropriately measure the magnitude of routing flexibility for multi-stage production systems.

The developed equations are presented from page 37 to page 41. A simplified example is also given from pages 41 to 48 in order to describe the implementation of these equations.

2. Development of appropriate control methods that can efficiently direct part flows in the JIT system that allows alternate routes.

The control methods used in this research are combinations of scheduling rules and machine selection rules. The descriptions of these control methods are presented on pages 58 through 63.

3. Realization of the relationship between each control method and the selected performance measures.

- The machine selection rules appear to have no statistically significant effects on the performance of this multi-stage JIT system. The discussion relating to this finding is presented on pages 85 through 88.
 - The control methods have no statistically significant effect on the throughput for this multi-stage JIT system. However, they do show statistical significance on the backorder and average WIP. The discussion of this finding can be found on pages 85 through 88.
 - Although overall some scheduling rules, such as FCFS and SLACK*, performed better than the others, the ranking of the performance in average WIP among control methods changed when the variability of processing time and demand rate changed. The results indicate that a system designer must carefully select a control method based on the variability of demand rate and processing time so that the system performance can be improved. The discussion relating to this finding is presented on pages 88 through 93, 103 through 104, 108 through 110.
4. Realization of the relationship between routing flexibility and selected system performance for the system.
- This research found that routing flexibility exhibits a statistically significant effect on the backorder and average WIP for this multi-stage JIT system. In other words, higher routing flexibility has better performance than lower routing flexibility. The relationship between the routing flexibility and the backorder and average WIP follows a diminishing rate of returns. The discussion relating to this finding is presented on pages 99 through 100, and 113 through 114.
 - The high level of routing flexibility has only slightly better performance on the backorder and average WIP than the medium level of routing flexibility. The system designer must carefully evaluate the tradeoff between the investment on the

increase of routing flexibility and the improvement made by the increase of routing flexibility. The discussion relating to this finding is presented on pages 99 through 100, and 113 through 114.

5. Realization of the relationship between routing flexibility and other experimental factors with respect to the performance measures.
 - The research found that the routing flexibility shows statistically significant interaction with the variability of demand rate and the variability of processing time on the backorder and average WIP for this multi-stage JIT system. Under high variability of demand rate and high variability of processing time, the low level of routing flexibility has a substantially larger backorder and average WIP than the medium and high levels of routing flexibility have. The result indicates that JIT systems with higher routing flexibility are capable of adapting to changes in demand and processing time. The discussion relating to this finding can be found on pages 105 through 106, and 114 through 115.

Future Research Areas

Due to time and economic constraints, the scope of this research was limited to a 4-stage Kanban-controlled pull-type flow shop. The four experimental factors were also restricted to certain levels so that the number of experiments was appropriate for the available resources. In order to further understand the issues of routing flexibility for multi-stage JIT systems, several research areas should be conducted in the future. These research areas are identified and described below.

1. Although the equations for measuring routing flexibility developed in this research have several advantages over the existing measures, they are basically relative measures. The relative measure is capable of comparing the degree of routing

flexibility between two different routings for a similar type of system. However, an absolute measure is needed, when comparison must be made between the routings for two different types of systems. Past research has failed to develop an absolute measure for measuring routing flexibility because of its complexity. Future research may focus on developing an absolute measure of routing flexibility for a certain type of production system.

2. For simplicity, the three levels of system's routing flexibility for this research have identical routing flexibility at each stage. Each part type is assumed to have an identical number of machines available to process them under the same level of routing flexibility. In order to gain more insight on the effects of routing flexibility, more levels of routing flexibility can be included for future research so that the sensitivity of routing flexibility should be investigated. Furthermore, the routing flexibility at different stages may be varied so that the effects of stages' routing flexibility with respect to the system performance can be examined.
3. Since a multi-stage JIT system with alternate routings requires a great deal of decision making on the part flows, the control methods should receive further attention. The machine selection rules appear to have no statistically significant effect on the system performance due to the use of a centralized Kanban post and a storage area between stages. In order to let the machine selection rules come into effect, future research should utilize decentralized Kanban posts and storage areas so that the performance of machine selection rules can be examined. In these studies, each machine or a group of similar machines may have its own Kanban post and storage area.
4. The flexible or general-purpose machines implemented in modern production facilities are costly. Although this research concluded that a multi-stage JIT system with higher degree of routing flexibility has better performance than those with lower

routing flexibility. However, in order to increase the degree of routing flexibility for the system, procurement of additional machines or tool magazines is sometimes unavoidable. Therefore, the economical justification of the increase of routing flexibility with respect to the monetary value of the improvement of system performance should be studied in the future.

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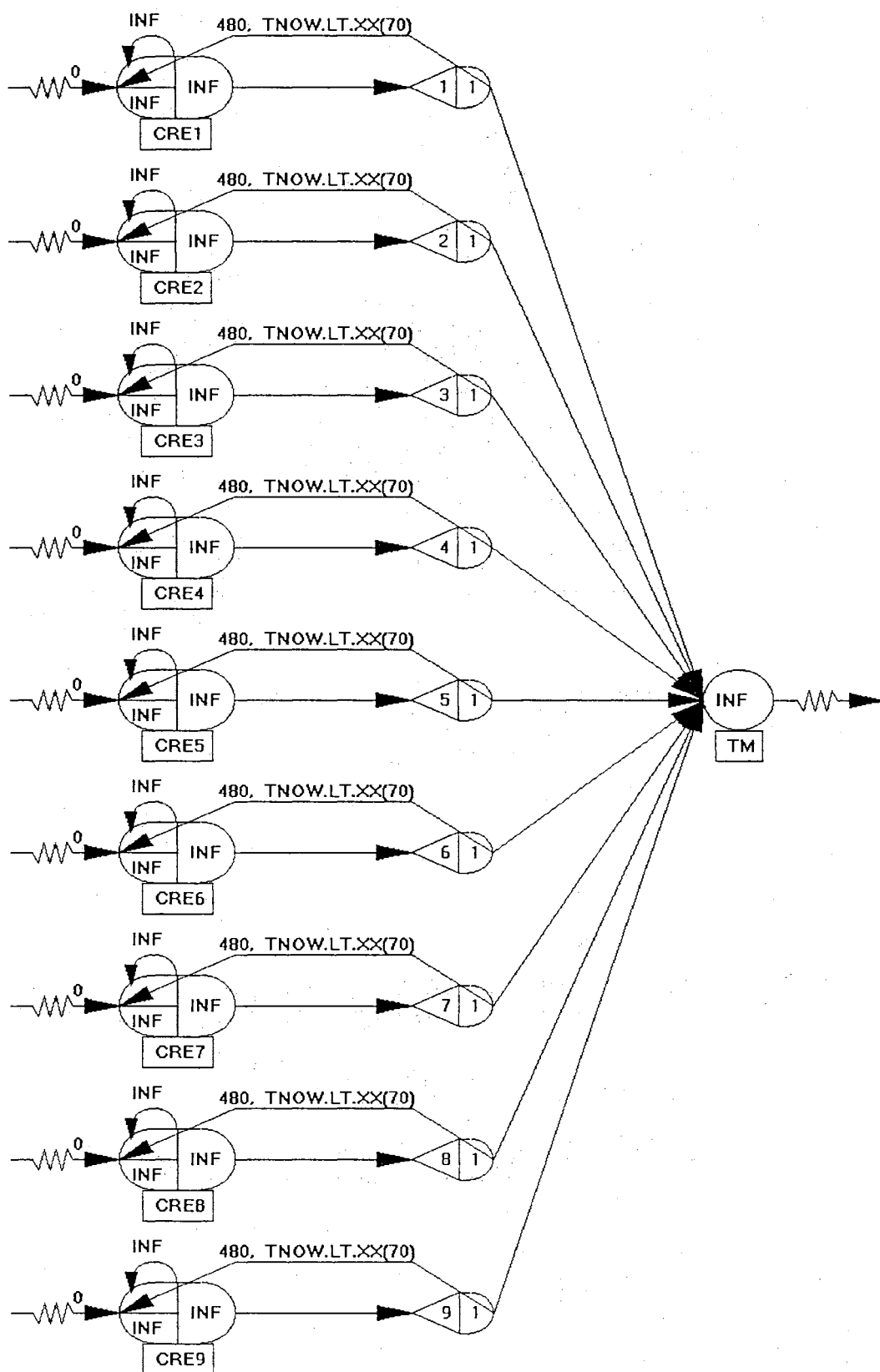
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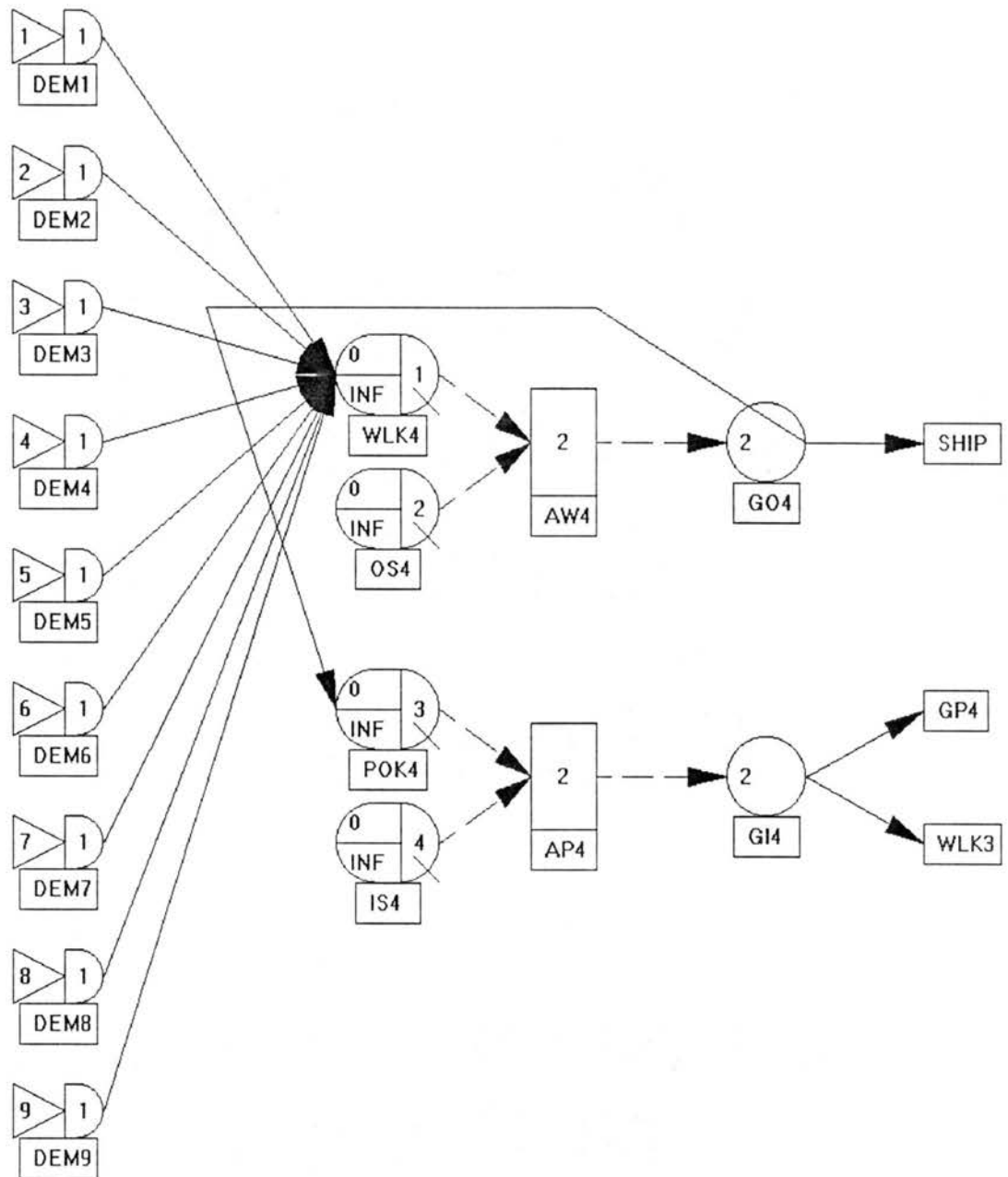
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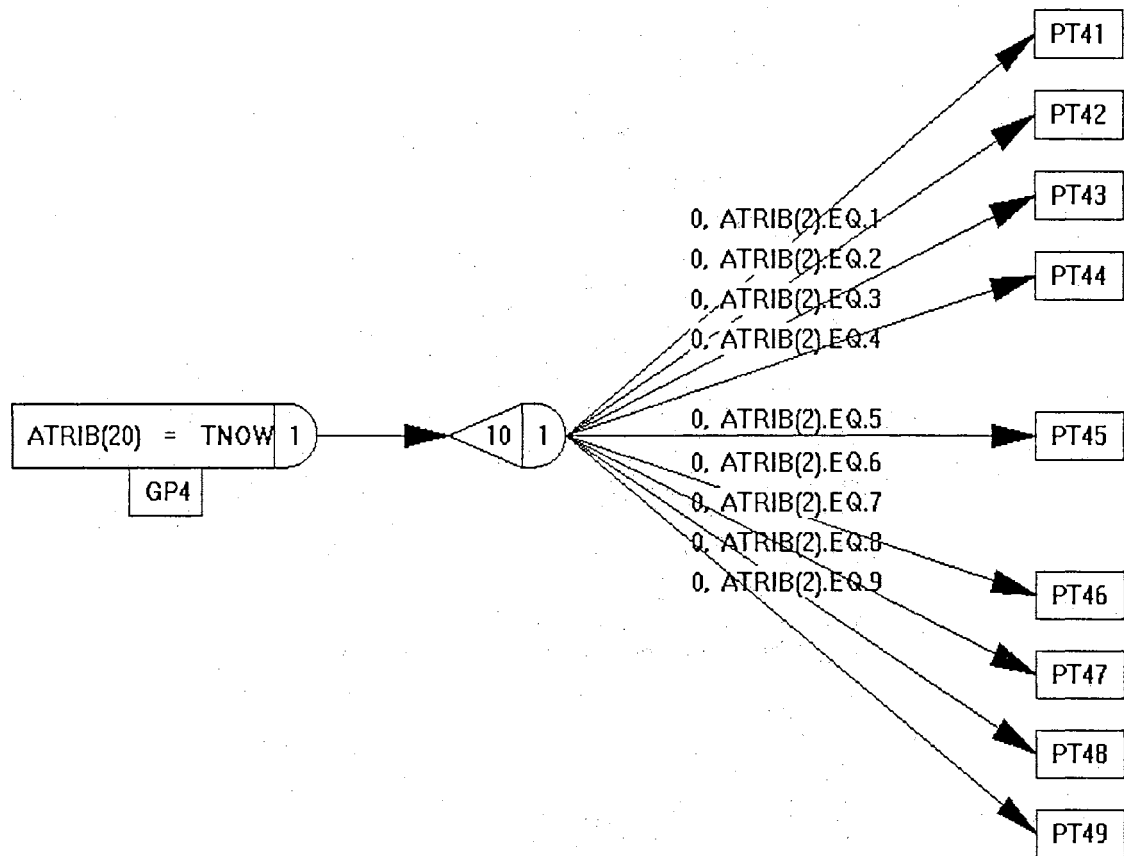
APPENDIXES

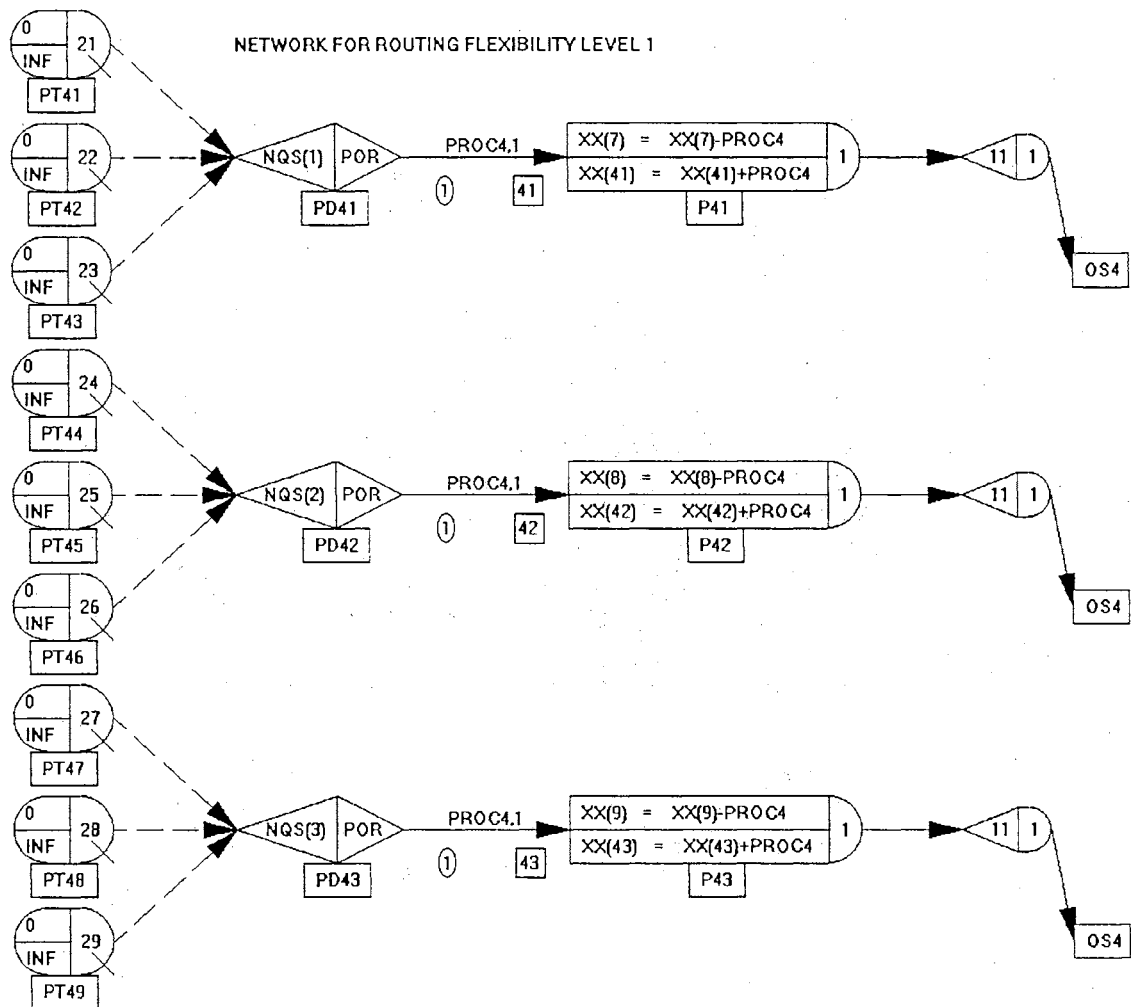
APPENDIX A

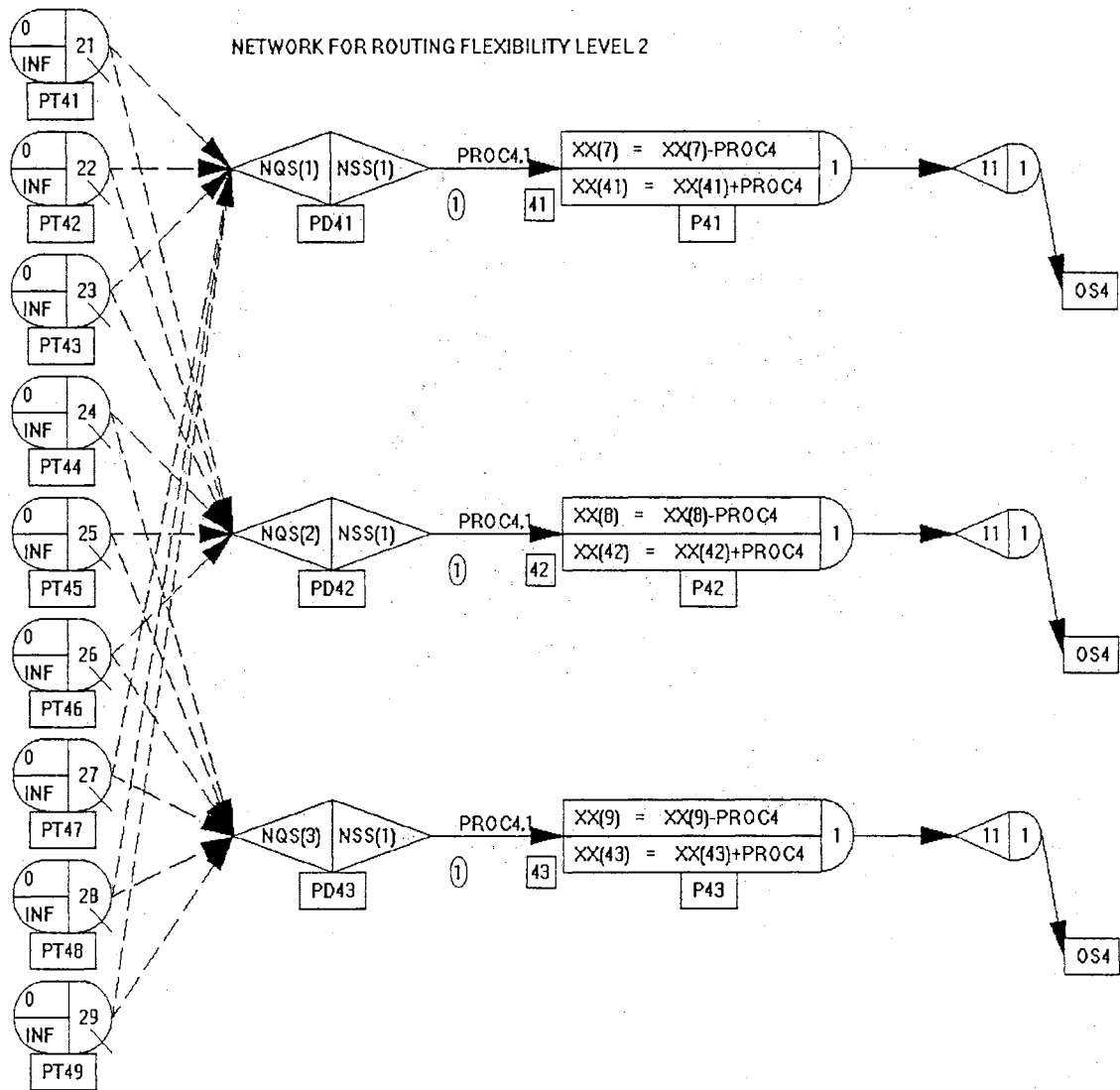
SLAM II NETWORKS

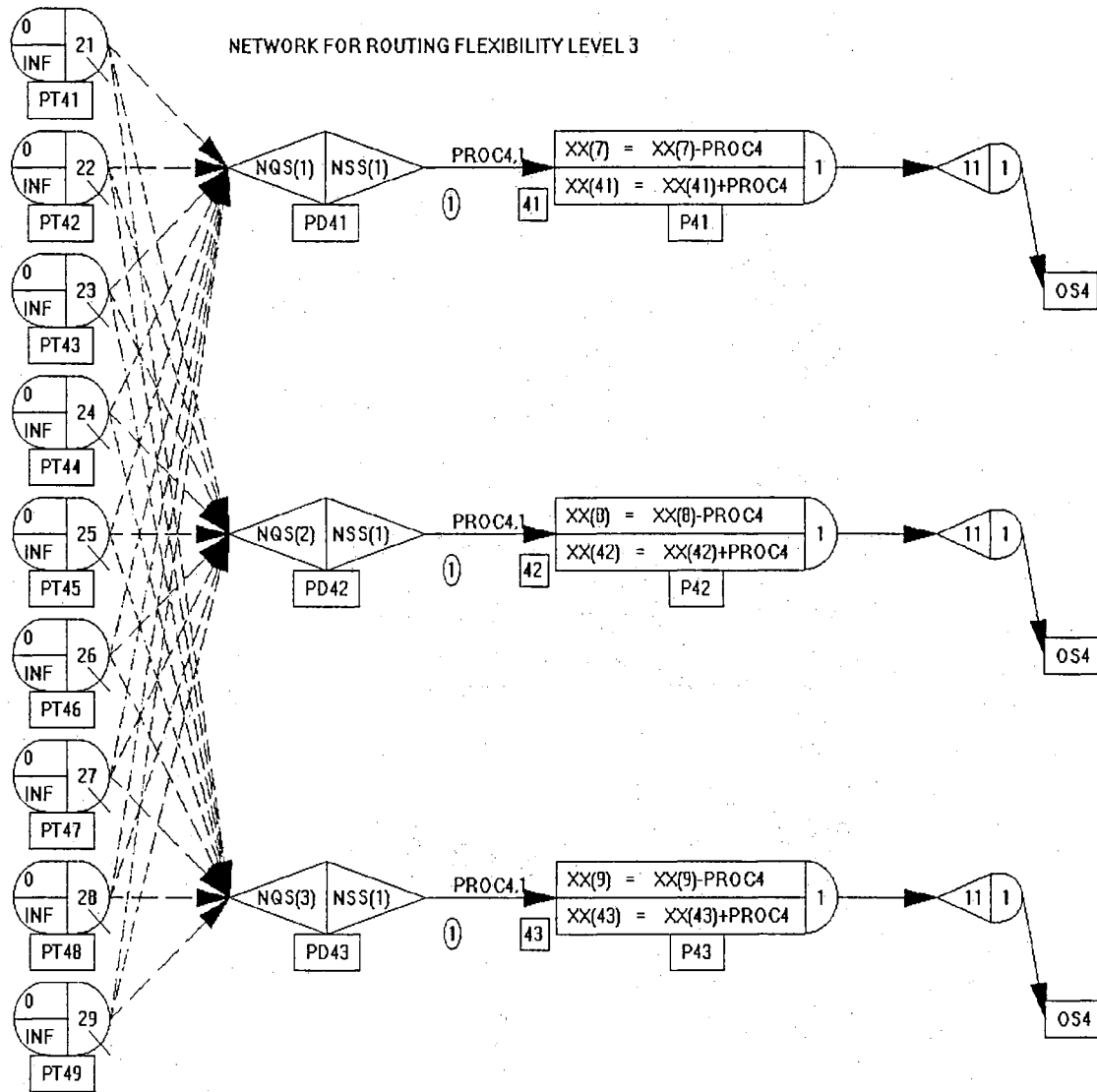


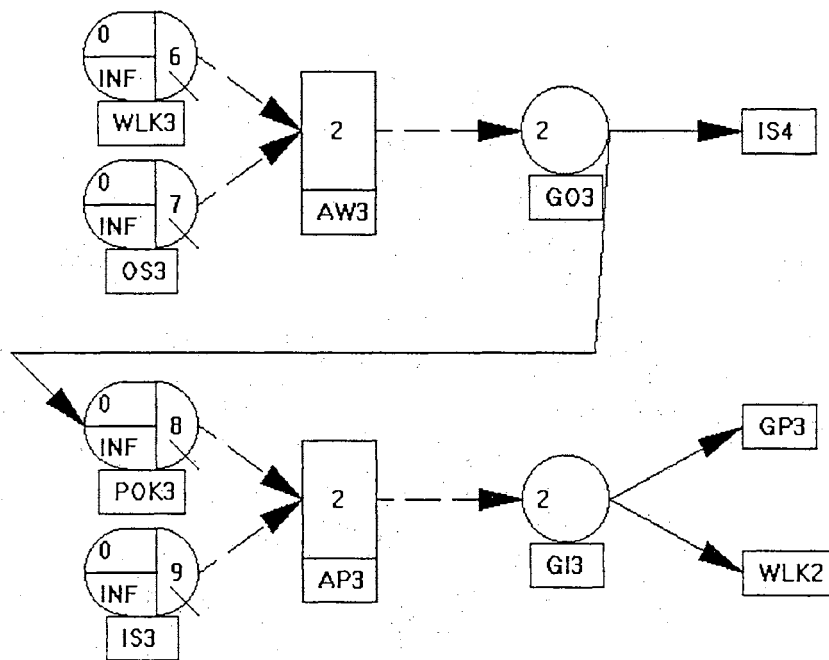


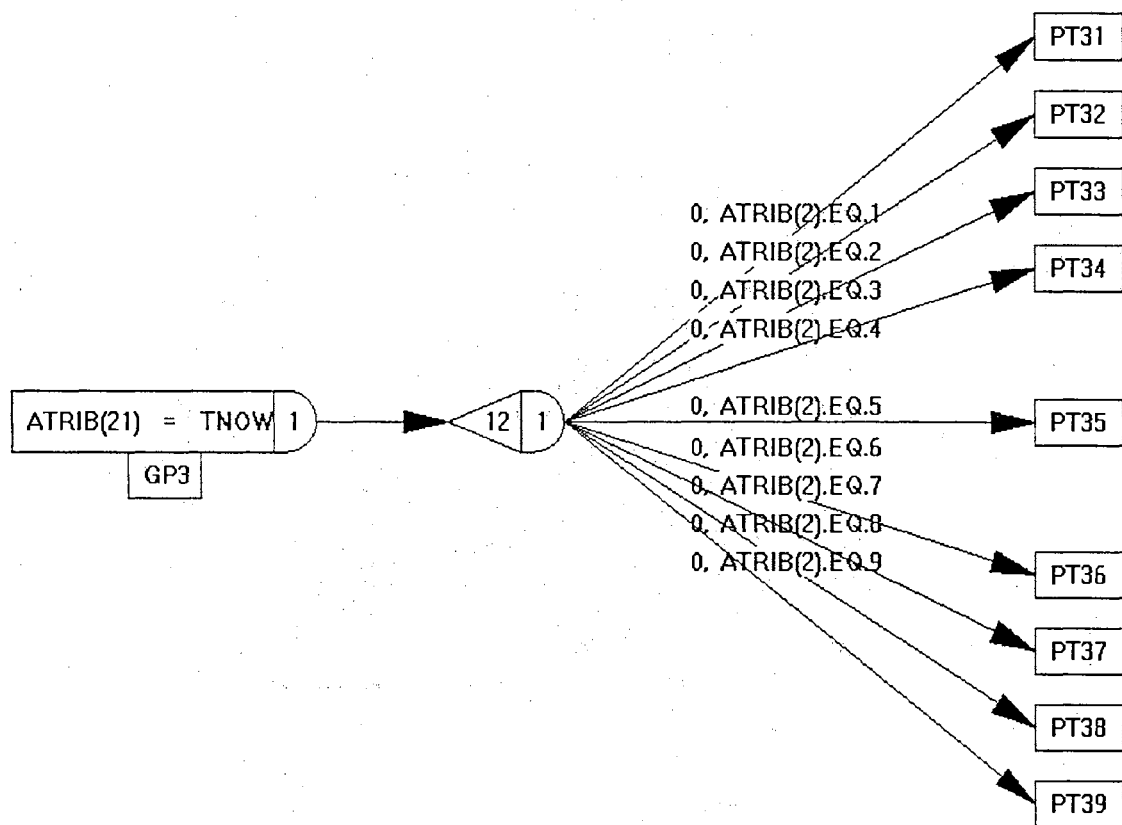


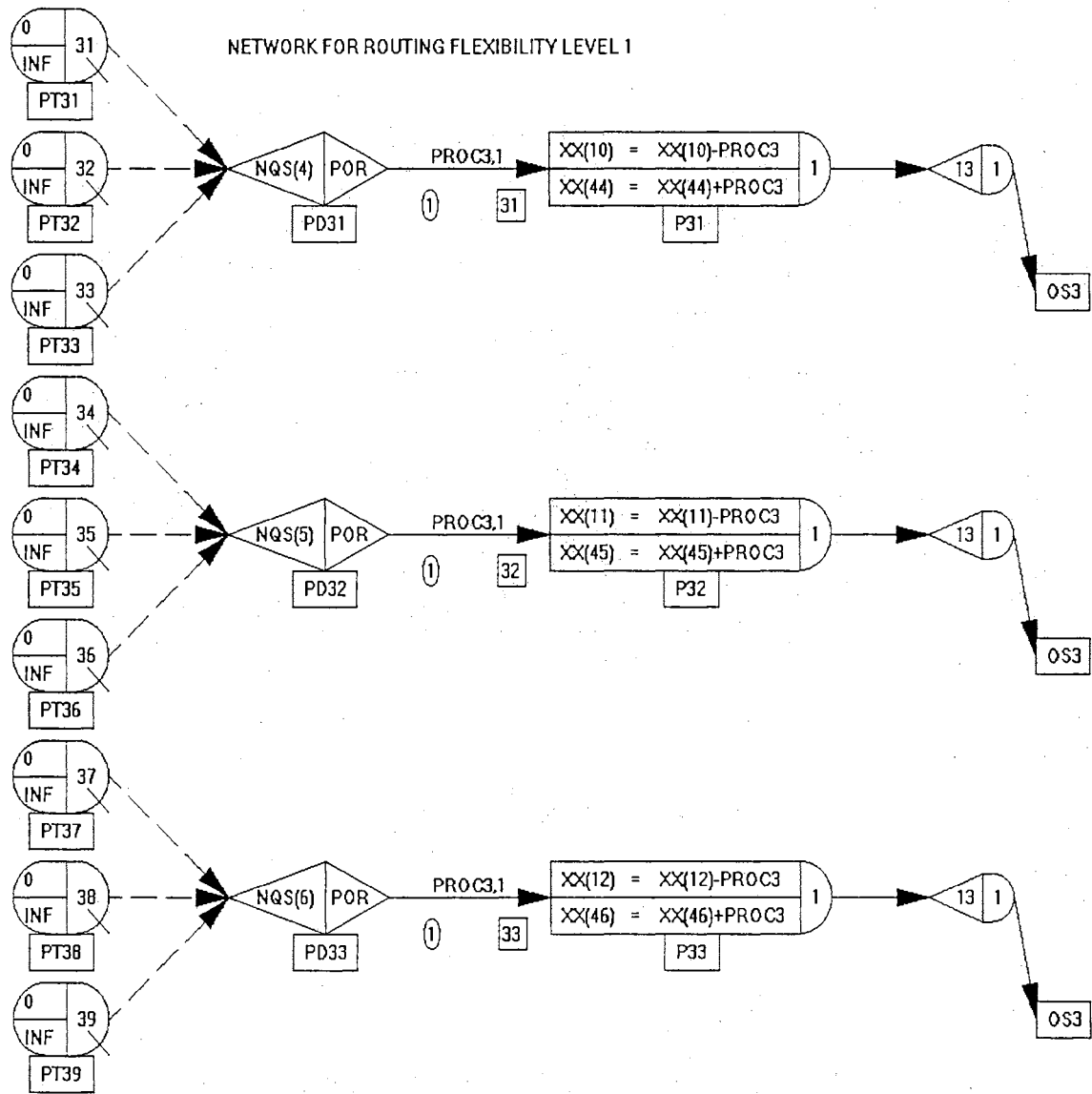


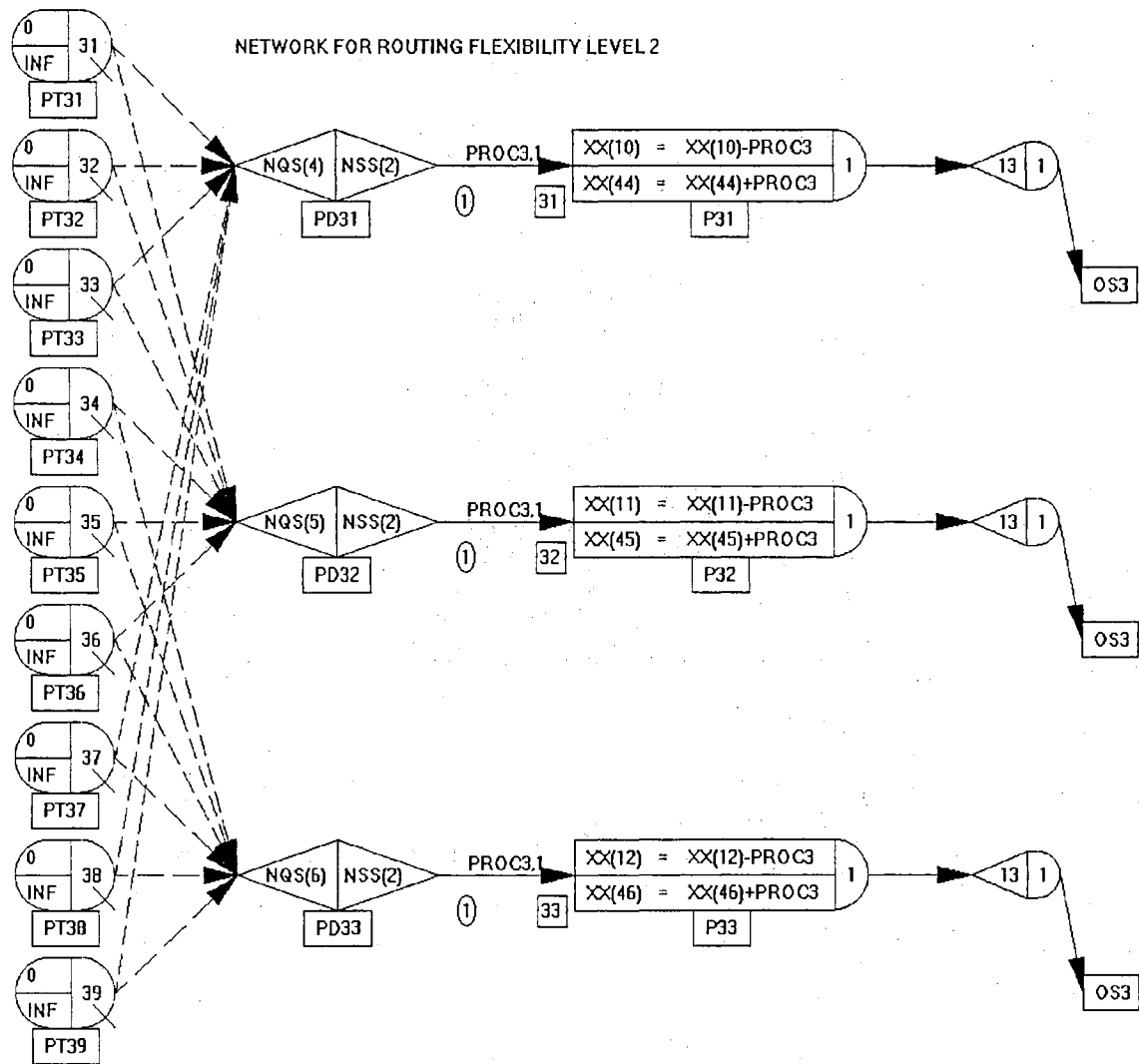


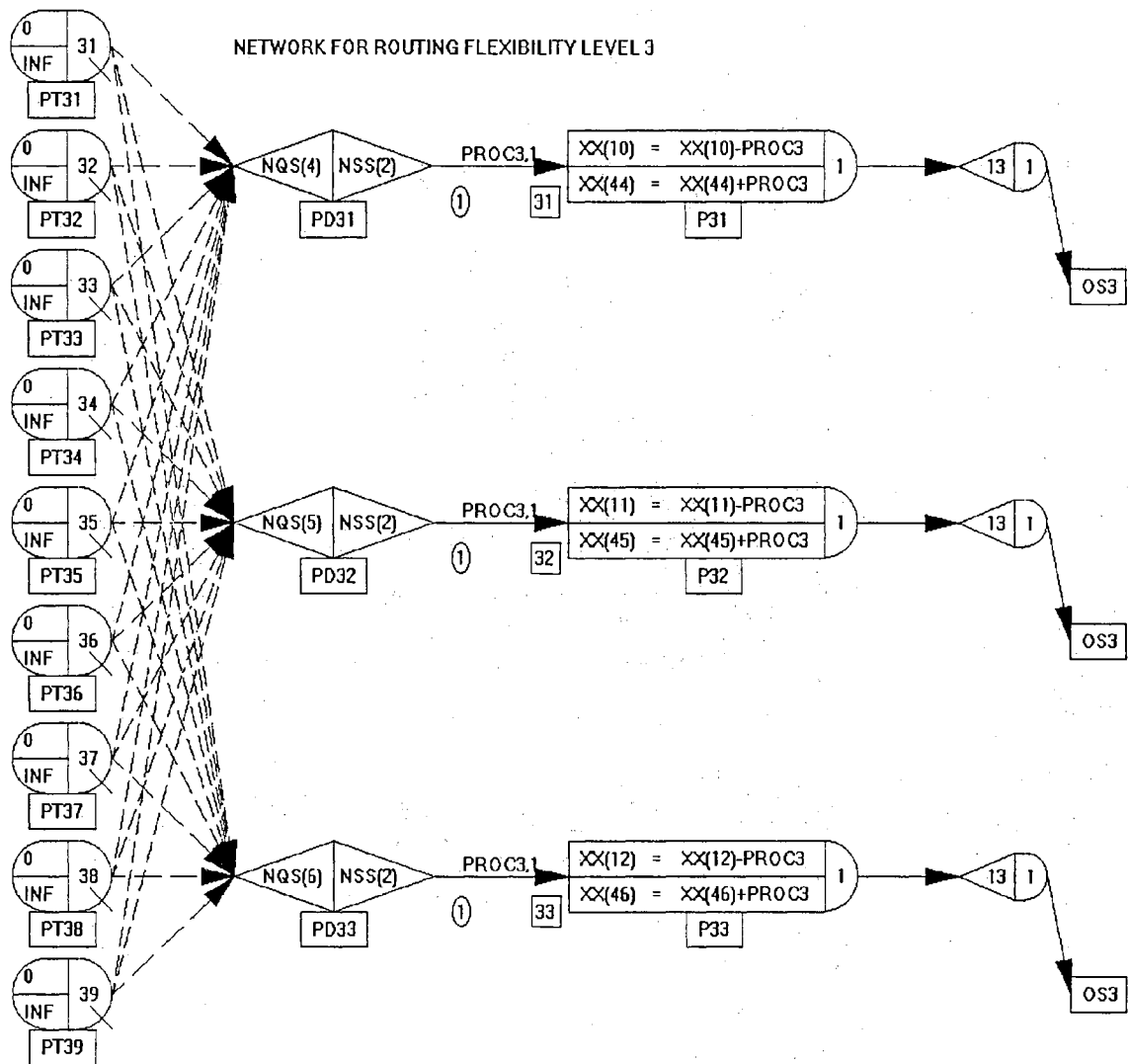


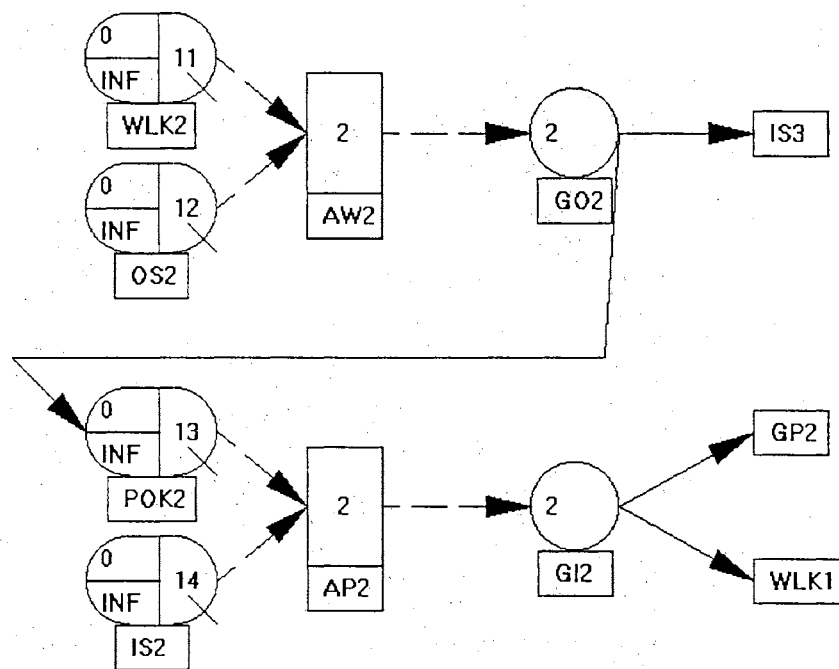


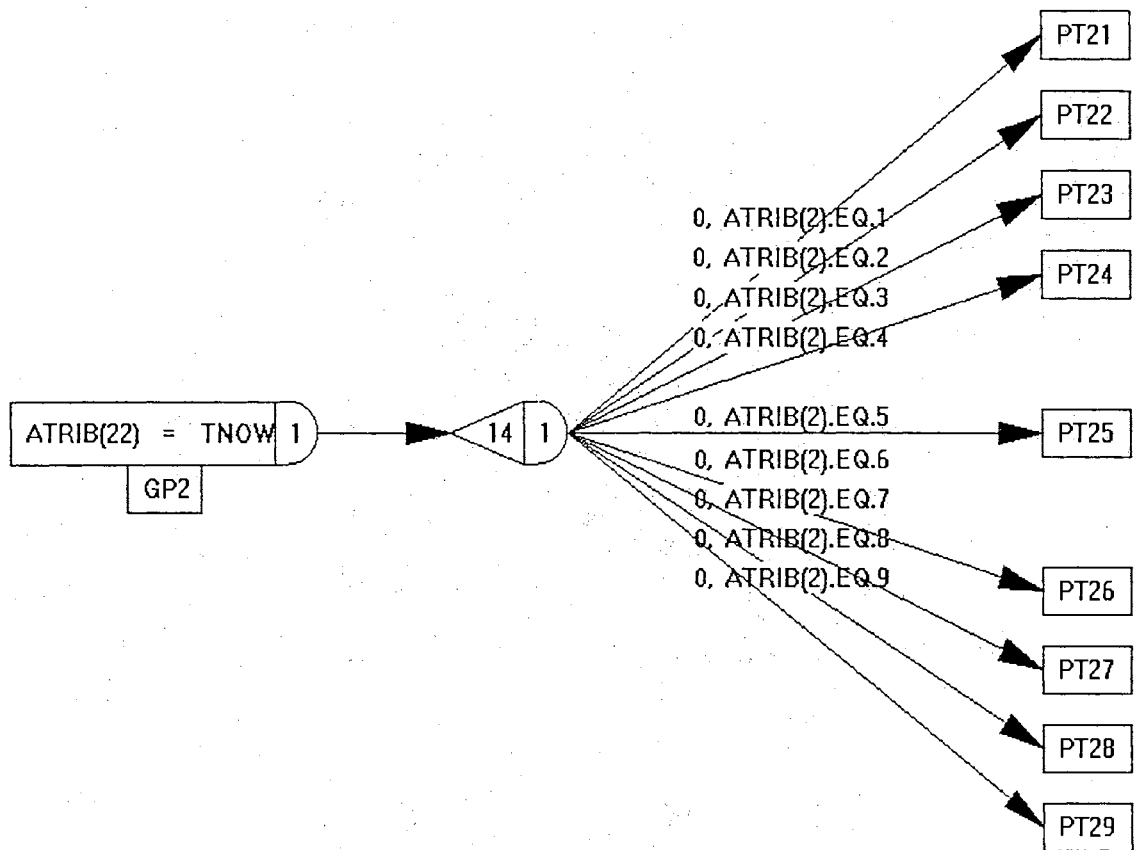


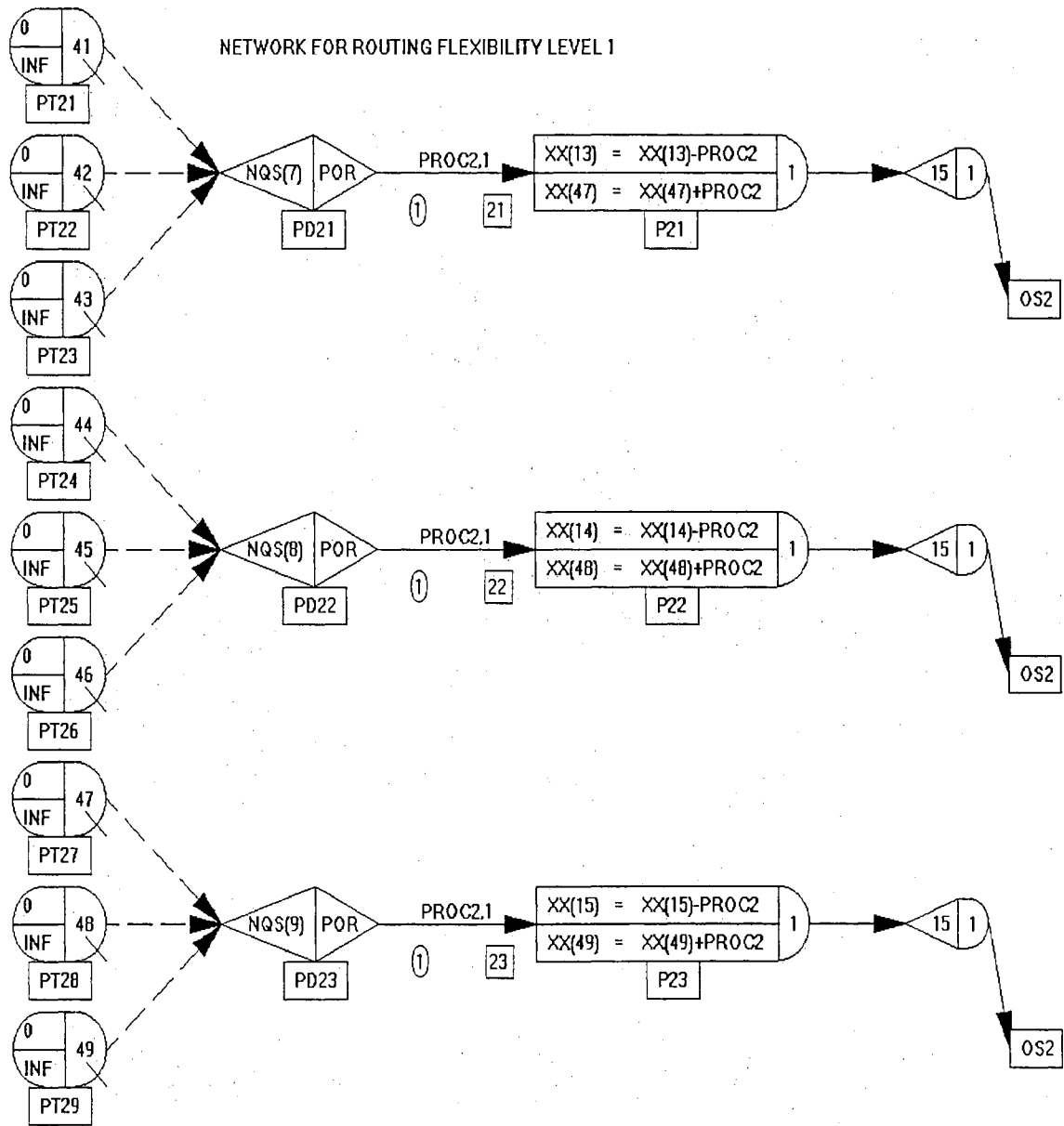


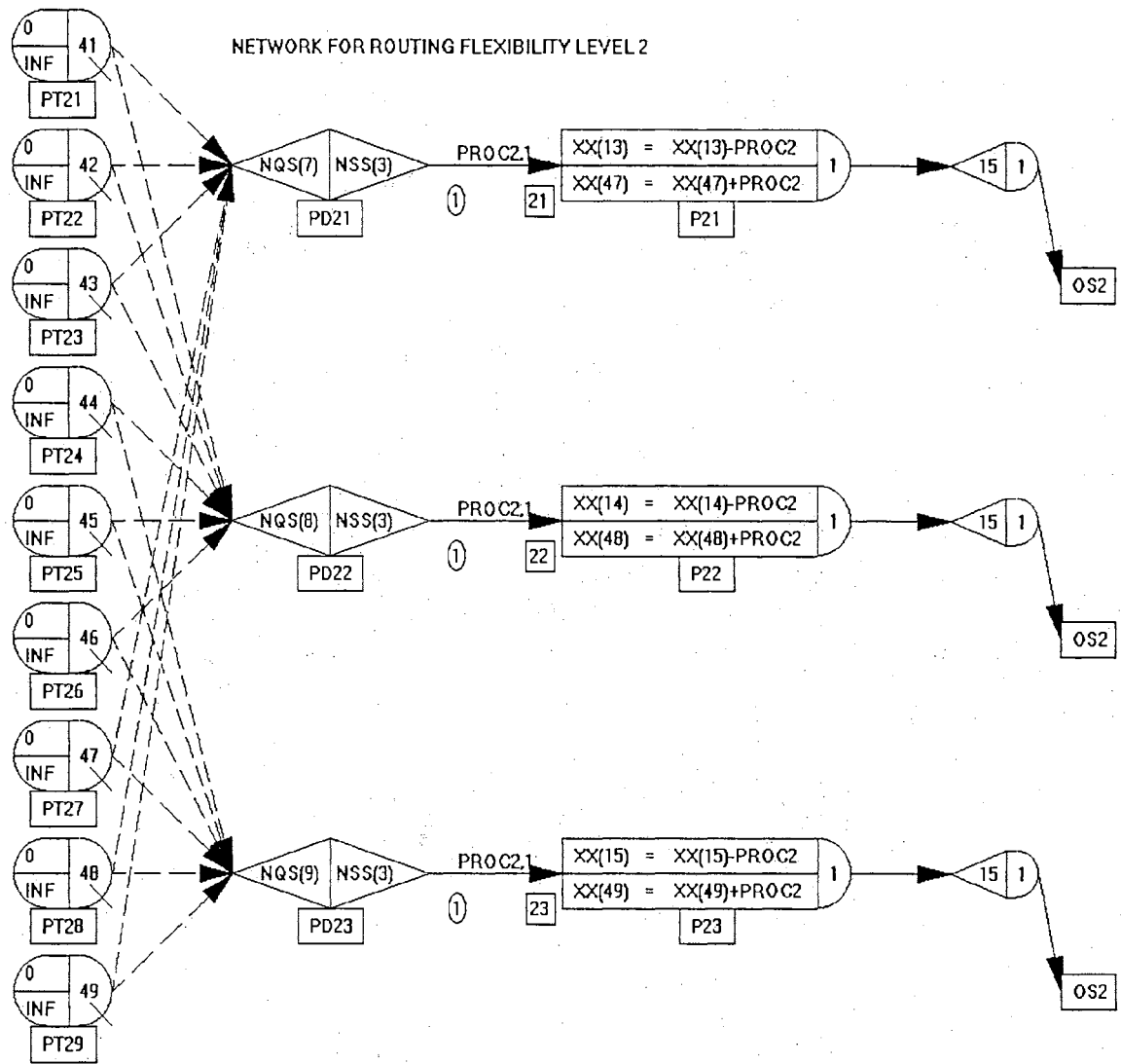


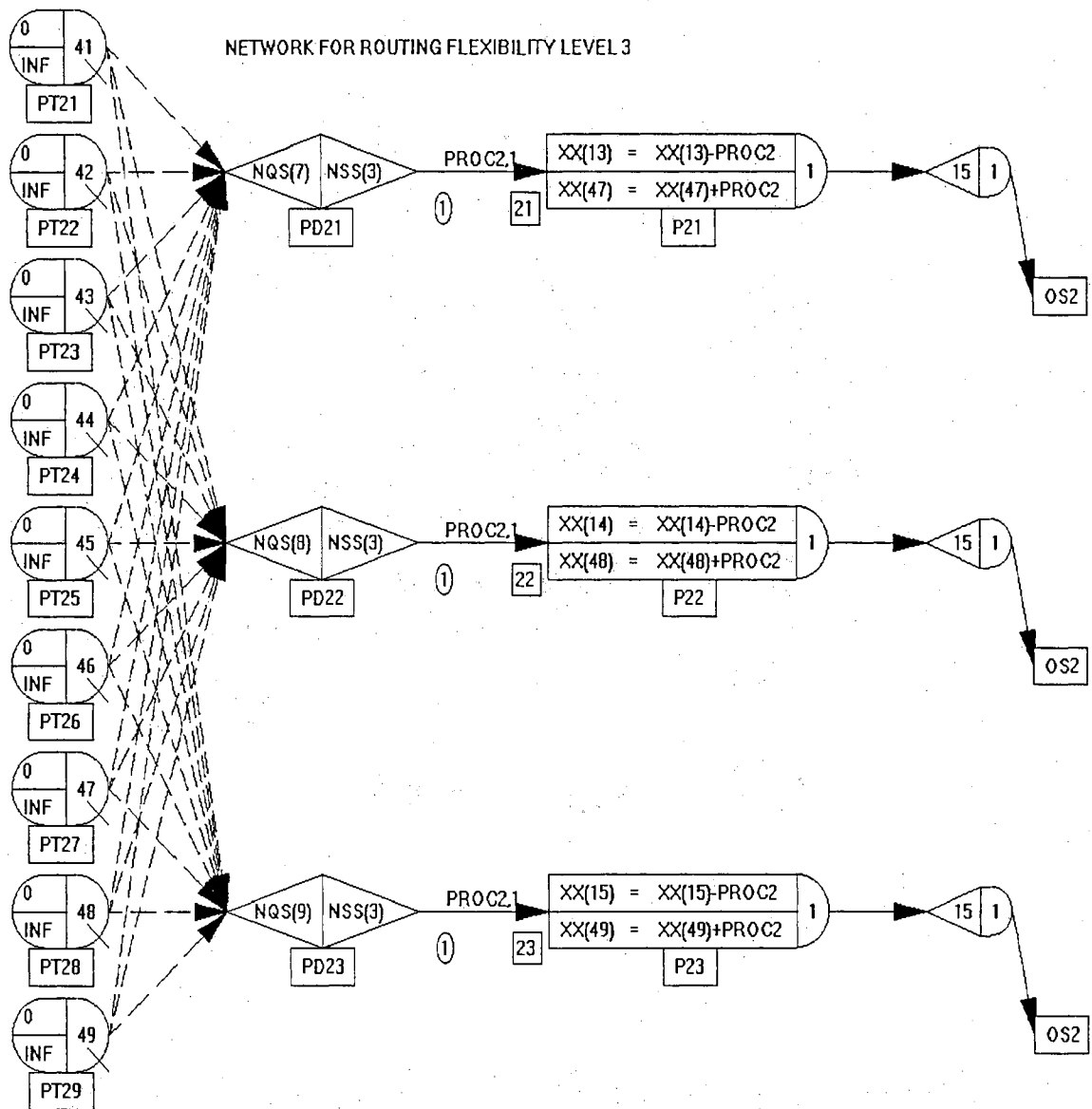


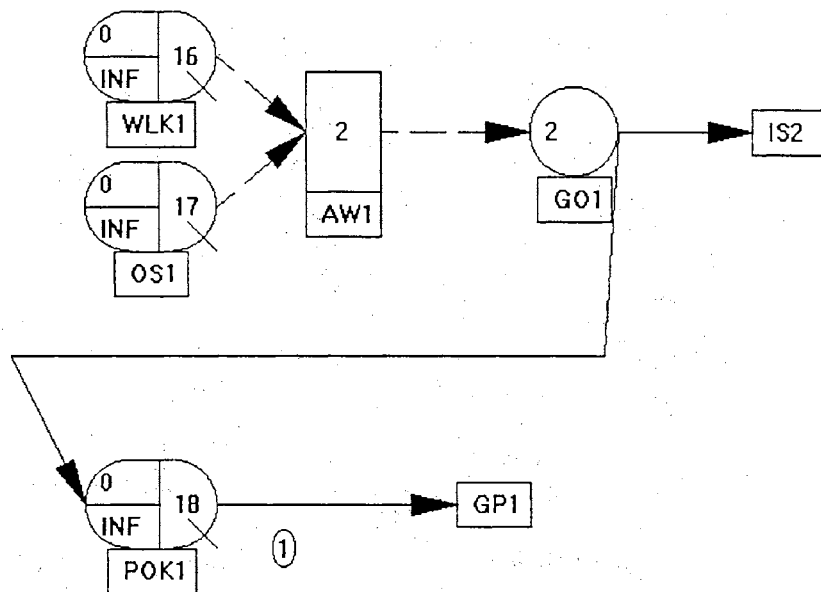


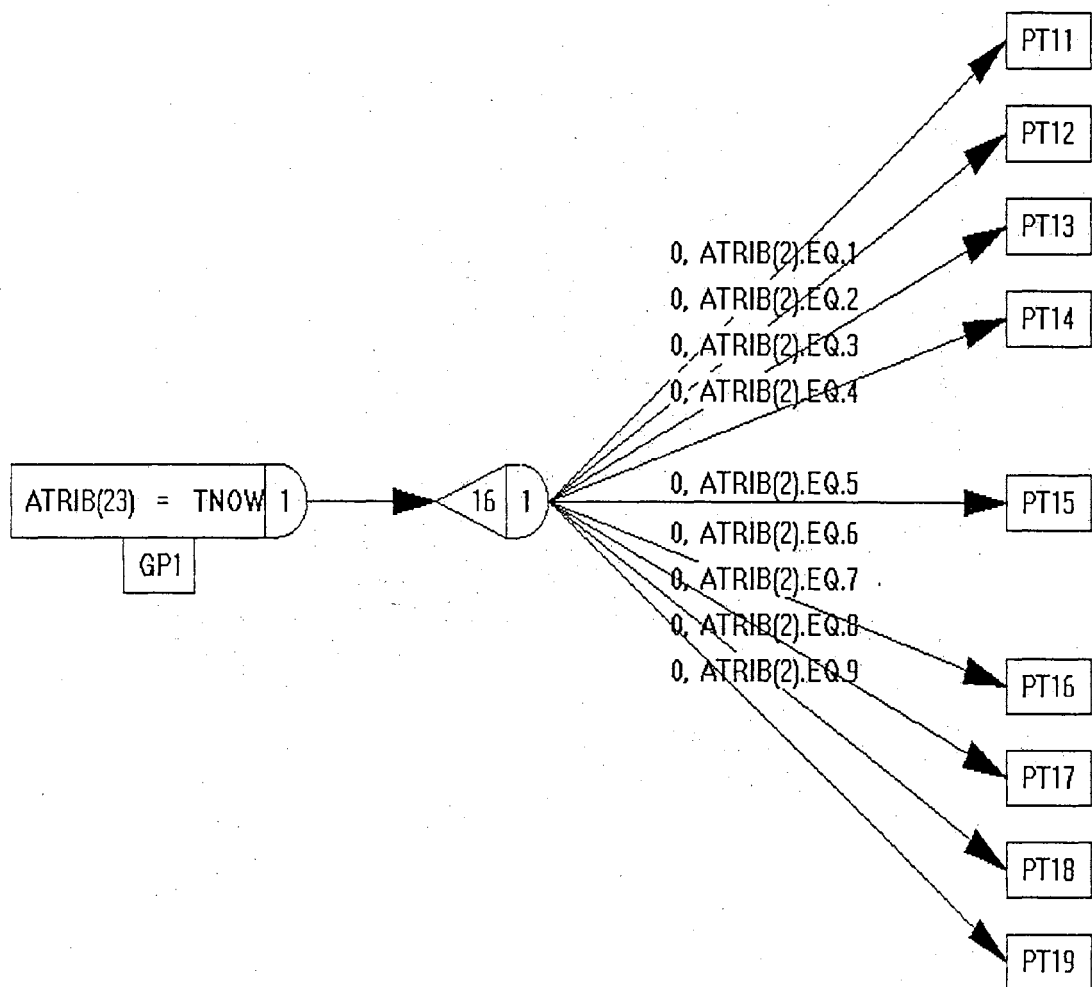


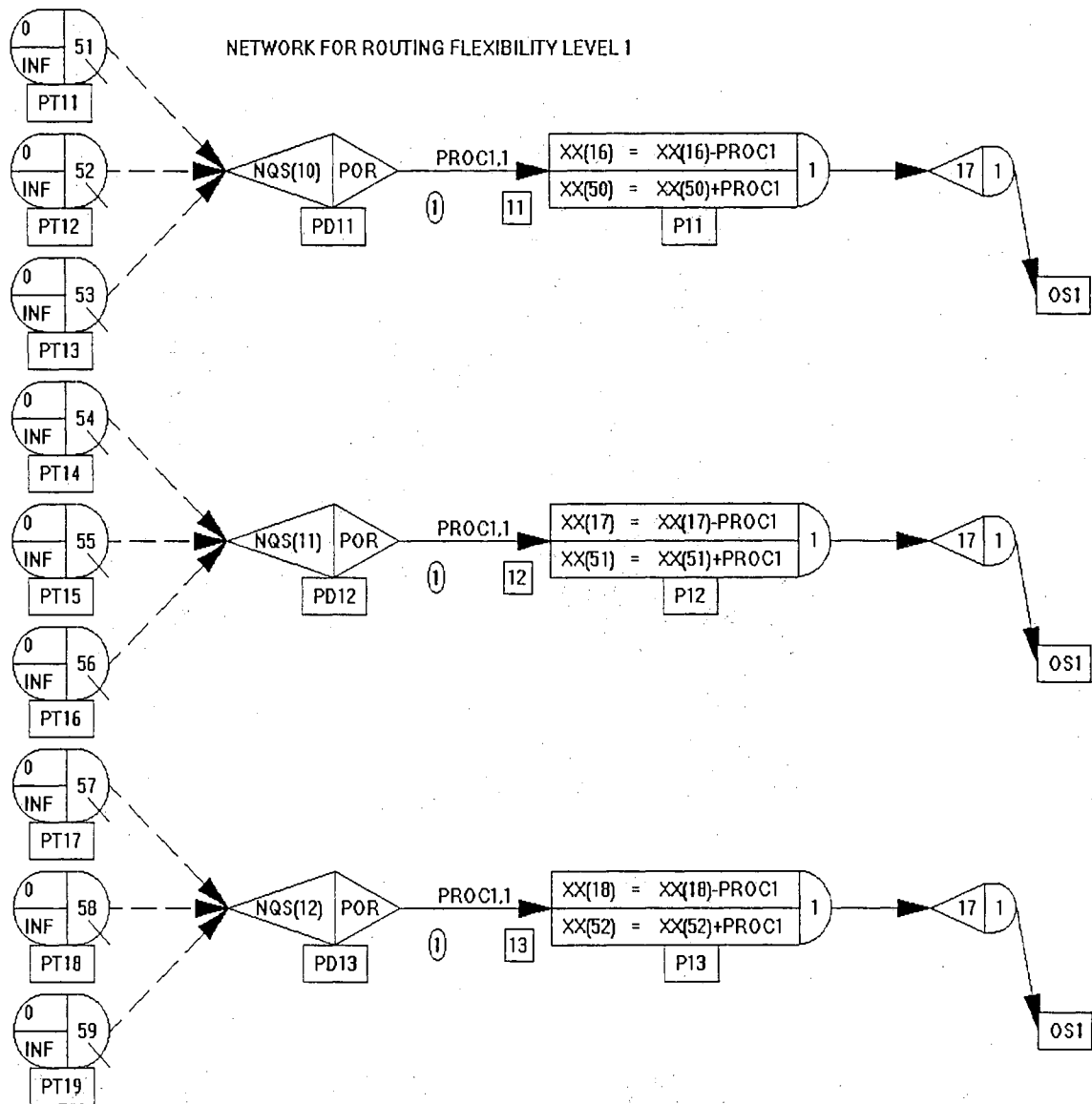


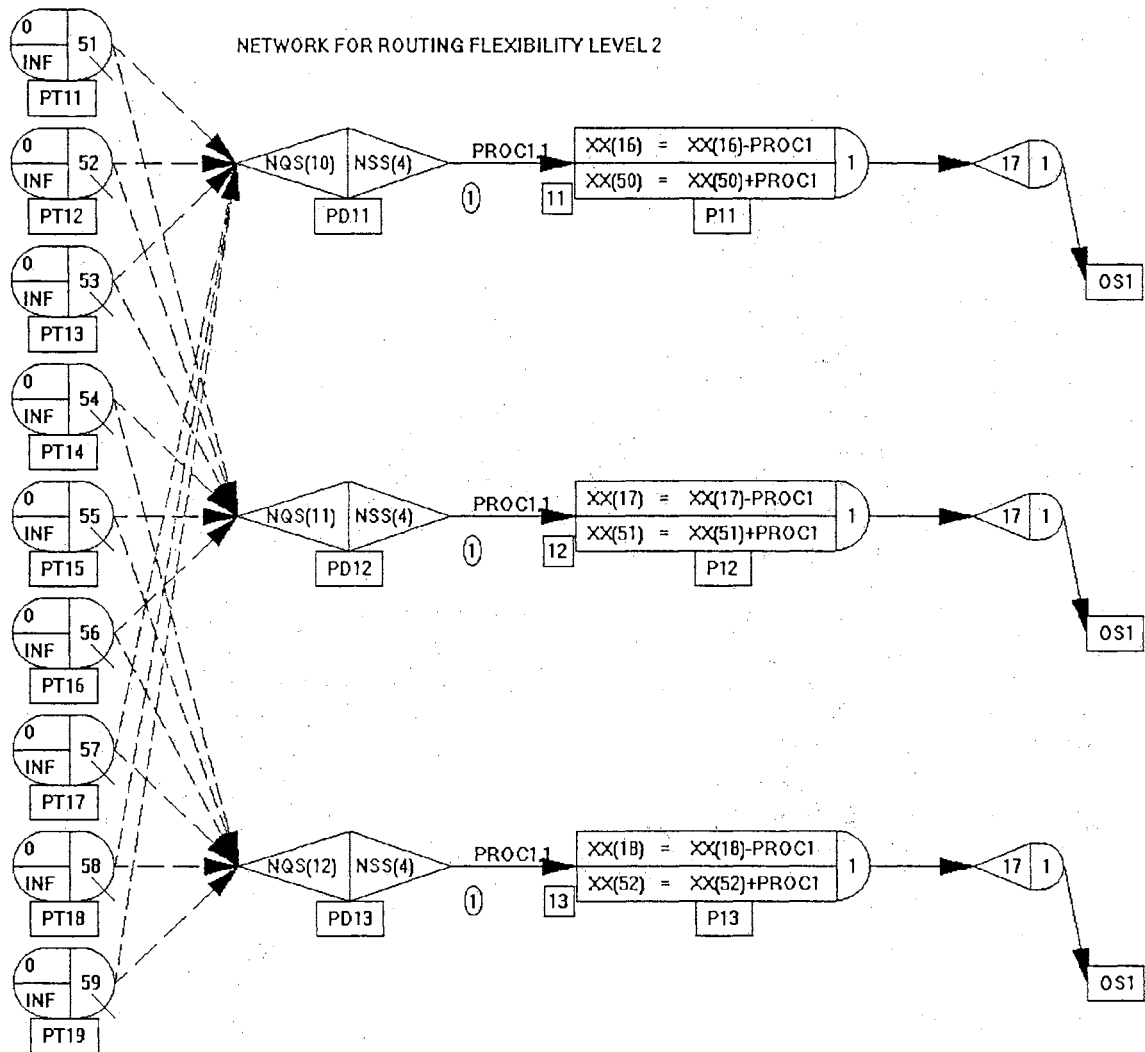


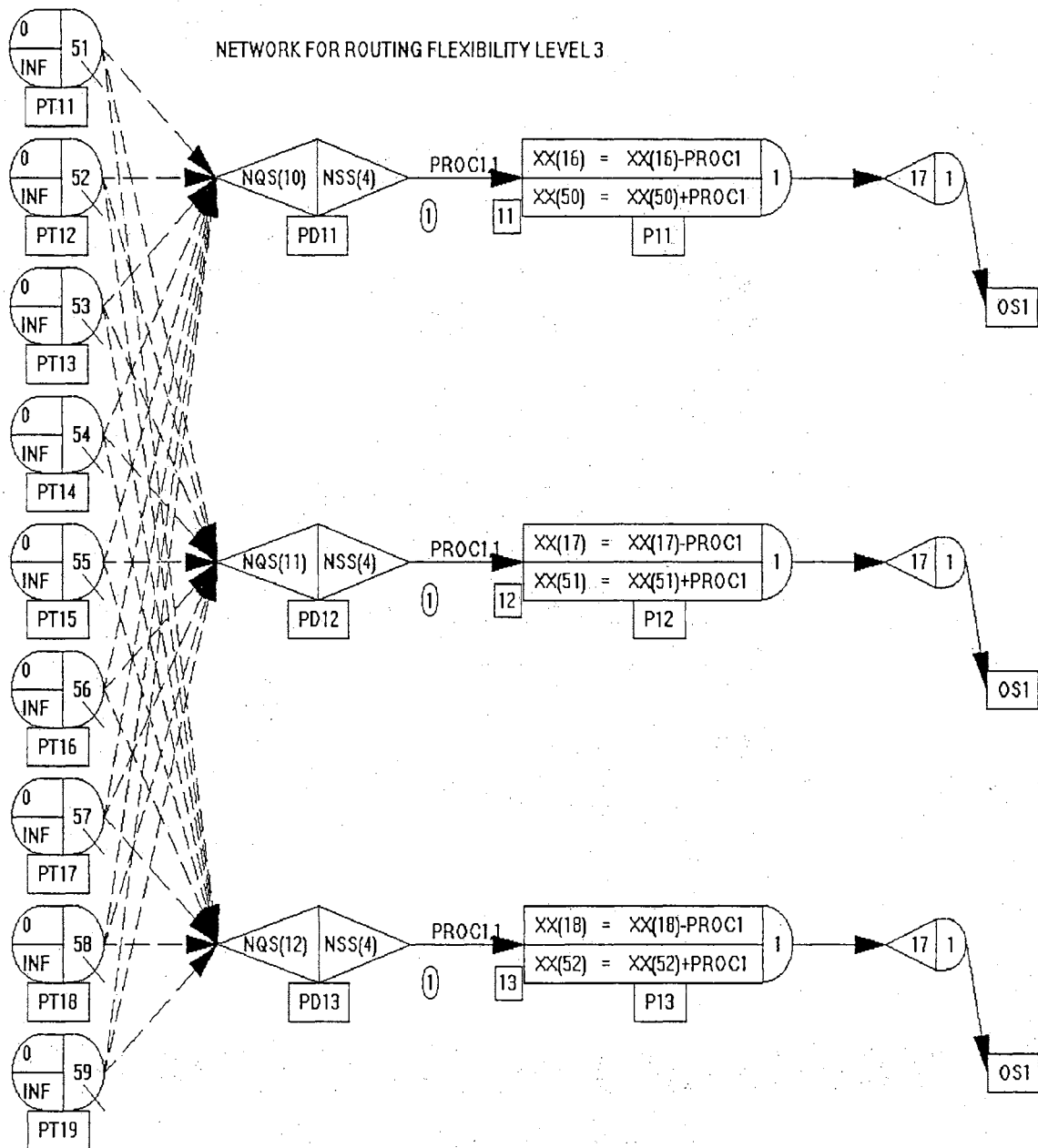


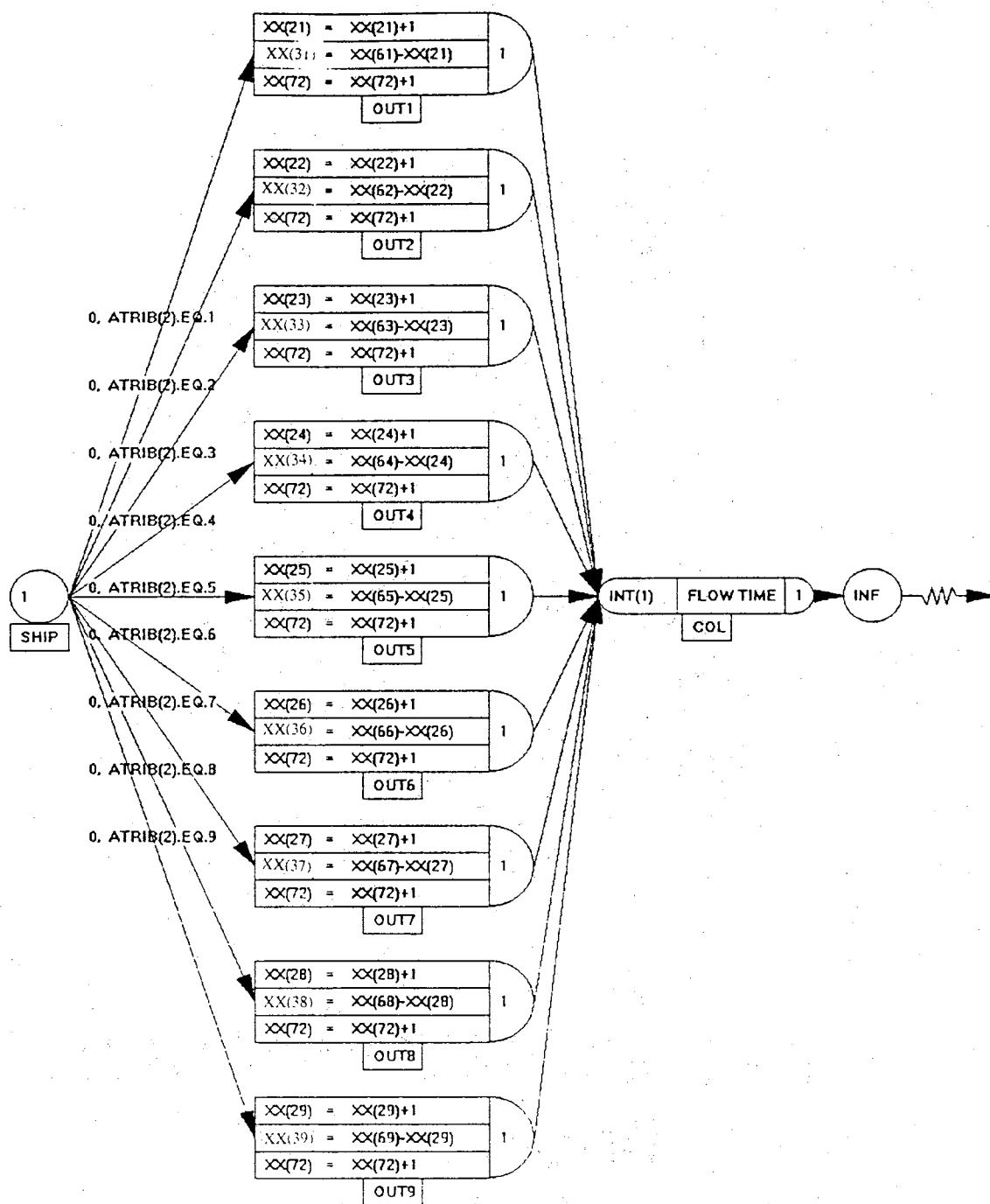












APPENDIX B

SLAM II STATEMENTS

```

*****
; SLAM II STATEMENT NETWORK FOR THE ROUTING FLEXIBILITY IN
; A JIT SYSTEM
; PREPARED BY MIN-CHUN YU
*****
;
GEN,MINCHUN YU,JIT,08/05/97,10,N,N,,,Y,72;
LIMITS,59,25,10000;
;
*****
; INITIALIZE EXPERIMENTAL FACTORS
; XX(1): ROUTING FLEXIBILITY LEVEL (1-3)
; XX(2): PART SELECTION RULE (SCHEDULING RULE) (1-5)
; XX(3): MACHINE SELECTION RULE (1-3)
; XX(4): COEFFICIENT OF VARIATION FOR DEMAND RATE (0.1, 0.3)
; XX(5): COEFFICIENT OF VARIATION FOR PROCESSING TIME (0.1, 0.3)
*****
;
INTLC,XX(1)=1,XX(2)=1,XX(3)=1,XX(4)=0.1,XX(5)=0.1;
;
***** TIME (MINUTES) TO STOP CREATE ENTITIES *****
;
INTLC,XX(70)=191520;
;
***** TIME (MINUTES) TO CLEAR STATISTICS *****
;
INTLC,XX(71)=144000;
;
*****
; DEFINE STATISTICS
*****
;
STAT,2,STAGE 1 UTILIZATION;
STAT,3,STAGE 2 UTILIZATION;
STAT,4,STAGE 3 UTILIZATION;
STAT,5,STAGE 4 UTILIZATION;
STAT,6,SYSTEM UTILIZATION;
STAT,7,THROUGHPUT;
STAT,8,TOTAL DEMAND;
STAT,9,BACKORDER;
STAT,10,AVERAGE WIP;
;
*****
; RANDOM NUMBER STREAMS (FIRST REPLICATION):
; IS1: DEMAND RATE

```

```

; IS2: PROCESSING TIME FOR STAGE 1
; IS3: PROCESSING TIME FOR STAGE 2
; IS4: PROCESSING TIME FOR STAGE 3
; IS5: PROCESSING TIME FOR STAGE 4
;*****
;
;
SEEDS,8875866(1),3566142(2),263503(3),6082674(4),9504499(5);
;
;***** PART ATTRIBUTES AND FLOBAL VARIABLES *****
;
EQUIVALENCE/ATRIB(2),PARTYPE;
EQUIVALENCE/ATRIB(3),PARTFAM;
EQUIVALENCE/ATRIB(4),PROC1;
EQUIVALENCE/ATRIB(5),PROC2;
EQUIVALENCE/ATRIB(6),PROC3;
EQUIVALENCE/ATRIB(7),PROC4;
EQUIVALENCE/XX(1),RFL;
EQUIVALENCE/XX(2),PSR;
EQUIVALENCE/XX(3),MSR;
EQUIVALENCE/XX(4),VDM;
EQUIVALENCE/XX(5),VPT;
;
;***** NETWORK BEGINS *****
NETWORK;
;
;*****
; CREATE NINE PART TYPES AND THEIR ATTRIBUTES (EVENT 1-9)
;*****
;
CRE1  CREATE;
      EVENT,1;
      ACT,480,TNOW.LT.XX(70),CRE1;
      ACT,,TNOW.GE.XX(70),TM;
CRE2  CREATE;
      EVENT,2;
      ACT,480,TNOW.LT.XX(70),CRE2;
      ACT,,TNOW.GE.XX(70),TM;
CRE3  CREATE;
      EVENT,3;
      ACT,480,TNOW.LT.XX(70),CRE3;
      ACT,,TNOW.GE.XX(70),TM;
CRE4  CREATE;
      EVENT,4;
      ACT,480,TNOW.LT.XX(70),CRE4;
      ACT,,TNOW.GE.XX(70),TM;

```

```

CRE5  CREATE;
      EVENT,5;
      ACT,480,TNOW.LT.XX(70),CRE5;
      ACT,,TNOW.GE.XX(70),TM;
CRE6  CREATE;
      EVENT,6;
      ACT,480,TNOW.LT.XX(70),CRE6;
      ACT,,TNOW.GE.XX(70),TM;
CRE7  CREATE;
      EVENT,7;
      ACT,480,TNOW.LT.XX(70),CRE7;
      ACT,,TNOW.GE.XX(70),TM;
CRE8  CREATE;
      EVENT,8;
      ACT,480,TNOW.LT.XX(70),CRE8;
      ACT,,TNOW.GE.XX(70),TM;
CRE9  CREATE;
      EVENT,9;
      ACT,480,TNOW.LT.XX(70),CRE9;
      ACT,,TNOW.GE.XX(70),TM;
TM    TERM;
;
;*****
; GENERATE DEMAND FOR EACH PART TYPE
;*****
;
DEM1  ENTER,1;
      ACT,,,WLK4;
DEM2  ENTER,2;
      ACT,,,WLK4;
DEM3  ENTER,3;
      ACT,,,WLK4;
DEM4  ENTER,4;
      ACT,,,WLK4;
DEM5  ENTER,5;
      ACT,,,WLK4;
DEM6  ENTER,6;
      ACT,,,WLK4;
DEM7  ENTER,7;
      ACT,,,WLK4;
DEM8  ENTER,8;
      ACT,,,WLK4;
DEM9  ENTER,9;
      ACT,,,WLK4;
;

```

```

*****
; WITHDRAW FINISHED PARTS AT THE
; OUTPUT STORAGE OF STAGE 4
*****
;
; ***** WITHDRAWAL KANBAN POST OF STAGE 4 *****
WLK4  QUEUE(1),,,,AW4;
;
; ***** OUTPUT STORAGE OF STAGE 4 *****
OS4   QUEUE(2),,,,AW4;
;
; *****
; MATCH PART TYPE ATTRIBUTE BETWEEN WITHDRAWAL
; KANBANS AND PARTS IN OUTPUT STORAGE AT STAGE 4
*****
;
AW4   MATCH,2,WLK4/GO4,OS4;
;
GO4   GOON,2;
      ACT,,,SHIP;
      ACT,,,POK4;
;
; *****
; INITIATE PRODUCTION FOR STAGE 4
*****
;
; ***** PRODUCTION-ORDERING KANBAN POST OF STAGE 4 *****
POK4  QUEUE(3),,,,AP4;
;
; ***** INPUT STORAGE OF STAGE 4 *****
IS4   QUEUE(4),,,,AP4;
;
; *****
; MATCH PART TYPE ATTRIBUTE BETWEEN PRODUCTION-ORDERING
; KANBANS AND PARTS IN INPUT STORAGE AT STAGE 4
*****
;
AP4   MATCH,2,POK4/GI4,IS4;
;
GI4   GOON,2;
      ACT,,,GP4;
      ACT,,,WLK3;
;
GP4   ASSIGN,TRIB(20)=TNOW;
      EVENT,10,1;

```

```

ACT,,PARTYPE.EQ.1,PT41;
ACT,,PARTYPE.EQ.2,PT42;
ACT,,PARTYPE.EQ.3,PT43;
ACT,,PARTYPE.EQ.4,PT44;
ACT,,PARTYPE.EQ.5,PT45;
ACT,,PARTYPE.EQ.6,PT46;
ACT,,PARTYPE.EQ.7,PT47;
ACT,,PARTYPE.EQ.8,PT48;
ACT,,PARTYPE.EQ.9,PT49;
;
;*****
;
; ROUTING FLEXIBILITY LEVEL 1
;*****
;
PT41  QUEUE(21),,,,PD41;
PT42  QUEUE(22),,,,PD41;
PT43  QUEUE(23),,,,PD41;
PT44  QUEUE(24),,,,PD42;
PT45  QUEUE(25),,,,PD42;
PT46  QUEUE(26),,,,PD42;
PT47  QUEUE(27),,,,PD43;
PT48  QUEUE(28),,,,PD43;
PT49  QUEUE(29),,,,PD43;
;
;*****
;
; ROUTING FLEXIBILITY LEVEL 2
;*****
;
PT41  QUEUE(21),,,,PD41,PD42;
PT42  QUEUE(22),,,,PD41,PD42;
PT43  QUEUE(23),,,,PD41,PD42;
PT44  QUEUE(24),,,,PD42,PD43;
PT45  QUEUE(25),,,,PD42,PD43;
PT46  QUEUE(26),,,,PD42,PD43;
PT47  QUEUE(27),,,,PD43,PD41;
PT48  QUEUE(28),,,,PD43,PD41;
PT49  QUEUE(29),,,,PD43,PD41;
;
;*****
;
; ROUTING FLEXIBILITY LEVEL 3
;*****
;
PT41  QUEUE(21),,,,PD41,PD42,PD43;
PT42  QUEUE(22),,,,PD41,PD42,PD43;
PT43  QUEUE(23),,,,PD41,PD42,PD43;

```

```

PT44  QUEUE(24),,,,PD41,PD42,PD43;
PT45  QUEUE(25),,,,PD41,PD42,PD43;
PT46  QUEUE(26),,,,PD41,PD42,PD43;
PT47  QUEUE(27),,,,PD41,PD42,PD43;
PT48  QUEUE(28),,,,PD41,PD42,PD43;
PT49  QUEUE(29),,,,PD41,PD42,PD43;
;
;*****
; IMPLEMENT PART SELECTION RULES (NQS) AND MACHINE SELECTION
; RULES (NSS) TO DIRECT PART FLOWS WITHIN STAGE 4
;*****
;
;***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 1 *****
;
PD41  SELECT,NQS(1),,,PT41,PT42,PT43;
      ACT(1)/41,PROC4,,P41;
PD42  SELECT,NQS(2),,,PT44,PT45,PT46;
      ACT(1)/42,PROC4,,P42;
PD43  SELECT,NQS(3),,,PT47,PT48,PT49;
      ACT(1)/43,PROC4,,P43;
;
;***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 2 *****
;
PD41  SELECT,NQS(1),NSS(1),,PT41,PT42,PT43,PT47,PT48,PT49;
      ACT(1)/41,PROC4,,P41;
PD42  SELECT,NQS(2),NSS(1),,PT44,PT45,PT46,PT41,PT42,PT43;
      ACT(1)/42,PROC4,,P42;
PD43  SELECT,NQS(3),NSS(1),,PT47,PT48,PT49,PT44,PT45,PT46;
      ACT(1)/43,PROC4,,P43;
;
;***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 3 *****
;
PD41  SELECT,NQS(1),NSS(1),,PT41,PT42,PT43,PT44,PT45,PT46,PT47,PT48,
      PT49;
      ACT(1)/41,PROC4,,P41;
PD42  SELECT,NQS(2),NSS(1),,PT41,PT42,PT43,PT44,PT45,PT46,PT47,PT48,
      PT49;
      ACT(1)/42,PROC4,,P42;
PD43  SELECT,NQS(3),NSS(1),,PT41,PT42,PT43,PT44,PT45,PT46,PT47,PT48,
      PT49;
      ACT(1)/43,PROC4,,P43;
;
P41   ASSIGN,XX(7)=XX(7)-PROC4,XX(41)=XX(41)+PROC4;
      EVENT,11,1;
      ACT,,,OS4;

```

```

P42  ASSIGN,XX(8)=XX(8)-PROC4,XX(42)=XX(42)+PROC4;
      EVENT,11,1;
      ACT,,,OS4;
P43  ASSIGN,XX(9)=XX(9)-PROC4,XX(43)=XX(43)+PROC4;
      EVENT,11,1;
      ACT,,,OS4;

;
;*****
; WITHDRAW FINISHED PARTS AT THE
; OUTPUT STORAGE OF STAGE 3
;*****
;
;***** WITHDRAWAL KANBAN POST OF STAGE 3 *****
WLK3  QUEUE(6),,,,AW3;
;
;***** OUTPUT STORAGE OF STAGE 3 *****
OS3   QUEUE(7),,,,AW3;
;
;*****
; MATCH PART TYPE ATTRIBUTE BETWEEN WITHDRAWAL
; KANBANS AND PARTS IN OUTPUT STORAGE AT STAGE 3
;*****
;
AW3   MATCH,2,WLK3/GO3,OS3;
;
GO3   GOON,2;
      ACT,,,IS4;
      ACT,,,POK3;
;
;*****
; INITIATE PRODUCTION FOR STAGE 3
;*****
;
;***** PRODUCTION-ORDERING KANBAN POST OF STAGE 3 *****
POK3  QUEUE(8),,,,AP3;
;
;***** INPUT STORAGE OF STAGE 3 *****
IS3   QUEUE(9),,,,AP3;
;
;*****
; MATCH PART TYPE ATTRIBUTE BETWEEN PRODUCTION-ORDERING
; KANBANS AND PARTS IN INPUT STORAGE AT STAGE 3
;*****
;
AP3   MATCH,2,POK3/GI3,IS3;

```

```

;
GI3    GOON,2;
        ACT,,,GP3;
        ACT,,,WLK2;
;
GP3    ASSIGN,ATRIB(21)=TNOW;
        EVENT,12,1;
        ACT,,PARTYPE.EQ.1,PT31;
        ACT,,PARTYPE.EQ.2,PT32;
        ACT,,PARTYPE.EQ.3,PT33;
        ACT,,PARTYPE.EQ.4,PT34;
        ACT,,PARTYPE.EQ.5,PT35;
        ACT,,PARTYPE.EQ.6,PT36;
        ACT,,PARTYPE.EQ.7,PT37;
        ACT,,PARTYPE.EQ.8,PT38;
        ACT,,PARTYPE.EQ.9,PT39;
;
;*****
; ROUTING FLEXIBILITY LEVEL 1
;*****
;
PT31    QUEUE(31),,,,PD31;
PT32    QUEUE(32),,,,PD31;
PT33    QUEUE(33),,,,PD31;
PT34    QUEUE(34),,,,PD32;
PT35    QUEUE(35),,,,PD32;
PT36    QUEUE(36),,,,PD32;
PT37    QUEUE(37),,,,PD33;
PT38    QUEUE(38),,,,PD33;
PT39    QUEUE(39),,,,PD33;
;
;*****
; ROUTING FLEXIBILITY LEVEL 2
;*****
;
PT31    QUEUE(31),,,,PD31,PD32;
PT32    QUEUE(32),,,,PD31,PD32;
PT33    QUEUE(33),,,,PD31,PD32;
PT34    QUEUE(34),,,,PD32,PD33;
PT35    QUEUE(35),,,,PD32,PD33;
PT36    QUEUE(36),,,,PD32,PD33;
PT37    QUEUE(37),,,,PD33,PD31;
PT38    QUEUE(38),,,,PD33,PD31;
PT39    QUEUE(39),,,,PD33,PD31;
;

```

```

*****
; ROUTING FLEXIBILITY LEVEL 3
*****
;
PT31  QUEUE(31),,,,PD31,PD32,PD33;
PT32  QUEUE(32),,,,PD31,PD32,PD33;
PT33  QUEUE(33),,,,PD31,PD32,PD33;
PT34  QUEUE(34),,,,PD31,PD32,PD33;
PT35  QUEUE(35),,,,PD31,PD32,PD33;
PT36  QUEUE(36),,,,PD31,PD32,PD33;
PT37  QUEUE(37),,,,PD31,PD32,PD33;
PT38  QUEUE(38),,,,PD31,PD32,PD33;
PT39  QUEUE(39),,,,PD31,PD32,PD33;
;
*****
; IMPLEMENT PART SELECTION RULES (NQS) AND MACHINE SELECTION
; RULES (NSS) TO DIRECT PART FLOWS WITHIN STAGE 3
*****
;
***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 1 *****
;
PD31  SELECT,NQS(4),,,PT31,PT32,PT33;
      ACT(1)/31,PROC3,,P31;
PD32  SELECT,NQS(5),,,PT34,PT35,PT36;
      ACT(1)/32,PROC3,,P32;
PD33  SELECT,NQS(6),,,PT37,PT38,PT39;
      ACT(1)/33,PROC3,,P33;
;
***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 2 *****
;
PD31  SELECT,NQS(4),NSS(2),,PT31,PT32,PT33,PT37,PT38,PT39;
      ACT(1)/31,PROC3,,P31;
PD32  SELECT,NQS(5),NSS(2),,PT34,PT35,PT36,PT31,PT32,PT33;
      ACT(1)/32,PROC3,,P32;
PD33  SELECT,NQS(6),NSS(2),,PT37,PT38,PT39,PT34,PT35,PT36;
      ACT(1)/33,PROC3,,P33;
;
***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 3 *****
;
PD31  SELECT,NQS(4),NSS(2),,PT31,PT32,PT33,PT34,PT35,PT36,PT37,PT38,
      PT39;
      ACT(1)/31,PROC3,,P31;
PD32  SELECT,NQS(5),NSS(2),,PT31,PT32,PT33,PT34,PT35,PT36,PT37,PT38,
      PT39;
      ACT(1)/32,PROC3,,P32;

```

```

PD33  SELECT,NQS(6),NSS(2),, PT31,PT32,PT33,PT34,PT35,PT36,PT37,PT38,
      PT39;
      ACT(1)/33,PROC3,,P33;
;
P31   ASSIGN,XX(10)=XX(10)-PROC3,XX(44)=XX(44)+PROC3;
      EVENT,13,1;
      ACT,,,OS3;
P32   ASSIGN,XX(11)=XX(11)-PROC3,XX(45)=XX(45)+PROC3;
      EVENT,13,1;
      ACT,,,OS3;
P33   ASSIGN,XX(12)=XX(12)-PROC3,XX(46)=XX(46)+PROC3;
      EVENT,13,1;
      ACT,,,OS3;
;
;*****
; WITHDRAW FINISHED PARTS AT THE
; OUTPUT STORAGE OF STAGE 2
;*****
;
;***** WITHDRAWAL KANBAN POST OF STAGE 2 *****
WLK2  QUEUE(11),,,,AW2;
;
;***** OUTPUT STORAGE OF STAGE 2 *****
OS2   QUEUE(12),,,,AW2;
;
;*****
; MATCH PART TYPE ATTRIBUTE BETWEEN WITHDRAWAL
; KANBANS AND PARTS IN OUTPUT STORAGE AT STAGE 2
;*****
;
AW2   MATCH,2,WLK2/GO2,OS2;
;
GO2   GOON,2;
      ACT,,,IS3;
      ACT,,,POK2;
;
;*****
; INITIATE PRODUCTION FOR STAGE 2
;*****
;
;***** PRODUCTION-ORDERING KANBAN POST OF STAGE 2 *****
POK2  QUEUE(13),,,,AP2;
;
;***** INPUT STORAGE OF STAGE 2 *****
IS2   QUEUE(14),,,,AP2;

```

```

;
;*****
; MATCH PART TYPE ATTRIBUTE BETWEEN PRODUCTION-ORDERING
; KANBANS AND PARTS IN INPUT STORAGE AT STAGE 2
;*****
;
AP2  MATCH,2,POK2/GI2,IS2;
;
GI2  GOON,2;
      ACT,,,GP2;
      ACT,,,WLK1;
;
GP2  ASSIGN,ATRI(22)=TNOW;
      EVENT,14,1;
      ACT,,,PARTYPE.EQ.1,PT21;
      ACT,,,PARTYPE.EQ.2,PT22;
      ACT,,,PARTYPE.EQ.3,PT23;
      ACT,,,PARTYPE.EQ.4,PT24;
      ACT,,,PARTYPE.EQ.5,PT25;
      ACT,,,PARTYPE.EQ.6,PT26;
      ACT,,,PARTYPE.EQ.7,PT27;
      ACT,,,PARTYPE.EQ.8,PT28;
      ACT,,,PARTYPE.EQ.9,PT29;
;
;*****
;  ROUTING FLEXIBILITY LEVEL 1
;*****
;
PT21  QUEUE(41),,,,PD21;
PT22  QUEUE(42),,,,PD21;
PT23  QUEUE(43),,,,PD21;
PT24  QUEUE(44),,,,PD22;
PT25  QUEUE(45),,,,PD22;
PT26  QUEUE(46),,,,PD22;
PT27  QUEUE(47),,,,PD23;
PT28  QUEUE(48),,,,PD23;
PT29  QUEUE(49),,,,PD23;
;
;*****
;  ROUTING FLEXIBILITY LEVEL 2
;*****
;
PT21  QUEUE(41),,,,PD21,PD22;
PT22  QUEUE(42),,,,PD21,PD22;
PT23  QUEUE(43),,,,PD21,PD22;

```

```

PT24  QUEUE(44),,,,PD22,PD23;
PT25  QUEUE(45),,,,PD22,PD23;
PT26  QUEUE(46),,,,PD22,PD23;
PT27  QUEUE(47),,,,PD23,PD21;
PT28  QUEUE(48),,,,PD23,PD21;
PT29  QUEUE(49),,,,PD23,PD21;
;
;*****
; ROUTING FLEXIBILITY LEVEL 3
;*****
;
PT21  QUEUE(41),,,,PD21,PD22,PD23;
PT22  QUEUE(42),,,,PD21,PD22,PD23;
PT23  QUEUE(43),,,,PD21,PD22,PD23;
PT24  QUEUE(44),,,,PD21,PD22,PD23;
PT25  QUEUE(45),,,,PD21,PD22,PD23;
PT26  QUEUE(46),,,,PD21,PD22,PD23;
PT27  QUEUE(47),,,,PD21,PD22,PD23;
PT28  QUEUE(48),,,,PD21,PD22,PD23;
PT29  QUEUE(49),,,,PD21,PD22,PD23;
;
;*****
; IMPLEMENT PART SELECTION RULES (NQS) AND MACHINE SELECTION
; RULES (NSS) TO DIRECT PART FLOWS WITHIN STAGE 2
;*****
;
;***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 1 *****
;
PD21  SELECT,NQS(7),,,PT21,PT22,PT23;
      ACT(1)/21,PROC2,,P21;
PD22  SELECT,NQS(8),,,PT24,PT25,PT26;
      ACT(1)/22,PROC2,,P22;
PD23  SELECT,NQS(9),,,PT27,PT28,PT29;
      ACT(1)/23,PROC2,,P23;
;
;***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 2 *****
;
PD21  SELECT,NQS(7),NSS(3),,PT21,PT22,PT23,PT27,PT28,PT29;
      ACT(1)/21,PROC2,,P21;
PD22  SELECT,NQS(8),NSS(3),,PT24,PT25,PT26,PT21,PT22,PT23;
      ACT(1)/22,PROC2,,P22;
PD23  SELECT,NQS(9),NSS(3),,PT27,PT28,PT29,PT24,PT25,PT26;
      ACT(1)/23,PROC2,,P23;
;
;***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 3 *****

```

```

;
PD21  SELECT,NQS(7),NSS(3),,PT21,PT22,PT23,PT24,PT25,PT26,PT27,PT28,
      PT29;
      ACT(1)/21,PROC2,,P21;
PD22  SELECT,NQS(8),NSS(3),, PT21,PT22,PT23,PT24,PT25,PT26,PT27,PT28,
      PT29;
      ACT(1)/22,PROC2,,P22;
PD23  SELECT,NQS(9),NSS(3),, PT21,PT22,PT23,PT24,PT25,PT26,PT27,PT28,
      PT29;
      ACT(1)/23,PROC2,,P23;
;
P21   ASSIGN,XX(13)=XX(13)-PROC2,XX(47)=XX(47)+PROC2;
      EVENT,15,1;
      ACT,,,OS2;
P22   ASSIGN,XX(14)=XX(14)-PROC2,XX(48)=XX(48)+PROC2;
      EVENT,15,1;
      ACT,,,OS2;
P23   ASSIGN,XX(15)=XX(15)-PROC2,XX(49)=XX(49)+PROC2;
      EVENT,15,1;
      ACT,,,OS2;
;
;*****
; WITHDRAW FINISHED PARTS AT THE
; OUTPUT STORAGE OF STAGE 1
;*****
;
;***** WITHDRAWAL KANBAN POST OF STAGE 1 *****
WLK1  QUEUE(16),,,,AW1;
;
;***** OUTPUT STORAGE OF STAGE 1 *****
OS1   QUEUE(17),,,,AW1;
;
;*****
; MATCH PART TYPE ATTRIBUTE BETWEEN WITHDRAWAL
; KANBANS AND PARTS IN OUTPUT STORAGE AT STAGE 1
;*****
;
AW1   MATCH,2,WLK1/GO1,OS1;
;
GO1   GOON,2;
      ACT,,,IS2;
      ACT,,,POK1;
;
;*****
; INITIATE PRODUCTION FOR STAGE 1

```

```

*****
;
;
;***** PRODUCTION-ORDERING KANBAN POST OF STAGE 1 *****
POK1  QUEUE(18),,,,GP1;
;
GP1   ASSIGN,ATRI(23)=TNOW;
      EVENT,16,1;
      ACT,,PARTYPE.EQ.1,PT11;
      ACT,,PARTYPE.EQ.2,PT12;
      ACT,,PARTYPE.EQ.3,PT13;
      ACT,,PARTYPE.EQ.4,PT14;
      ACT,,PARTYPE.EQ.5,PT15;
      ACT,,PARTYPE.EQ.6,PT16;
      ACT,,PARTYPE.EQ.7,PT17;
      ACT,,PARTYPE.EQ.8,PT18;
      ACT,,PARTYPE.EQ.9,PT19;
;
;*****
; ROUTING FLEXIBILITY LEVEL 1
;*****
;
PT11  QUEUE(51),,,,PD11;
PT12  QUEUE(52),,,,PD11;
PT13  QUEUE(53),,,,PD11;
PT14  QUEUE(54),,,,PD12;
PT15  QUEUE(55),,,,PD12;
PT16  QUEUE(56),,,,PD12;
PT17  QUEUE(57),,,,PD13;
PT18  QUEUE(58),,,,PD13;
PT19  QUEUE(59),,,,PD13;
;
;*****
; ROUTING FLEXIBILITY LEVEL 2
;*****
;
PT11  QUEUE(51),,,,PD11,PD12;
PT12  QUEUE(52),,,,PD11,PD12;
PT13  QUEUE(53),,,,PD11,PD12;
PT14  QUEUE(54),,,,PD12,PD13;
PT15  QUEUE(55),,,,PD12,PD13;
PT16  QUEUE(56),,,,PD12,PD13;
PT17  QUEUE(57),,,,PD13,PD11;
PT18  QUEUE(58),,,,PD13,PD11;
PT19  QUEUE(59),,,,PD13,PD11;
;

```

```

*****
; ROUTING FLEXIBILITY LEVEL 3
*****
;
PT11  QUEUE(51),,,,PD11,PD12,PD13;
PT12  QUEUE(52),,,,PD11,PD12,PD13;
PT13  QUEUE(53),,,,PD11,PD12,PD13;
PT14  QUEUE(54),,,,PD11,PD12,PD13;
PT15  QUEUE(55),,,,PD11,PD12,PD13;
PT16  QUEUE(56),,,,PD11,PD12,PD13;
PT17  QUEUE(57),,,,PD11,PD12,PD13;
PT18  QUEUE(58),,,,PD11,PD12,PD13;
PT19  QUEUE(59),,,,PD11,PD12,PD13;
;
*****
; IMPLEMENT PART SELECTION RULES (NQS) AND MACHINE SELECTION
; RULES (NSS) TO DIRECT PART FLOWS WITHIN STAGE 1
*****
;
***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 1 *****
;
PD11  SELECT,NQS(10),,,PT11,PT12,PT13;
      ACT(1)/11,PROC1,,P11;
PD12  SELECT,NQS(11),,,PT14,PT15,PT16;
      ACT(1)/12,PROC1,,P12;
PD13  SELECT,NQS(12),,,PT17,PT18,PT19;
      ACT(1)/13,PROC1,,P13;
;
***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 2 *****
;
PD11  SELECT,NQS(10),NSS(4),,PT11,PT12,PT13,PT17,PT18,PT19;
      ACT(1)/11,PROC1,,P11;
PD12  SELECT,NQS(11),NSS(4),,PT14,PT15,PT16,PT11,PT12,PT13;
      ACT(1)/12,PROC1,,P12;
PD13  SELECT,NQS(12),NSS(4),,PT17,PT18,PT19,PT14,PT15,PT16;
      ACT(1)/13,PROC1,,P13;
;
***** CONTROL MECHANISM FOR ROUTING FLEXIBILITY LEVEL 3 *****
;
PD11  SELECT,NQS(10),NSS(4),,PT11,PT12,PT13,PT14,PT15,PT16,PT17,PT18,
      PT19;
      ACT(1)/11,PROC1,,P11;
PD12  SELECT,NQS(11),NSS(4),,PT11,PT12,PT13,PT14,PT15,PT16,PT17,PT18,
      PT19;
      ACT(1)/12,PROC1,,P12;

```

```

PD13  SELECT,NQS(12),NSS(4),, PT11,PT12,PT13,PT14,PT15,PT16,PT17,PT18,
      PT19;
      ACT(1)/13,PROC1,,P13;
;
P11   ASSIGN,XX(16)=XX(16)-PROC1,XX(50)=XX(50)+PROC1;
      EVENT,17,1;
      ACT,,,OS1;
P12   ASSIGN,XX(17)=XX(17)-PROC1,XX(51)=XX(51)+PROC1;
      EVENT,17,1;
      ACT,,,OS1;
P13   ASSIGN,XX(18)=XX(18)-PROC1,XX(52)=XX(52)+PROC1;
      EVENT,17,1;
      ACT,,,OS1;
;
SHIP  GOON,1;
      ACT,,PARTYPE.EQ.1,OUT1;
      ACT,,PARTYPE.EQ.2,OUT2;
      ACT,,PARTYPE.EQ.3,OUT3;
      ACT,,PARTYPE.EQ.4,OUT4;
      ACT,,PARTYPE.EQ.5,OUT5;
      ACT,,PARTYPE.EQ.6,OUT6;
      ACT,,PARTYPE.EQ.7,OUT7;
      ACT,,PARTYPE.EQ.8,OUT8;
      ACT,,PARTYPE.EQ.9,OUT9;
;
OUT1  ASSIGN,XX(21)=XX(21)+1,XX(31)=XX(61)-XX(21),XX(72)=XX(72)+1;
      ACT,,,COL;
OUT2  ASSIGN,XX(22)=XX(22)+1,XX(32)=XX(62)-XX(22),XX(72)=XX(72)+1;
      ACT,,,COL;
OUT3  ASSIGN,XX(23)=XX(23)+1,XX(33)=XX(63)-XX(23),XX(72)=XX(72)+1;
      ACT,,,COL;
OUT4  ASSIGN,XX(24)=XX(24)+1,XX(34)=XX(64)-XX(24),XX(72)=XX(72)+1;
      ACT,,,COL;
OUT5  ASSIGN,XX(25)=XX(25)+1,XX(35)=XX(65)-XX(25),XX(72)=XX(72)+1;
      ACT,,,COL;
OUT6  ASSIGN,XX(26)=XX(26)+1,XX(36)=XX(66)-XX(26),XX(72)=XX(72)+1;
      ACT,,,COL;
OUT7  ASSIGN,XX(27)=XX(27)+1,XX(37)=XX(67)-XX(27),XX(72)=XX(72)+1;
      ACT,,,COL;
OUT8  ASSIGN,XX(28)=XX(28)+1,XX(38)=XX(68)-XX(28),XX(72)=XX(72)+1;
      ACT,,,COL;
OUT9  ASSIGN,XX(29)=XX(29)+1,XX(39)=XX(69)-XX(29),XX(72)=XX(72)+1;
      ACT,,,COL;
;
COL   COLCT(1),INT(1),FLOW TIME;

```

```

        TERM;
        END;
INIT,0,192000;
MONTR,CLEAR,144000;
;
;*****
; RANDOM NUMBER STREAMS FOR REPLICATION 2-10
;*****
;
SIM;
SEEDS,8374647(1),2799842(2),8268532(3),1838613(4),2171713(5);
MONTR,CLEAR,144000;
SIM;
SEEDS,1844683(1),6602775(2),5142096(3),2704562(4),1309417(5);
MONTR,CLEAR,144000;
SIM;
SEEDS,9238262(1),1621550(2),934214(3),3814879(4),2368919(5);
MONTR,CLEAR,144000;
SIM;
SEEDS,2540737(1),232277(2),1507233(3),2700231(4),6618183(5);
MONTR,CLEAR,144000;
SIM;
SEEDS,977901(1),1079107(2),7488355(3),1758324(4),4560146(5);
MONTR,CLEAR,144000;
SIM;
SEEDS,6068333(1),2995681(2),9171383(3),8570486(4),1792126(5);
MONTR,CLEAR,144000;
SIM;
SEEDS,1392971(1),324818(2),5058317(3),1063646(4),4389641(5);
MONTR,CLEAR,144000;
SIM;
SEEDS,7671480(1),2239346(2),7094392(3),9201160(4),6645600(5);
MONTR,CLEAR,144000;
SIM;
SEEDS,9629244(1),1968007(2),6734751(3),9588859(4),7089644(5);
MONTR,CLEAR,144000;
;
FINISH;

```

APPENDIX C
LOGIC FOR EVENT NODES

LOGIC FOR EVENT NODES 1-9

1. Assign attributes to part type n. Attributes include part type number, part family number, demand rate, processing time for each stage, and total processing time.
2. Insert one unit of part type n along with the assigned attributes to ENTER nodes DEM_n.

LOGIC FOR EVENT NODES 10, 12, 14, 16

1. Identify the part family for an incoming part at stage k.
2. Add the required processing time of the incoming part to a global variable that maintain the total work (in terms of processing time) for a machine at stage k.

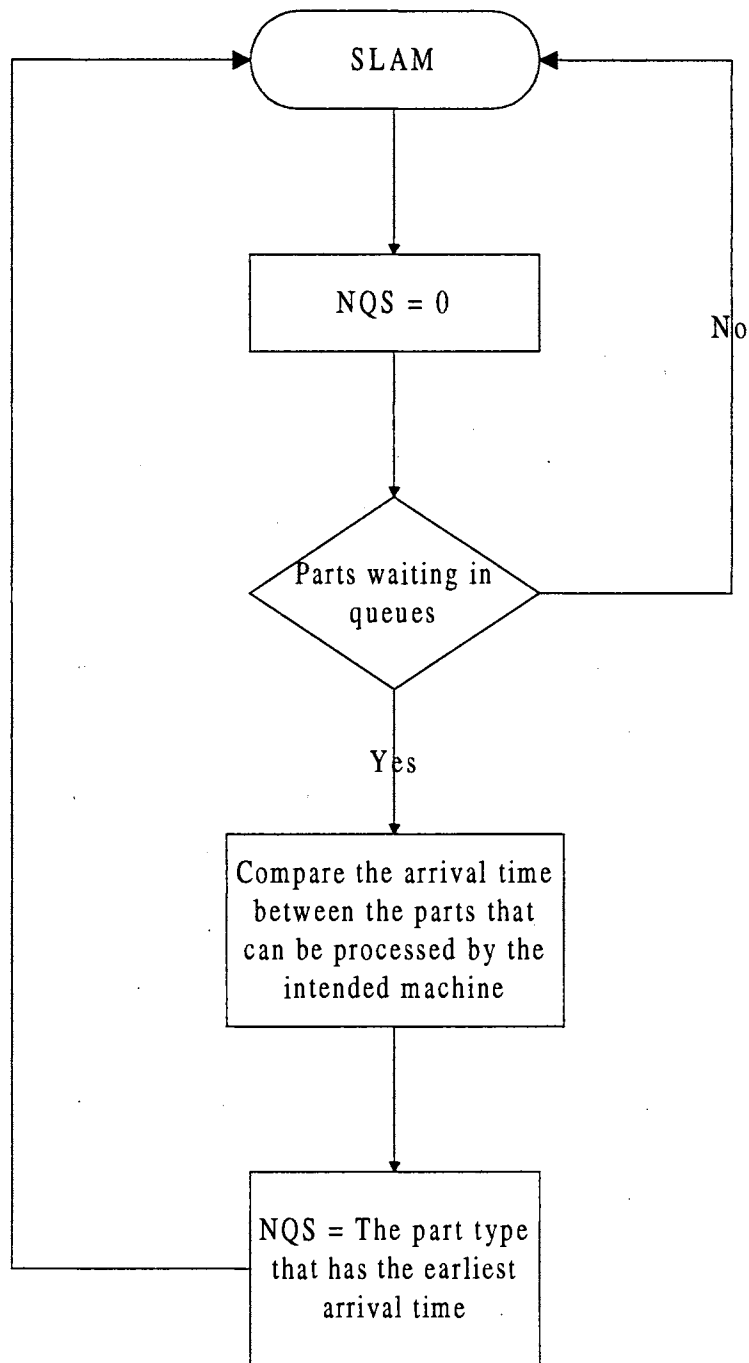
LOGIC FOR EVENT NODES 11, 13, 15, 17

1. Identify the part family for a completed part at stage k.
2. Subtract the processing time of the completed part from a global variable that maintain the total work (in terms of processing time) for a machine at stage k.

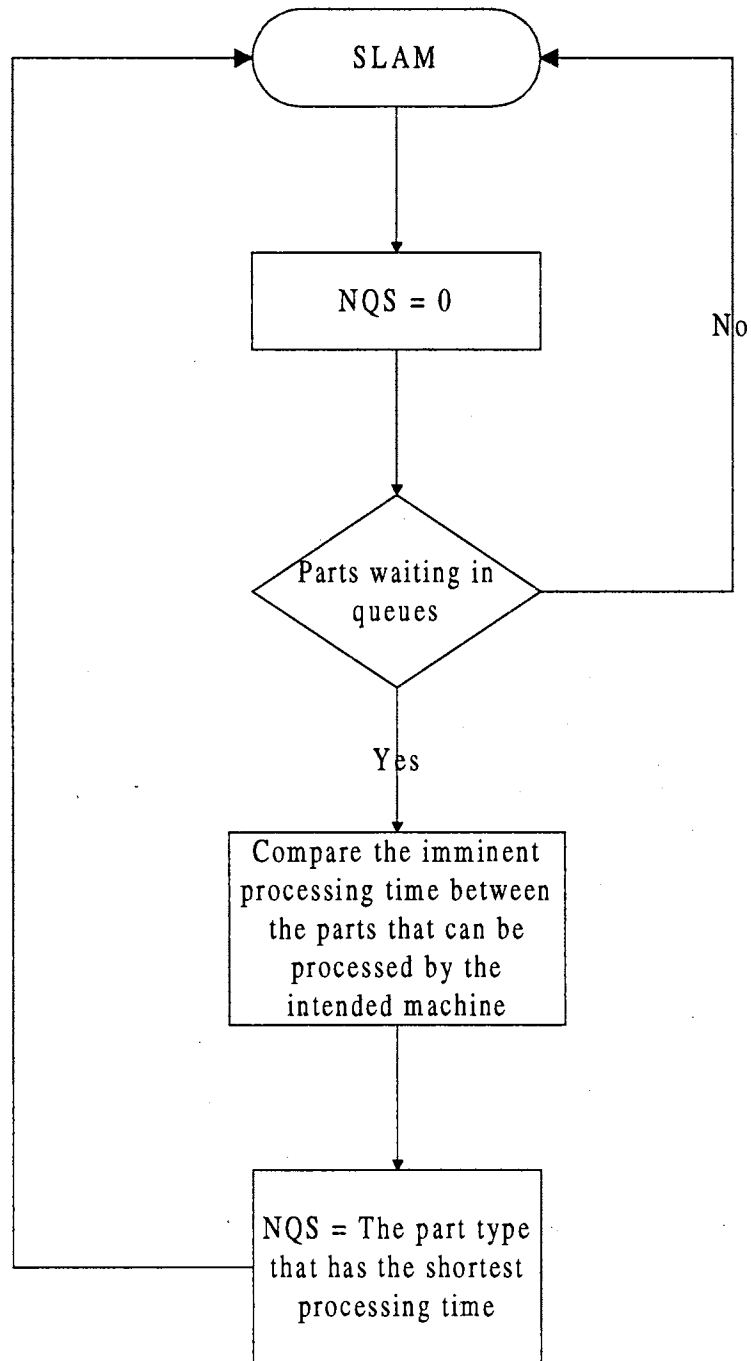
APPENDIX D

FLOWCHARTS FOR USER-DEFINED NQS FUNCTIONS

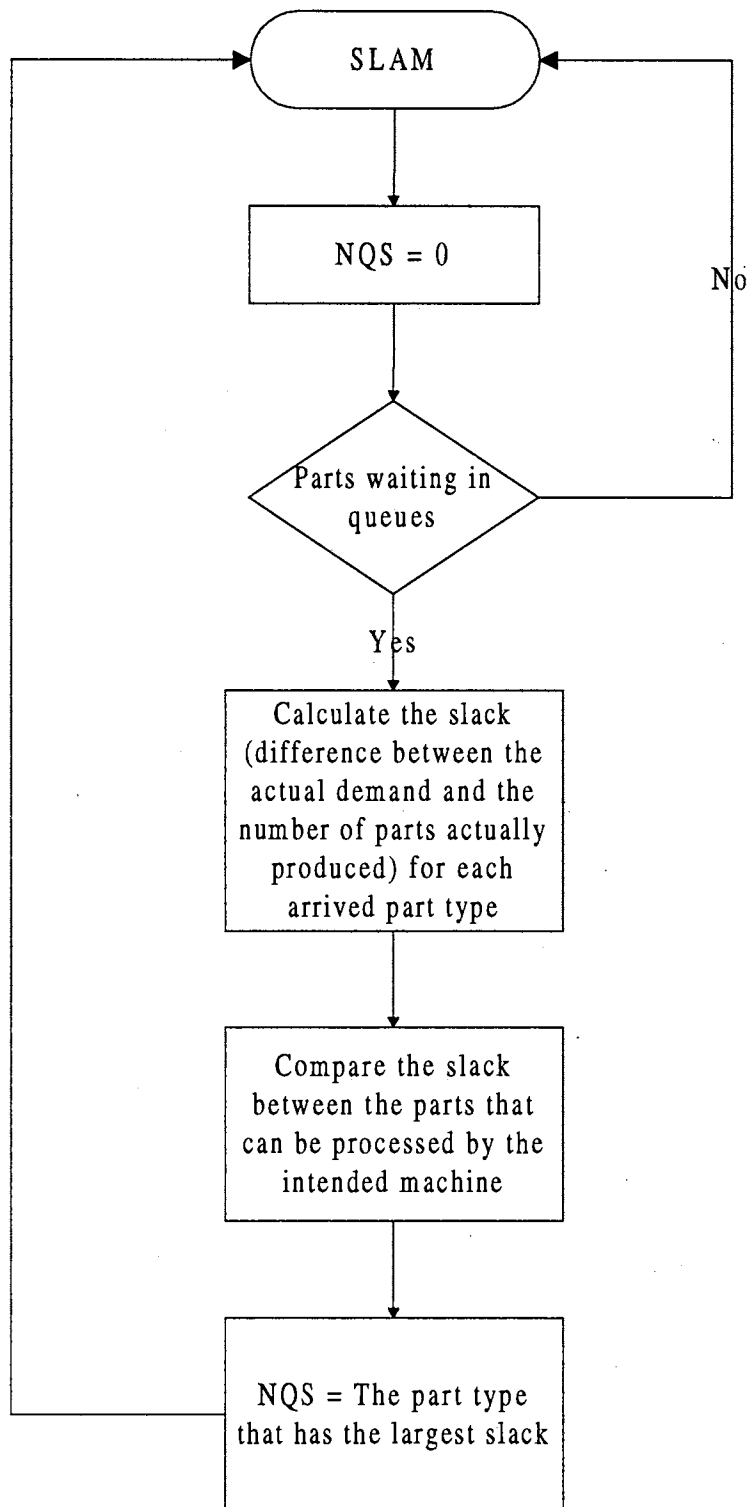
SCHEDULING RULE: FCFS



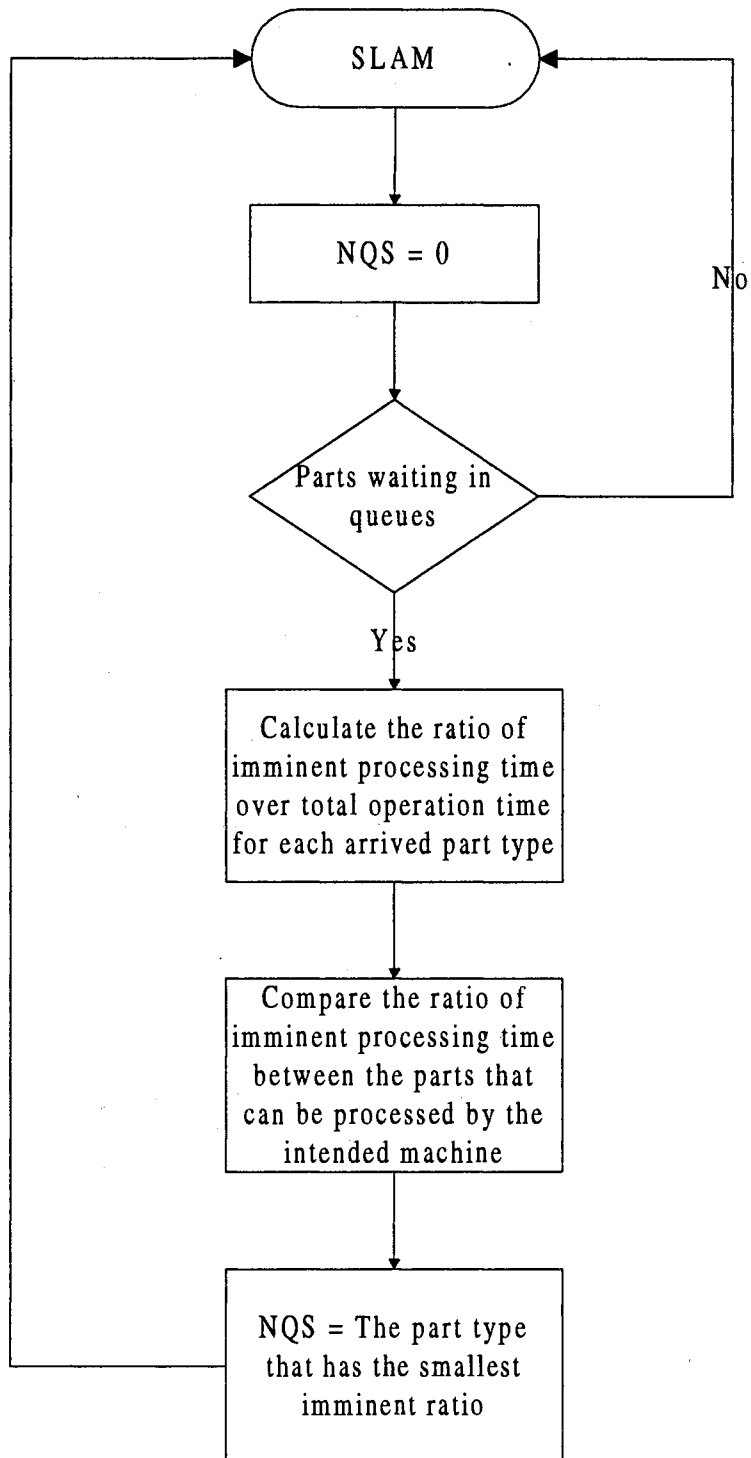
SCHEDULING RULE: SPT



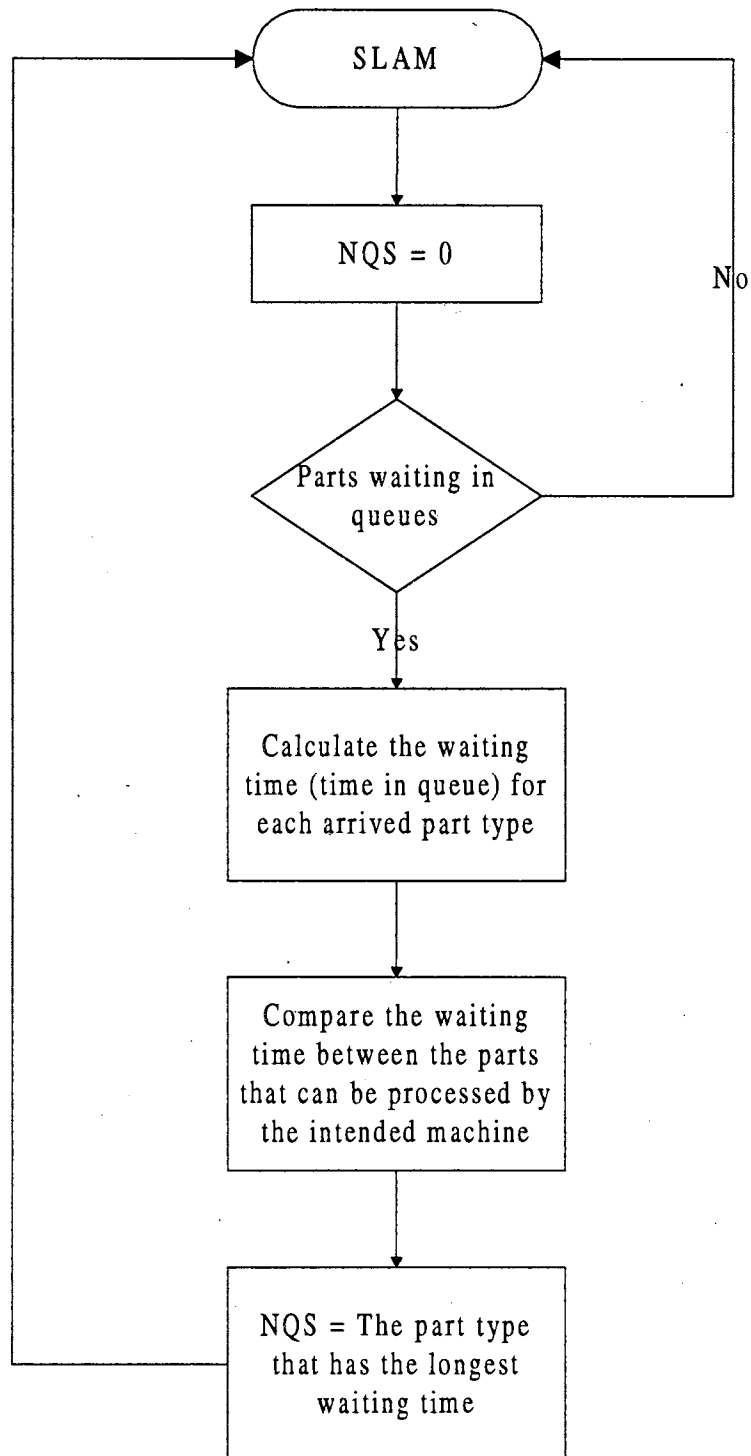
SCHEDULING RULE: SLACK*



SCHEDULING RULE: SPT/TOT



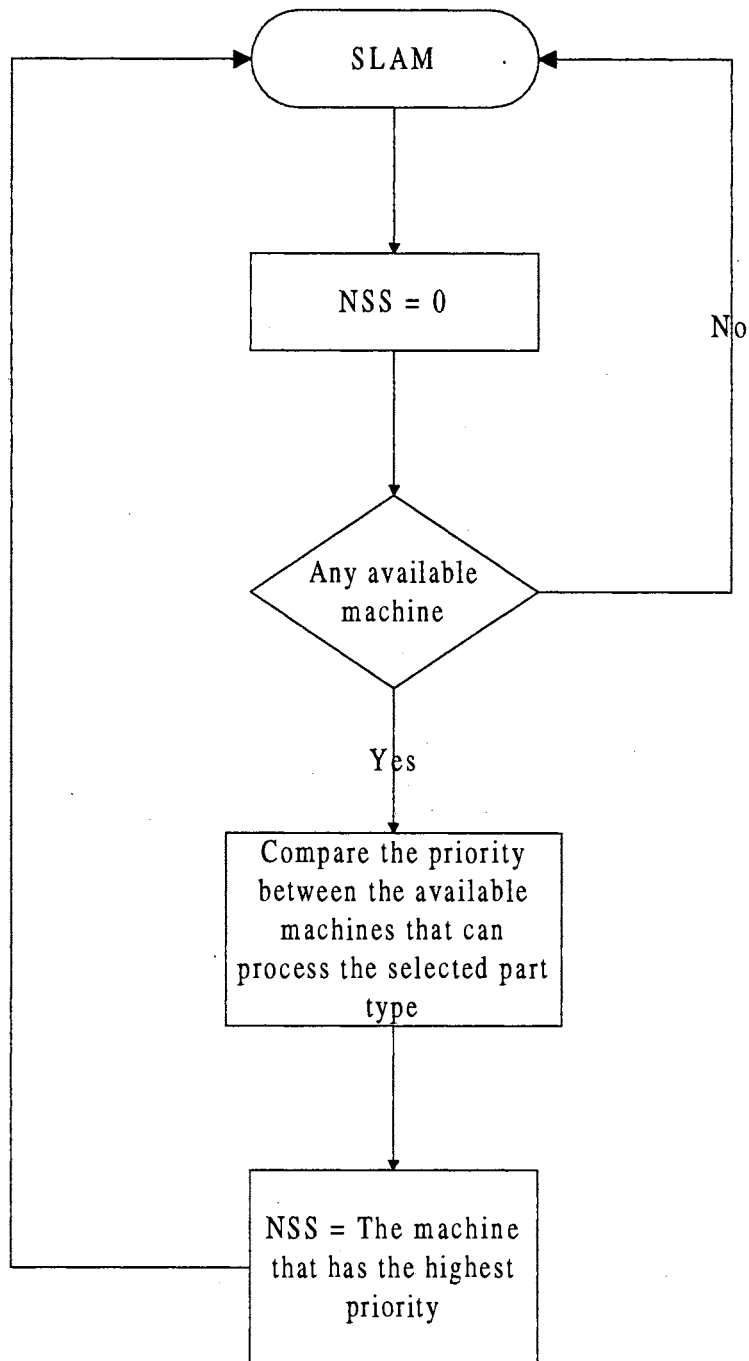
SCHEDULING RULE: LWT



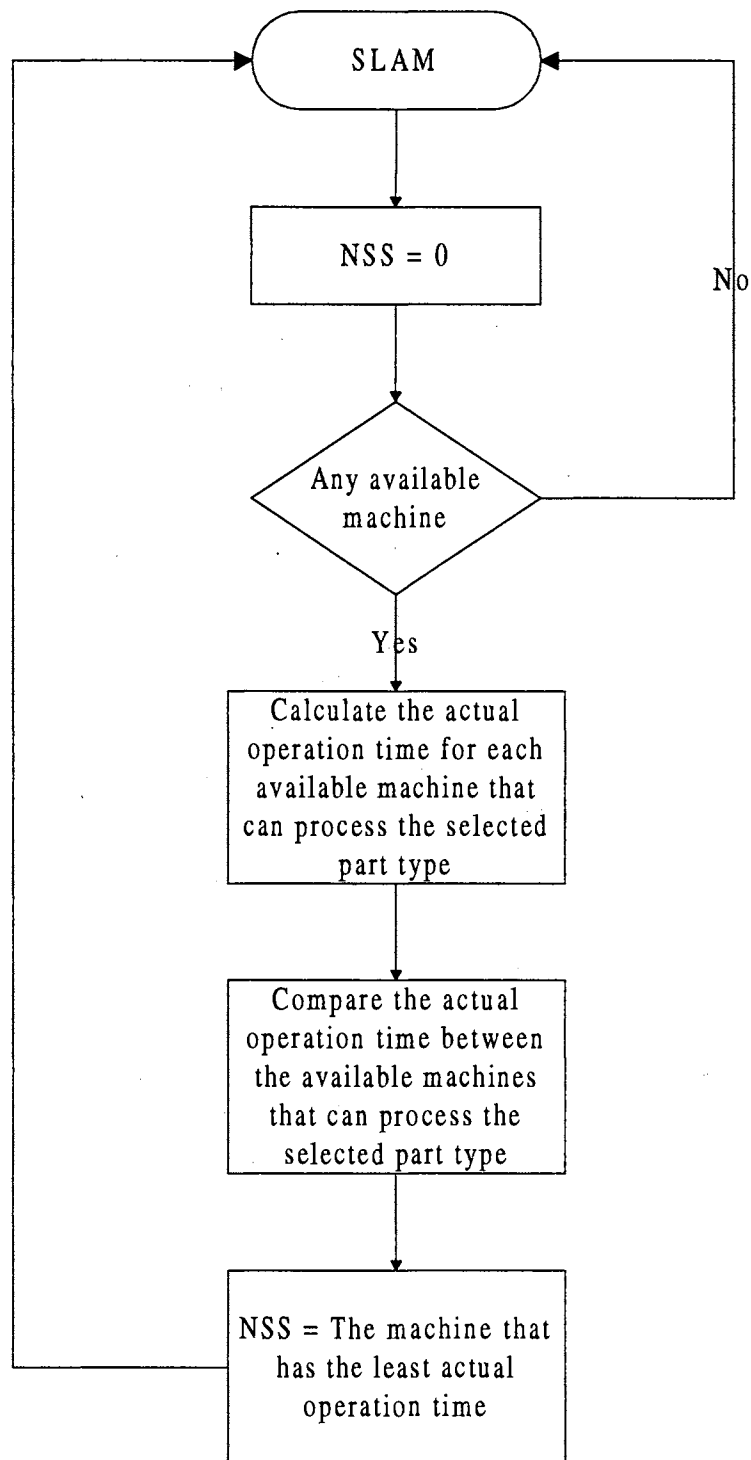
APPENDIX E

FLOWCHARTS FOR USER-DEFINED NSS FUNCTIONS

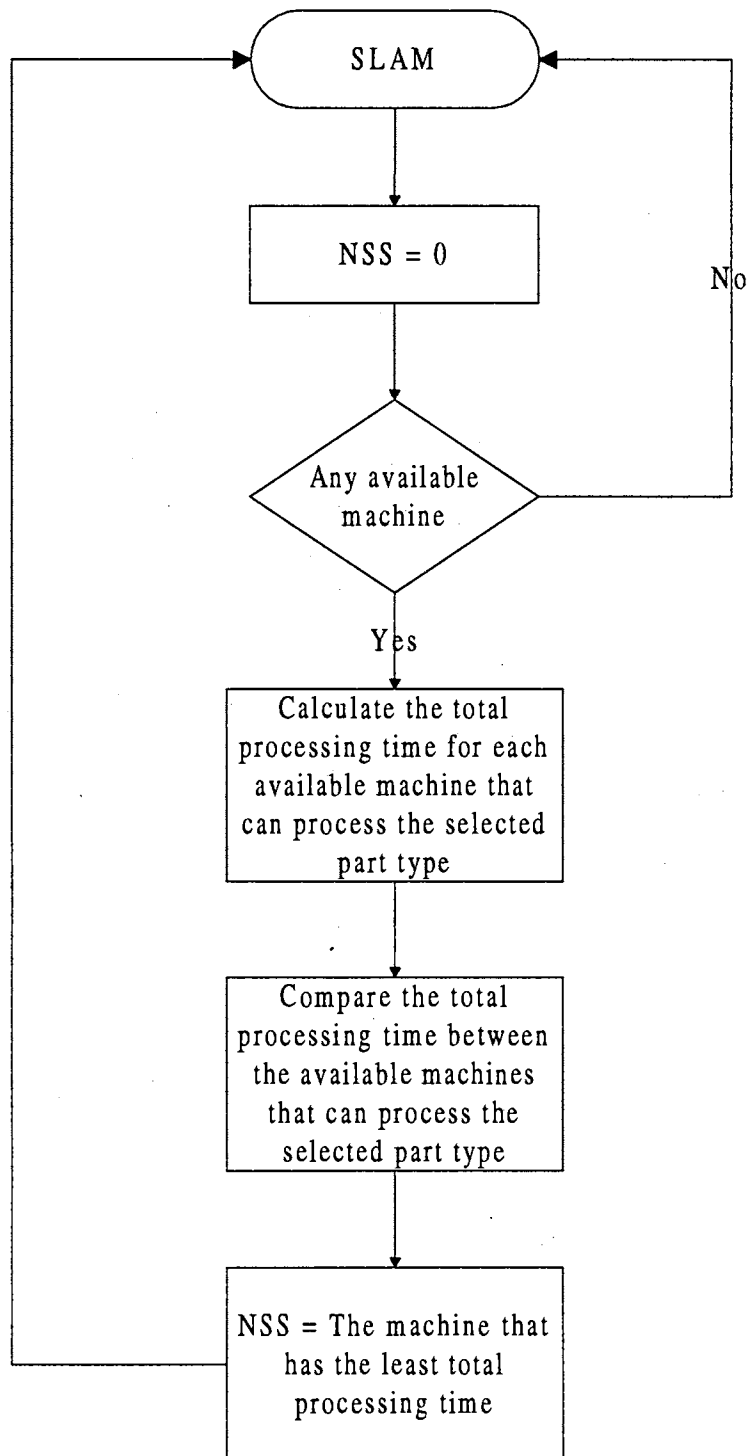
MACHINE SELECTION RULE: PRIOR



MACHINE SELECTION RULE: LUM



MACHINE SELECTION RULE: MWINQ




VITA

Min-Chun Yu

Candidate for the Degree of

Doctor of Philosophy

Thesis: AN INVESTIGATION OF THE EFFECTS OF ROUTING
FLEXIBILITY FOR A MULTI-STAGE JUST-IN-TIME SYSTEM

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