

Methodologies for Manufacturing System Selection and for  
Planning and Operation of a Flexible Manufacturing System

by

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(ABSTRACT)

A hierarchical methodology is developed for the overall design of manufacturing systems. The methodology consists of solutions to four levels of problems, namely, (1) manufacturing system selection, (2) shop loading, (3) machine loading and tool allocation, and (4) testing the feasibility of a schedule and determining strategies for the operational control of the system. Although, these problem levels are developed in a hierarchical sense, they can be applied independently by assuming appropriate inputs to the problem level under consideration. The third and the fourth level problems are addressed in this research for the flexible manufacturing system.

The first level of the hierarchical methodology addresses the problem of manufacturing system selection. The mathematical model formulated for this problem captures the basic and integrated relationships among the systems and system components. This model provides a practical approach and a precise tool to determine an optimal mix of systems, to assign appropriate machines to each system, and to select the best

material handling system for each system to best suit long-term production requirements at minimum costs. The second level of the hierarchical methodology addresses the shop loading problem. A mathematical model is developed for partitioning parts among the manufacturing systems selected at the first level to minimize total operating costs. For the third level problem, a mathematical model is formulated to obtain routings of parts through an FMS and to assign appropriate cutting tools to each machine in the system to minimize total machining cost. For the fourth level problem, a simulation model is developed for testing the feasibility of the solution obtained at the third level. It also helps to determine strategies for the operational control of the system.

The computational experience with the mathematical models is presented using the MPSX-MIP/370 package. Sensitivity analysis is also performed to further understand system behavior under various operating conditions. Several new findings of the research are reported. Because of the special structure of the mathematical models, a computational refinement for their solution is also proposed based on Lagrangian relaxation.

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## 1.0 INTRODUCTION

### 1.1 PROBLEM STATEMENT

A flexible manufacturing system (FMS) consists of a group of NC processing stations connected together by an automated workpiece handling system and operated under central computer control (Groover,1980). It is designed to combine the efficiency of a high-production transfer line and the flexibility of a job shop to best suit the batch production of mid-volume and mid-variety of products.

An FMS is viewed as a crucial step toward the concept of the "factory of the future" (Saul,1985). It is also viewed as a solution to several problems that arise in batch production of products in discrete manufacturing environment such as: long lead times, high inventory levels, and low efficiency (Groover,1984, Philips,1985). Its effectiveness is, however, directly related to its design and operational strategies.

A series of problems have to be addressed for the successful development and implementation of an FMS. The major problems are:

1. system selection and justification

2. part (family) selection
3. machine selection
4. material handling system selection
5. system operation.

System justification, part family selection, machine selection, and material handling system selection problems appear at the system design stage and should be resolved in an integrated manner. System operation problems, on the other hand, can be decomposed into planning, machine loading, and system control problems and are best solved using a hierarchical approach (Sarin and Wilhelm, 1983, Stecke, 1984).

Typically, there exist a wide variety of production systems involving different layouts, system components, and operating strategies that can be used to achieve desired production requirements. An FMS happens to be just one of these production systems. Therefore, the first problem that arises in the design of an overall manufacturing system is concerning the determination of a system or a mix of systems that best meets the given production requirements. This problem has drawn little attention in the literature. Most of the studies concerning FMS, for instance, assume that the adoption of an FMS has already been decided (see Draper Lab., 1981, Suri and Whitney, 1984, Stecke, 1984) or assume that an FMS is already economically justified (see Cook, 1979,



Co,1984, chapter 4). As a result the problems addressed at the design stage are concerned with the selection of a set of parts for an FMS, estimation of the minimum machine requirements for processing the selected parts, and the selection of an appropriate material handling system to transport these parts in an FMS, while satisfying constraints corresponding to available space, budget, and the like. While these studies provide tools to solve individual system design problems, the following drawbacks are observed:

1. an FMS may not best suit production requirements,
2. optimizing each subproblem (e.g. selection of a material handling system or selection of a computer control system) may not lead to an overall optimal system design, and
3. an FMS performance may be optimized in these studies at other system's expense during both the design and operational stages.

For example, the selection of parts from a larger set of parts for an FMS may increase its profitability or system utilization while at the same time lowering utilizations of other systems and increasing production costs of remaining parts thereby leading to a higher overall manufacturing cost.

Ideally, the overall system performance (including the performances of an FMS and other production systems within the manufacturing environment) should be treated as a leading decision criterion in the manufacturing system design and selection process. In this regard a systematic and integrated approach (as also discussed by Sarin and Wilhelm, 1983) should be adopted to simultaneously solve the manufacturing system design, selection, and justification problems. This would lead to the selection of the best mix of system(s), and the optimal determination of machine requirements, and an appropriate material handling system for each selected system to achieve global minimum manufacturing cost taking into consideration the assignment of part families to these systems.

Once an FMS is selected as one of the manufacturing systems it must share production loads with other subsystems (Suri and Whitney, 1984). Therefore, at the operational level parts must be allocated to the FMS and other systems so that the overall operating costs are minimized. Furthermore, once parts are assigned to various systems, one of the important planning problems is the routing of assigned parts through a system and the loading of required cutting tools on machines for overall system effectiveness. We address here the part routing and tool loading problem of an FMS only. Similar methodologies can be developed for other systems. In partic-

ular, the problems of interest for the operation of an FMS are:

1. determination of part routings,
2. determination of an optimal sequence of parts for processing at each machine, and
3. allocation of required cutting tools among the limited capacity tool magazines of machine tools.

## 1.2 RESEARCH OBJECTIVES

The purpose of this research is to develop a comprehensive methodology for manufacturing system selection and operation in an FMS-related manufacturing environment. The methodology can be used:

1. at system design stage,
  - a. to select cost-effective manufacturing system(s),
  - b. to determine necessary system components (machines, material handling system, etc.),
  - c. to partition production requirements for each selected system, and
2. at system operation stage,
  - a. to assign parts to existing systems,
  - b. to allocate required cutting tools to each machine of an FMS, and

- c. to route parts through the machines of an FMS and to determine the best control policies.

A four-step approach comprising of three mathematical models and one simulation model is employed to develop this methodology.

At the first step, a mathematical model is developed for the system selection and design problem. This model is used to identify a feasible and cost-effective manufacturing system. The system configuration and its basic components are determined by considering long-term production requirements and available manufacturing technology. Economic justification for the system(s) is also achieved by this model.

At the second step, the shop loading problem is addressed. A mathematical model is then used to optimally partition given production requirements among the manufacturing systems selected in step 1 for a given planning period. Subcontracting is also considered as an alternative in this model, if viable, based on cost parameters and available capacity of each system.

The machine loading and tool allocation problem is addressed at the third step. A mathematical model is developed for an FMS. It is used to determine the routings of parts assigned

to the system and to allocate appropriate cutting tools to each workstation to achieve minimum overall machining cost.

Finally, a simulation model is developed for a specific FMS to evaluate the feasibility of part routings and tool assignments obtained as a result of step 3. The simulation model is also used to estimate the actual efficiency factor of this system and to test various control strategies regarding the dispatching of parts for processing at a workstation, number of pallets in the system, cart speed and cart request rule.

Even though the third and the fourth steps employed in the methodology are developed here for an FMS, they can be developed in a similar manner for other systems and accordingly the methodology can be applied to model the operation of other manufacturing systems. This is, therefore, an effective methodology to help select and operate manufacturing systems including an FMS.

Next, we briefly describe the models and the hierarchical structure of this methodology in Section 1.4, after describing the main contributions of this research.

### 1.3 CONTRIBUTIONS OF THIS RESEARCH

There are the following main contributions of this research:

1. it provides an effective hierarchical approach for manufacturing system selection, design and operation including an FMS,
2. it provides
  - a. a quantitative justification tool for manufacturing system selection,
  - b. an integrated tool for system component requirements planning,
  - c. a quantitative tool for determining precisely the operating conditions under which each system is a preferred system,
3. it provides a practical approach for the multiple shop loading problem, and
4. it provides a practical approach for loading tools on machines and for routing parts through the machines in an FMS.

### 1.4 DESCRIPTION OF THE OVERALL METHODOLOGY

The methodology developed in this research is a hierarchical approach for the overall manufacturing system design problem and is depicted in Figure 1.1.

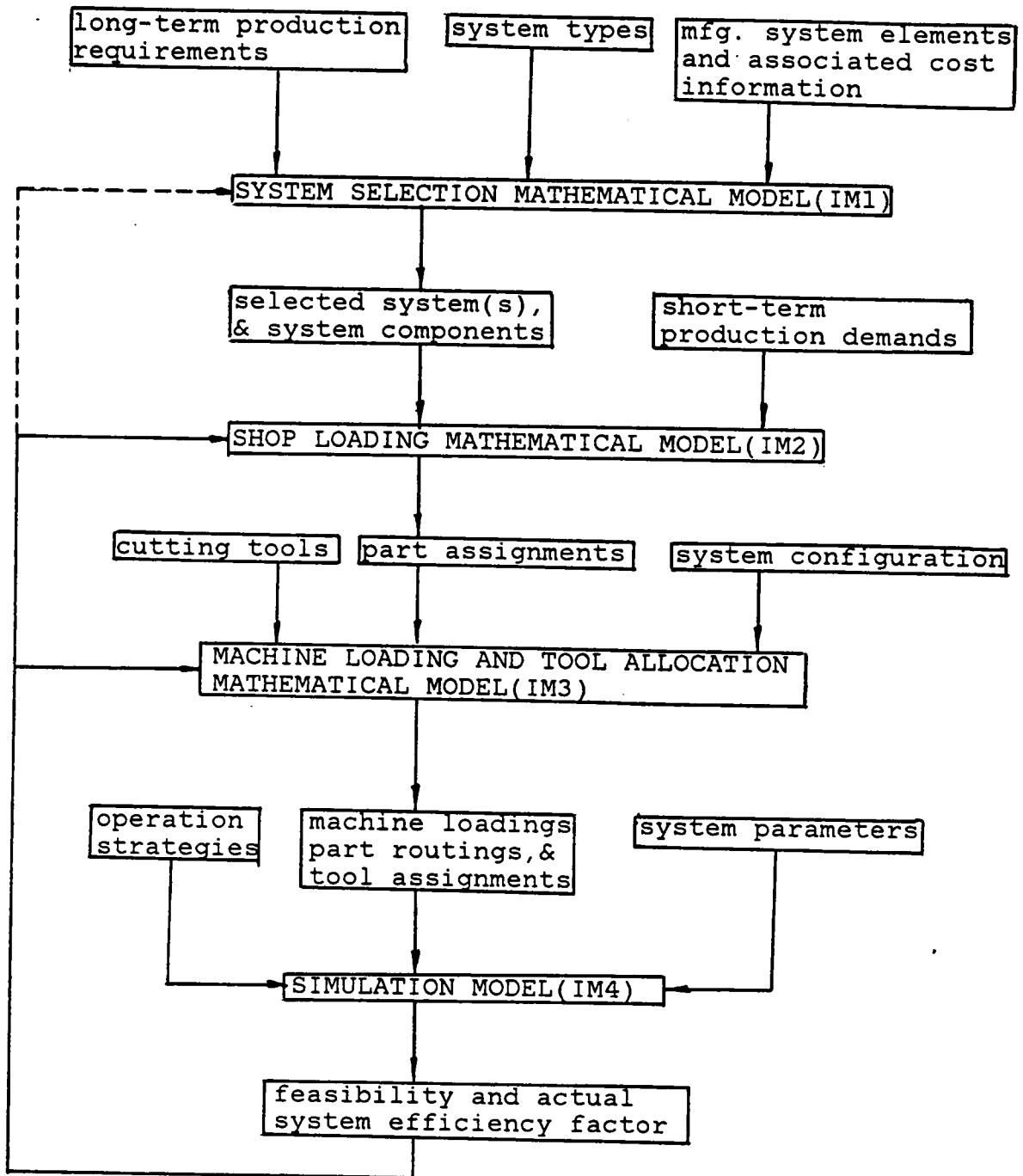


Figure 1.1 Hierarchical Methodology for Overall Manufacturing System Design

It consists of four hierarchical steps involving four models: (1) the system selection model (IM1), (2) the shop loading model (IM2), (3) the machine and tool loading model (IM3), and (4) the simulation model (IM4). Although these models are developed in a hierarchical sense, each can be used independently. The first three models are mathematical models and serve as a screening and selection process to analyze system selection, design, and allocation problems, given production requirements, system parameters and system cost information. Many system alternatives and operating conditions can be evaluated using these models. The simulation model actually emulates the system operations, taking into account the dynamic, time-dependent system behaviors. Its primary purpose is to validate the system efficiency factor assumed for the FMS in the mathematical models and to evaluate the feasibility of optimal tool allocations and machine loadings generated by the machine loading and tool allocation mathematical model. It can also be used to investigate various control strategies at operational level, against different system parameters and objectives, if so desired.

At the first step (designated as the system selection and design stage), the system selection model(IM1) selects a mix of systems, determines appropriate machines for each system and assigns production requirement to each system taking into consideration the long-range production requirements, avail-



able system types, system components compatible with each system type, and the associated cost information.

At the second step (designated as the planning stage), the shop loading model(IM2) takes capacities of manufacturing systems selected in step 1 and short-term production demands as inputs and generates an optimal allocation of parts to each of the manufacturing systems including the possibility of subcontracting work. At the third step (designated as the machine loading stage), the machine loading and tool allocation model(IM3) is developed for an FMS and takes assigned jobs from the shop loading model(IM2), the information of available cutting tools, and the FMS configuration as inputs and generates part routings and tool assignments for each workstation.

At step 4 (designated as the control stage), the simulation model(IM4) then actually simulates the predetermined schedule over the given planning period to test the feasibility of the routings obtained from model(IM3) and estimates the real system efficiency factor. The results from the simulation model analysis are fed back to modify the system efficiency factor used in the mathematical model of step 3 (IM3) and to resolve the problem, if necessary, before the production order is actually released for implementation. For instance, if some assigned parts can not be finished within the given

time span by applying various control strategies in step 4, then the system efficiency factor previously assumed for this system at the mathematical model (IM3) must be reduced in order to obtain a "realistic" schedule.

To apply this methodology, a manufacturing data base should be created for keeping the information of demand characteristics, part characteristics, available manufacturing technologies, system efficiencies, and associated costs. As more information is gathered, more evaluations are performed, and more experiences are accumulated; the data become more accurate and the design and planning processes become more efficient.

The detail descriptions of the development of each model and results of their implementations are presented in the following chapters after a review of the related literature.

## 1.5 ORGANIZATION OF WORK

Chapter 2 reviews FMS-related studies, which are classified and reviewed according to the following categories:

1. system selection, justification, and system component requirements planning
2. shop loading and machine loading

3. system performance evaluation and operating parameters analysis.

Chapter 3 develops an analysis procedure and a mathematical model for the manufacturing system selection and design problem using an integer programming solution technique.

Chapter 4 presents an analysis procedure and the two mathematical models for assigning parts to production systems existing in a factory, and for allocating tools and operations of given parts to workstations in an FMS, based on available capacities and associated cost information. An Example problem is given for each model to demonstrate their applicability. Post-optimality analysis is also carried out to further understand the system selection and operational planning problems.

Chapter 5 covers the development of the simulation model and presents results of its implementation in conjunction with the mathematical model (IM3). The results and conclusions of this research are presented in Chapter 6 and some possible extensions of this work are also discussed.

Appendix A gives a brief description of the IBM MPSX-MIP/370 code. Appendix B describes a refinement of the computational approach that was investigated for the solution of the math-

emathical models presented in Chapter 4. Such an approach can be developed for the mathematical model presented in Chapter 3 as well. Appendices C, D, and E include the source listings of the example problems for the mathematical models discussed in Chapters 3 and 4. Appendix F contains a basic part-flow diagram for the simulation model. Appendix G, H, I, an J contain listings of the parameters and variables used in the simulation model. Appendix K and L provide the source listings of the simulation program. A procedure for determining the sample size is given in Appendix M.

## 2.0 A REVIEW OF FMS-RELATED STUDIES

There have been two parallel directions in FMS research: (1) system component improvements and (2) system design, planning, and operational optimization. The primary research regarding the system component improvement has been to develop more reliable and more flexible material handling systems (e.g. by adding fixturing techniques and robots in the system) to extend workstation capabilities (e.g. by incorporating assembly, flame cutting, painting operations and automatic tool changing/monitoring and adaptive control), to improve the control system (by upgrading sensory perception, intelligence, diagnostics, operating data bases, hierarchical decision making and real-time control) at the least cost, and to establish interface standards and new measurement methods (Bollinger,1980, Simpson, Hocken and Albus,1982). Regarding the second aspect many production planning and optimization techniques have been developed and presented in the literature to handle the complex FMS design and operation problems. These FMS-related studies are classified and reviewed here under the following three categories:

1. system selection, justification, and component requirements planning,
2. shop loading and machine loading, and

3. system performance evaluation and operating parameters analysis.

## 2.1 SYSTEM SELECTION, JUSTIFICATION, AND DESIGN

Even though a comprehensive model pertaining to the problems of manufacturing system selection, justification, and design is not available in the literature, these problems have been studied separately from various viewpoints. The literature related to these problems is reviewed in this section under the following subtitles: (1) system selection and justification and (2) system design procedure and component requirements planning.

### 2.1.1 SYSTEM SELECTION AND JUSTIFICATION

The advantages of an FMS have been widely discussed (Kearney and Trecker, 1979, Suresh and Meredith, 1984, Goover and Zimmer, 1984). An FMS is typically expected to increase productivity, scheduling flexibility, and system utilization, and to save labor cost, setup time, and floor space for the mid-variety and mid-volume production of discrete products (Kearney and Trecker, 1983). However, in spite of these advantages, there are less than one hundred of FMSs in operation worldwide (Castle, 1984, Drozda, 1983) since they were first introduced in 1965 (Bryce and Roberts, 1982). One of

the major reasons in this regard has been the difficulty in justifying an FMS. Because of its high initial investment, advancement of technology regarding software and hardware, and also the uncertainty of production requirements, decision regarding the installation of an FMS involves a high degree of risk. Additionally, the definition of mid-variety and mid-volume production (see Gooverand Zimmer, 1984, Kearney and Trecker, 1983, Holland, 1983) is not precise enough for a decision maker to determine the point at which the decision regarding system selection is for an FMS. In reality, the volume-variety concept can provide only a rough criterion in the decision process.

The measures commonly used to justify an FMS include the return on investment, net present value, and payback period (Bergstorm, 1984, Suri, 1984, Fortsch, 1984). However, researchers have questioned the relevance of these traditional economic measures for the justification of an FMS. Gold (1982) argues that most capital budgeting evaluation criteria have evolved from efforts to deal with a continuing flow of incremental improvements; FMS as well as other computerized manufacturing systems represent much more than that. Traditional capital budgeting techniques fail to account for those intangible benefits. It is therefore suggested that senior management adopt a top-down planning approach that commits the firm to progressively broaden ap-

plications of the FMS concept. Kaplan(1983) suggests that new measures of manufacturing performance should be developed which better suit FMS and future automated factory. The critique is that contemporary cost accounting is based upon mass production of a mature product with known characteristics and a stable technology. As companies move toward the automated and highly flexible manufacturing system, with relatively high fixed costs and low variable costs, and small batch production of a variety of products, the assumptions of contemporary cost accounting system become increasingly irrelevant and the traditional manufacturing performance measures, which are rooted in a desire to minimize direct cost, clearly become inappropriate. Consequently, new measures that deal with nontraditional performance indicators are needed.

Stobaugh and Teleses(1983), and Goldhar and Jelinek(1984) propose that long-term strategic concerns should also play a leading role in the justification process. The impact of these new technologies on a company's long-term competitiveness, profitability, and survival must be taken into account when selecting a new production system. However, these additional criteria appear difficult to be incorporated into a quantitative decision model. Realizing this, Michael and Miller(1984) propose a quick fix solution for managers seeking to justify such a system by suggesting to still use traditional discounted cash flow methodology but



to consider a non-quantitative strategic justification approach when the traditional approach fails to justify it. A similar concept is also presented in the paper by Herroelen and Lambrecht(1984).

Randhawa and Bedworth(1985) suggest a set of influential factors that are believed to be capable of forming a basis for comparing an FMS with conventional manufacturing systems. They report that, among the five potentially influential factors, manufacturing cost is consistently considered to be the most important attribute, while delivery promise and top management involvement are also very important in the FMS justification process. The considerations of other factors like social impact are suggested by Lewis(1984) for the justification of an FMS.

Most of the studies reviewed above basically take strategic approach in justifying an FMS. Next, we review the system modeling techniques, presented in the literature, to economically justify an FMS.

The first work in this regard is presented by Leimkuhler(1981) who compared two production systems: a traditional production line and a computerized manufacturing system (CMS). Instead of developing a generalized decision model, he employed an example to illustrate the economic

factors involved in the system selection procedure and concluded that the advantages of CMS over a traditional system are very sensitive to capital-labor cost ratio and the intensity of system usage. That is, the higher the labor cost the more favorable is the selection for CMS. The argument, that is put forth, is that by comparing the cost of labor and capital requirements vs. output curves for different types of production systems, it is possible to identify breakeven points where a particular type of system is economically preferred over other systems for particular products or product mixes. Such information can also be used to determine the optimal way to expand capacity for long-run conversion and growth programs. By varying the cost parameters used in the analysis, it is possible to anticipate the effect of changes in the economic climate and changes in the design and cost of hardware.

The analysis presented in the paper is for the production of a prismatic part. The proposed production line is assumed to process the part by routing it among six different types of processing stations, each of which requires an operator, while the CMS uses an off-line load/unload station, a material handling system, a computer controlled transporter, and a multifunctional machining center, which can handle all six operations. A network of queues based model CAN-Q

(Solberg,1976) was used to estimate the production capacity for the two systems.

This study recognized the overall FMS advantages in flexibility and controllability; however, the analysis is based on only two economic factors: labor cost and initial investment. Also, the analysis is based on only one product and no engineering change is considered. Furthermore, it assumes that a universal workstation of CMS can handle all six operations so the CMS itself becomes a flow line consisting of operations like loading, transporting to workstation, machining and transporting to the unloading station. The decision problem thus becomes that of comparing two flow lines with one being labor intensive while the other being capital intensive. These assumptions greatly simplify the problem, ignore different system characteristics and render the model little applicability for the system selection problem.

Hays and Zimmers (1982) present an overall system approach for the justification problem by considering cost factors due to inventory, floor space, and part inspection, that normally come under the heading of overhead costs. A procedure is proposed to justify an FMS against the traditional manufacturing system of a job shop. It consists of the following steps:

1. select a representative sample of parts,
2. estimate their machining times,
3. determine the annual sales volume,
4. determine the number of pieces to be produced per lot,  
and
5. determine the setup and run times for each machine tool  
in FMS and in job shop.

An illustrative case is studied to demonstrate the justification process. The specific cost areas taken into account in this example are direct labor, material handling labor, part inspection, equipment maintenance, part set-up, production control, inventory, and rework. The economic analysis is based on the rate of return method. The analysis assumes that the proposed FMS can always find other compatible parts to work on for its "leftover" capacity and some supporting labors can work on a part-time basis for the FMS.

A simulation model is employed by Hutchinson and Holland(1982) to compare an FMS with a traditional transfer line under various operating environments, including the variability of the product and the uncertainties of the marketplace. It is reported that an FMS has an overall economic advantage over a transfer line because of its flexibility. A transfer line performs better only at low variable cost.

Warnecke and Vetti(1982) propose an investment planning procedure for FMS selection. A GPSS-based simulation program called MUSIK is developed for production planning purposes. They claim that by repetitively using the model for calculating the manufacturing cost for various time periods under the assumptions of average, optimistic, and pessimistic values of uncertain parameters, the manufacturing costs of the conventional manufacturing system and the FMS can be determined and a better one can be chosen.

Co and Liu(1984) develop a dynamic decision analysis approach to incorporate factors such as uncertainty of demand and engineering changes in the FMS justification process. Their approach allows the decision maker to dynamically interact with the computer program to evaluate cost effectiveness of the FMS and decide on a suitable configuration of the system. This is done by adding a machine at the bottleneck station or by changing production plan when the planned products are not sufficient for the projected demands. The planning is done on a yearly basis. CAN-Q is used to verify if the current system configuration is sufficient for the planned production of the following year. The simulation procedure is repeated until the end of the planning horizon. It is assumed in the analysis that a part family for the FMS has been selected and the corresponding process plan, machine types, machining data, cycle times, production demands and the costs of each machine

type and material handling system are known. Furthermore, the model is based on all the assumptions of the CAN-Q model (Solberg, 1976) and assumes product demands, part mixes, and product routings, and engineering designs to be random variables. The routing process is modelled by a Markov transition matrix, while the processing times and the actual production quantity are assumed to be uniformly distributed. An example problem is solved to illustrate the procedure. It is claimed that the same procedure can be used to analyze other manufacturing systems.

This approach incorporates FMS features like uncertainty of demand, flexibility of part routing, and variation in parts. It allows system growth in the planning horizon. It applies the life cycle cost concept to the system selection problem. However, it does not demonstrate how to apply it to other types of systems to make comparisons. Specifically, it is not a system selection model, not even a justification model, but is more like a machine requirement planning model. Furthermore, it allows the decision maker to arbitrarily fathom any alternative system configuration. It assumes product demands and routings as random variables but does not provide a methodology for assessing this probability distributions.

Leung(1983) develops an economic equipment replacement model for an FMS. The model addresses the problem as a multiple

machine replacement problem different from the traditional one-for-one or like-for-like cases. The issues, such as layout, transportation, material handling capacity, flexibility, capacity expansion, obsolescence, deterioration, and equipment depreciations are all incorporated in the model. The model is primarily to establish the FMS replacement sequence over a planning horizon. The problem of part assignment is also addressed. The objective of the model is to maximize the after-tax future worth of the system at the end of a specified planning horizon.

This model assumes stable market demands and adopts an AGVS as the only material handling system. It can not handle fluctuations in product demands and the change in product mix. Also, it can not capture other material handling system characteristics and their impacts on the system. Moreover, the model can not effectively solve large size problems, because of its tremendous computation burden. If large realistic problems are to be handled, further efforts like bounding strategies are needed.

To date, there has been no comprehensive decision model in existence for manufacturing system selection and justification. The difficulty is that each type of manufacturing system possesses its own characteristics. The features of different systems usually represent those advantages and

disadvantages which are hardly quantifiable but appear important for planning decisions in the dynamic manufacturing environment. A production system is expected to be low in investment and operating costs, but high in adaptability, profitability, and future competitiveness. An ideal decision model, therefore, is a model which can select a production system capable of meeting known demands, adapting expected demand changes, and resulting in the lowest overall manufacturing cost. Bearing these concepts in mind, various decision procedures for FMS design have been proposed in the literature and we examine them in the following section.

#### 2.1.2 SYSTEM SYNTHESIS PROCEDURE

Although no comprehensive system justification and selection model is available, the design procedure for an FMS has been extensively addressed. Hutchinson and Wynne(1973) first discussed issues in the design of an FMS and suggested a procedure involving the following steps:

1. determine machine types and number,
2. determine physical layout,
3. determine local buffers at each machine,
4. determine the type of material handling system, and
5. determine maximum number of pallets.



The criteria used for physical layout determination are material flow, ease of maintenance, tool exchange, space limitation, chip removal and power requirement. The maximum number of pallets allowed in the system is dictated by shuttle capacity, cart speed, track layout, and workload level.

Barash(1980) recommends the following procedure for the design of a CMS:

1. select a group of parts belonging to the same family based on production needs,
2. determine the processing content for each part,
3. determine the required machine characteristics, and the number and types of machines,
4. compose various feasible system configurations including the material handling system,
5. perform a mathematical analysis,
6. perform simulation, and
7. identify the best system and operating rules for this system.

In the above two proposed procedures the part mix and the production demands are assumed to be known. Both procedures are presented as conceptual approach. There is no methodology developed to implement them.

A procedure for FMS selection has also been suggested by Draper Lab(1981). It consists of the following eight steps:

1. part preselection,
2. FMS machine selection,
3. part selection,
4. material handling system and fixture selection,
5. batching,
6. balancing,
7. scheduling, and
8. real-time operation.

The first four steps belong to the system design problem while the remaining steps belong to the production planning and operation problems. Part preselection step screens out infeasible parts by virtue of geometry, weight, and material from a list of candidates for production by a generic FMS. Machine selection step selects a complement set of machines which is suited to the candidate workload in terms of capacity range and balance, and is reasonable in budget constraint and the ROI requirement, etc. Part selection step then deletes those economically unattractive candidates from a set of part feasible for production by a generic FMS, i.e. selects a subset most economically attractive for production on a particular FMS machine complement. At the material handling system and fixture selection step, a given budget

is allocated for material handling and fixturing in such a way as to most efficiently support a given production workload.

The part preselection and machine type selection are not real selections, but rather weeding out of the inappropriate items based on simple job characteristics and machine functions. A sequential decision algorithm is suggested in the study for part selection and material handling system/fixture selection. The algorithmic steps are as follows:

1. rundown a list of candidate parts to be chosen for some action,
2. find the best candidate to select from the list, and
3. repeat this process until some resource is used up to its capacity.

The definition of "the best candidate" is based upon a performance measure which is a function of all items left pending in the list. The best candidate to select is the one which, when removed from the pending list, causes the most improvement to the performance measure.

Following this concept, Whitney and Suri(1984) developed a computer selection model for part and machine selection. The model is designed for the situation that an FMS is proposed

to take over some existing parts currently manufactured by other machines. The input to the model consists of initial guidelines, part preselection, and current production. The initial guidelines pertain to maximum size of the system, number of machines, available space, budget constraints, total annual operation time of the system, and information about a compromise between the ROI and stability of the production conditions.

In part preselection, parts are sorted based on the attributes of the FMS-compatible parts such as machining cubes, material, shape, type of operations, tolerance, quantity, machining time, and fixturing. The input is the preselected part specifications. Information regarding current production includes part purchased cost, manufactured cost, FMS machine tool cost, material handling system cost, computer cost, FMS labor rate, overhead rate, hourly machine rate, and payback period.

A program, called PAMS (part and machine selection) was created to serve this purpose. It is an integer linear program. The objective is to maximize total dollar savings from parts minus total cost for FMS machines subject to constraints. The model is solved using a heuristic integer programming routine based on rounding off a classic linear programming solution.

Stecke(1984) also proposed a procedure to design an FMS. The design steps are as follows:

1. determine the range (part types, family of components) to be made (i.e. identify a subset to be made by FMS),
2. determine how these part types are to be manufactured, specify the capacity and functional requirement in terms of machine time and cutting tools,
3. specify types of different flexibilities required,
4. determine the type of FMS,
5. specify the type and capacity of material handling system,
6. determine type and size of the buffer,
7. decide the control system hierarchy,
8. select a vendor,
9. decide FMS layout,
10. determine number of pallets,
11. determine type and number of fixtures,
12. specify general strategies for running the FMS (for control and planning purposes), and
13. specify software development tasks.

No specific methodology is recommended to implement this procedure.

Browne, et al.(1984) proposed a detailed FMS design procedure, which is composed of three phases: part selection, system and elements selection, and implementaton. In part selection phase, group technology is suggested to select appropriate part families and to generate appropriate process plans. In the second phase, the type of an FMS is selected and the individual elements of the system are specified. The types of FMS candidates are DNC, DNC line, FMS cell, or FMS. The selection criteria are economic, technical, and the process/product characteristics (e.g. desired flexibility). Simulation is suggested as the best tool to handle the selection problem.

A more sophisticated FMS design model was developed by Cook(1979). The goal of this model is to evaluate the viability of an FMS for any specific set of parts. The model takes into account part mix, part routing, tool slots, machining parameters, and is limited to conveyor type of system configuration and to small rotational parts only. The model is composed of a supportive data base and four major modules: (1) part processing, (2) FMS configuration, (3) simulation, and (4) cost analysis modules.

The part processing module analyzes each operation of every part for a specific set of parts relative to every machine capable of carrying out that operation. Machinability, proc-

ess constraints, and other physical and machine limitations are considered in detail. The output of this model consists of the feed, speed, machining time, and cost for each operation on each machine.

The configuration module, receiving input from the first module and production demand rates, determines the best of machines to produce the set of parts at the desired rates. Knowing no truly optimal method for selecting the best set of machines, Cook(1979) resorts to a heuristic procedure that appears to produce good results. The algorithm works iteratively to determine a set of machines with the lowest capital cost that can produce parts at the desired rate.

The traffic flow problems are separated from the machine selection procedure by assigning a target machine utilization, which provides non-utilized time for material handling, machine maintenance, and scheduling problems. Load/unload time is taken into account as part of machine time. Therefore, some parts may stay at the same machine for less efficient processing, if the load/unload time is relatively long; otherwise, they tend to be routed to a variety of more efficient machines. The algorithm operates as follows:

1. assign each operation to a machine that can execute that operation at least cost, thus resulting in the selection

of a large number of different machines which are cost effective as well as have lower machine utilizations

2. remove the least utilized machine from the machine set and reassign the operations to other machines
3. repeat the process until no machine can carry more operations

This algorithm has the following features:

1. it accounts for loading/setup time.
2. it loads machines to a maximum utilization.
3. it constrains machine loading by tool slot limitation.
4. it creates additional identical machines of a given type when necessary.

When the iteration stops, a number of alternate FMS configurations are gathered, all capable of producing the required output. Differences between them are due to tradeoffs between process efficiency and machine utilizations. The output for each configuration is a specific set of machines, parts routings, tooling assignment, backup capacity for machine failure, and other process related information.

Simulation model is used to gather the statistics on actual production, utilization, and breakdowns, according to operating strategies. Cost analysis module provides total cost



figures and determines the part cost at each system alternative. The input includes a system candidate, cost information, and demand figures from the initial processing program and the objective is to minimize part manufacturing cost.

The model does not select a material handling system. An attractive feature of this model is that it specifies machining parameters at the system design stage. Also, the concept of system efficiency factor is applied to compensate for the decrease in utilization because of congestion, breakdown, and other factors.

Co(1984) develops an interactive computer program called the FMS system synthesis model for estimating the machine requirements for a set of parts preselected for the FMS. This program was also used in the study by Co and Liu(1984) to calculate the production rate and identify the bottleneck workstation of an FMS. The inputs to the model include initial number of each machine type, part routings, production requirement of each part type, available investment capital, and the unit cost of each machine type.

Parts can be dropped from the production plan (a set of preselected parts) when the production requirement can not be met under the capital constraint. The program stops when the production capacity of the FMS is sufficient for the selected

set of parts. The outputs of this model are machine number of each type, the needed investment capital, the final set of part families selected for the FMS, and the estimated production rate of the system. There are the following drawbacks of this model:

1. no guidelines are suggested for dropping a part from the given production plan;
2. no decision criterion is given; and
3. the selected machines and parts are not necessarily the best design under the capital constraint.

But the model is capable of estimating the required machine number of each type for a given set of parts and of calculating machine utilizations within a negligible computation time.

### 2.1.3 CLOSING REMARK

This section has reviewed literature pertaining to system selection, justification, and design. Although no comprehensive model is available in the literature, each of the reviewed study contributes to the problem from a different viewpoint. Based on these works, a more generalized model is developed in Chapter 3. Next, we review literature on shop loading and machine loading.

## 2.2 SHOP LOADING AND MACHINE LOADING

Once decision regarding the selection of production system(s) has been made, the subsequent problems are (1) to assign parts to each production system and then (2) to assign tools to each machine center and to route the corresponding parts through the system. These two problems are treated separately here in the following two subsections.

### 2.2.1 SHOP LOADING AND JOB ASSIGNMENT PROBLEM

An FMS is an integrable unit of a larger manufacturing system. The overall objective of manufacturing system planning and operation planning is to optimize the overall system performance, rather than to optimize FMS productivity at other system's expense for it to become the "island of automation" the term used by Church(1982). Therefore, the problem of assigning-parts to systems becomes an important problem and needs to be explored.

Numerous studies dealing with scheduling, sequencing, and control problems have been published in the literature. Graves(1981), Blackstone, Philips, and Hogg(1982), and Ballakur and Steudel(1984) provide extensive survey on the general scheduling and sequencing problems. In this section only those studies directly related to shop loading (espe-

cially related to multiple shop loading problems or loading of an FMS) are reviewed.

Whitney and Suri(1984) first addressed this problem. They assumed that only two production systems are to be assigned: a traditional job shop and an FMS. A computer model, called PARSE (part selection) was developed for this purpose. In PARSE, a performance index called relative saving ratio,  $RS_i$ , which was derived from the papers by Senju and Toyoda(1968) and Toyoda(1975), was created as a decision criterion. To compute this ratio, the numerator was dollar saving and denominator was a function of resource utilizations. In PARSE, the resource utilization is measured in terms of tool slots and machining time needed. The formula is:

$$RS_i = \text{Dollar} * [ 1 - P_{wi}(1 - P_{ni}) ]$$

where

$$P_{wi} = 1 - \prod_{\text{machine classes}} [1 - U_{si}/(1 - U_s)]$$

$$1 - P_{ni} = 1 - \prod_{\text{machine classes}} [1 - U_{hi}/(1 - U_h)].$$

$U_s$  and  $U_h$  stand for cumulative tool slots and time.  $U_{si}$  and  $U_{hi}$  are for incremental slots and time needed by part  $i$ .  $P_{wi}$  is larger for parts that require more new tools and  $(1-P_{ni})$  is larger for parts that require more machining time. The required decision is to select part  $i$  with the largest  $RS_i$  to be processed on the FMS.

The model was developed for the situation where these parts are processed by traditional job shop and now FMS is taking over a subset of these parts to optimize the overall system performance (i.e. cost savings). It is assumed that other parts can always move into the job shop thereby maintaining the same utilization level. Consequently, the algorithm can find as many beneficial parts as needed to feed the FMS "leftover" capacity. However, in most of the shop loading decisions, the problem can not be modelled as such.

Greene and Sadowski(1984) present a mixed integer model for simultaneously solving the shop loading and scheduling problems in a multiple FMC (flexible manufactuirng cell, conceptually similar to FMS) environment. Several objectives are considered including minimization of makespan, mean flow time, and mean lateness. The constraints in the model are based on the following requirements:

1. each part must be assigned to only one of the FMCs,

2. each part must be completed,
3. each operation of a part must be finished before the next operation of the same part can start, and
4. each machine must not work on more than one part at a time.

A numerical example is given to illustrate the MIP model. An attractive feature of this formulation is that it solves both the shop loading and the scheduling problems jointly. However, the model grows rather rapidly in terms of number of decision variables and constraints with increase in the number of parts and machines. It is, nevertheless, the first model available in the literature which addresses the multiple shop loading problem.

Sarin and Dar-El(1984) and Dar-El and Sarin(1984) propose an algorithm for FMS loading and scheduling problem in a single system environment and implement it through a computer program. The algorithm ranks a big set of job candidates according to their manufacturing cost and due date penalty at the beginning of each planning period. The program selects a subset from the ranked parts for scheduling considerations during a preestimated planning period. The major objective is to achieve high level system utilization. It is claimed that the algorithm can solve moderate-size scheduling prob-

lems within a very short CPU time. High system utilization can be achieved by using alternative routings.

Sarin and Sherali(1985) present a 0-1 pure integer programming model for a single shop loading problem. The model selects a certain number of parts from a pregrouped part set and schedules them on an FMS. The constraints correspond to the preemption of parts and precedence relationships. The objective is to minimize makespan. A new feature of the model is that it considers alternate routing combinations (ARC) for each part and selects the best routing combinations.

### 2.2.2 MACHINE LOADING AND TOOL ALLOCATION

After parts have been assigned to each system, the detailed production planning decisions have to be made regarding the assignment of tools to machines and the assignment of parts to tools to fulfill processing requirements. There are many different methodologies discussed in the literature to solve this problem.

Chakravarty and Shtub(1984) formulate a tool allocation and workpiece assignment problem as a 0-1 mixed linear integer model. The decision variables are tool allocations to machines. Each tool is assumed to have different efficiency on each machine. The objective is to minimize total processing

time. In this model, parts are assigned to only one of the tools assuming that a tool can handle all the machining operations of that part; therefore part assignments are not decision variables. Hence, part routing and scheduling problems do not exist. The model does not consider tool life and resource limitations on machine capacity. The problem is to assign each tool to the most efficient machine, given tool-machine efficiency matrix. No solution algorithm is proposed for the model.

Stecke(1983) formulates the machine loading and tool allocation problem as a 0-1 non-linear mixed integer program. The major loading objectives are to balance the assigned machine processing times and to minimize workpiece movements. The constraints correspond to: (1) the assignment of each operation to at least one feasible machine, and (2) the requirement that the tool slots used by the operations assigned to a machine can not exceed the tool magazine capacity. This formulation resulted in both non-linear objective function and constraints.

The non-linear terms in the formulation are all products of 0-1 integer variables. Therefore, instead of solving it directly, a linearization approach was taken, resulting in a much larger problem. The procedure was to replace each cross product term with a new variable. Additional constraints were



added to insure that the new variables take on the correct value.

The linearization method employed was the one developed by Glover and Woolsey(1973,1974). This method allows the new variables (introduced for replacing those cross-product terms) to be continuous and reduces the number of added constraints by replacing those constraints that contain terms with common variables with a single constraint.

The model was implemented on the Caterpillar's FMS using a computer code, called MIPl, which is based on Balas' additive algorithm(1965) and was developed by Bravo et al.(1970), and further improved by McCarl et al.(1973).

This model emphasizes the problem of possible tool slot savings and extensively discusses the FMS surrogate objectives and different approaches for problem linearization. By taking advantage of system flexibility, the model assigns only operations (not parts) to machines. Part routings are therefore not available. Also, the scheduling and congestion problems are not considered. Tool lives are not taken into account. Furthermore, by allowing operations to be assigned more than once, more tools and more tool slot spaces are required, which might cause low machine utilizations and production output.

Following this study, another approach has been taken by Berrada and Stecke(1984) to solve the same non-linear problem (Stecke,1983) directly, bypassing the tedious manual linearization step. The objective is to balance the assigned workload on each machine tool while each operation can only be assigned to one machine. Instead of solving the whole problem simultaneously, a sequence of subproblems were defined, and solved by a branch and bound procedure that first solves a simple relaxed assignment problem, then checks for feasibility, and finally modifies the assignment to correct the violated constraints. The modification of the assignment is obtained by solving small integer problems via a branch and backtrack procedure for each machine when a constraint is violated. The optimal solution to the relaxed problem provides a lower bound to the original problem that is used both to fathom nodes in the binary enumeration tree and to select a node for further branching. A selection criterion was proposed to choose the most suitable branching variable. The features of the problem are essentially the same as that of Stecke's previous study(1983).

Another formulation was proposed by Kusiak(1983) for machine loading problem. The problem was modelled as a generalized transportation problem. The objective is to minimize total processing cost. The decision variables are the number of

operation units of each batch assigned to each work station.

The constraints correspond to:

1. the number of operation units per batch,
2. the machining time available on each station,
3. the limit on tool slots,
4. the limit on tool life, and
5. the maximum number of visits to workstations per batch.

Except for the fixed number of operation units per batch, all others are upper bounding constraints. The loading model is a 0-1 mixed integer program, which could usually be solved by cutting plane and branch and bound techniques. Considering the difficulty of obtaining an optimal solution to the loading problem in a reasonable time, especially for large size problem, subgradient algorithms were suggested to generate a feasible solution in a shorter computing time. However, the model was not directly solved; instead, a similar and simplified problem was used to illustrate the efficiency of the subgradient algorithms. The strength of the loading model is in its linear structure and some practical constraints like tool life and tool slot limits. There exist, however, the following drawbacks in the model:

1. the operations within a batch are assumed uniform and continuously divisible, i.e. a portion of a batch can be

arbitrarily assigned to each workstation with different unit cost;

2. every operation of a batch is assumed to have identical processing time;
3. when two batches assigned to the same machine need the same kind of tool, a new tool is assigned to the machine; thereby resulting in more tools than needed, to be assigned to the machine which, consequently, reduces machine capability and flexibility;
4. tool lives are assumed to be the same irrespective of the types of batches and the workstations they are assigned to; and
5. the model, like others, assigns only operations to machines, not parts; therefore the routing problem and system dynamics and congestion are avoided.

Co(1984) also presented a zero-one linear programming model for solving the machine loading problem. There are two sets of decision variables in the model: (1) the assignment of operations to the machines and (2) the assignment of tools to the machines. Four constraints were defined as follows:

1. each operation must be assigned to at least one machine, allowing alternative routing,
2. the number of tool slots on each machine is limited,

3. all tools needed for an operation must be assigned to the same machine, and
4. an upper and a lower limit to each machine workload are imposed to achieve workload balance.

The objectives considered in the study are maximizing total machine flexibility, and minimizing the maximum difference in machine workload (to balance the assigned workload), minimizing the sum of the absolute deviation in machine workloads, and maximizing the number of consecutive operations to be performed on the same machine (to minimize total travel distance).

Some constraints and objectives are non-linear and hence a linearization method was suggested. However, the formulations were not solved. It is suggested that the large-scale 0-1 linear programming problem can be solved efficiently by using implicit enumeration and cutting plane techniques. But, no computational results were provided. The formulation did not consider tool life, job routings, and system congestion effects.

### 2.2.3 CLOSING REMARK

In this section, studies relating to shop loading and machine loading problems were reviewed. Most of the formulations

reviewed were generative-type models, which employed or suggested optimization algorithms to seek the best set of candidate decisions for the loading and scheduling problems while satisfying system objectives and resource constraints. Integer programming appears to be the major technique applied to solve these problems. The advantage of the integer programming technique is that it can model a complex system rather quickly and directly reach the optimal solution. However, there are some critical drawbacks. The generative models are difficult to tailor to other systems. Large size problems are not easy to solve, and furthermore, they can not capture the dynamics, the interactions and the uncertainty of a production system.

Chapter 4 will be devoted to the development of a broad based shop loading, and machine loading generative models which cover congestion effects, part routing, tool selection, tool life, tool slot capacity and other aspects which have not been considered in one model so far. The shop loading and machine loading problems will be treated separately so that the model would be practically solvable.

The research in FMS has also given rise to the development of several evaluative models that are used for its analysis. Next, we briefly review these models and discuss results of

some parametric analyses to determine effective operating condition for an FMS.

## 2.3 SYSTEM PERFORMANCE EVALUATION AND OPERATING PARAMETER ANALYSIS

Four types of evaluative models are reviewed in this section. They are: (1) queue network models, (2) simulation models, (3) perturbation analysis, and (4) Petri Nets. The studies pertaining to the system and job-related parametric analysis by applying these modeling techniques are also reviewed in this section.

### 2.3.1 EVALUATIVE MODELING TECHNIQUES

#### 2.3.1.1 QUEUEING MODELS

Queueing models account for dynamics, interactions, and uncertainties in an FMS in an aggregate sense. The output measures given by these models are average values, which assume a steady-state operation of the system. The models usually require relatively little input data and short computer time and give reasonable estimates of system performances, as compared to simulation models. Therefore, queueing models can be used interactively to get a set of quick preliminary decision values.

The earliest queueing network model of FMS is CAN-Q developed by Solberg(1976). This model can evaluate a very large system with minimal operation data. The theoretical foundations and computational refinements of the model are based on the works of Jackson(1963), Buzen(1973), and Gordon and Newell(1967). It is based on the following assumptions: (1) the number of parts in the system is constant, (2) the local queue capacities are infinite, and (3) the arrival rates are exponentially distributed. It has proved to be an efficient instrument in making the preliminary design decisions to measure the performance of an FMS or for evaluating the effect of, for example, adding a machine or altering the material handling device.

Buzacott and Shanthikumar(1980) also formulated some simple queueing models for determining the production capacity of different FMSs. This study shows the desirability of a balanced work load, the benefit of diversity in the routing if there is adequate control of job releases, and the superiority of common storage for the system over local storage at machines. Dubois(1983) extended Solberg's CAN-Q model to estimate the influence of inprocess inventory level (number of parts allowed in the system).

More detailed models have been developed to refine the decisions obtained from queueing models. These models can formu-



late system features in more detail without loss of efficiency. Mean value analysis is one of the techniques of this type (Hildebrant,1980, Cavaille and Dubois,1981, and Shalev-Oven et al.,1984, and Suri and Hildebrant,1984). It represents a good compromise between the computational efficiency of the queueing models and a satisfactory accuracy of the predictions. Recently, Shalev-Oven et al.(1984) applied the Seidman and Schweitzer's(1982) mean value analysis based solution approach to queueing network models while allowing different queue disciplines. It showed that throughputs and flow times for various part types can be quite sensitive to the choice of priorities at a heavily loaded station.

#### 2.3.1.2 SIMULATION MODELS

While the queueing models overlook details of system characteristics and fail to describe specific system behaviors because of the complexity of an FMS, computer simulation models can examine how different system variables influence the system performances. In fact, simulation not only provides economical means of testing proposed improvements but also gives a framework for understanding the underlying causal relationship which directly effects the productivity and the efficiency of the system. At present, simulation is perhaps the most widely used computer based performance evaluation tool for FMS.

There is generally an option to use high-level languages, general-purpose simulation languages, or even some canned packages specialized for FMS to ease the model building and data input efforts. However, tradeoffs are involved in using these options (Bevans, 1982). The popular simulation languages used to model manufacturing systems are GPSS/H, GASP IV, Q-GERT, SIMSCRIPT V, SLAM, SIMAN, and MAP/1; the last two are dedicated to modeling FMS. An extensive review of the role of simulation in manufacturing systems design can be found in Bollinger and Crookall (1981).

Many FMS simulation models are available in the literature. Among them are the CATLINE model, the GCMS simulator, the CAMSAM simulator, the SIMSCRIPT-based FMS simulator, and SIM-Q model. Most of them are FORTRAN-based. The CATLINE system, developed by Mayer and Talavage (1976), was specifically written to model the Caterpillar Tractor Company's FMS (see Barash, 1980). Although developed for a real system, it still maintains the desired versatility necessary to test a proposed FMS system.

GCMS simulator is a more general model written in GASP IV by Lenz and Talavage (1977). Its efficient modular structure and user-written subroutines make the GCMS simulator potentially a very powerful universal tool for studying flexible manufacturing systems. It can model various kinds of FMSs to a

very high level of details, such as machine breakdown, part routing, dispatching rule, and material handling.

CAMSAM is another simulator, written in Q-GERT by Runner(1978). It can be used to test various control variables such as the number of loader, transporter speed, and level of in-process inventory. It was once used to model the Caterpillar Tractor Company's FMS under the same assumptions as those of CAN-Q and was shown to outperform the CAN-Q model.

A SIMSCRIPT-based FMS simulator was developed by the Kearney and Trecker Corporation for its own use. The input includes the permanent SIMSCRIPT variables and user-defined parameters. The output consists of production rate, the time a part spends in the system, and the pallet, shuttle and cart performances.

SIM-Q is a SLAM-based simulation model recently developed by Co(1984). It is not a canned simulation model but a tool to ease simulation modeling. The methodology follows the conceptual framework of CAN-Q and provides user with flexibility to interface the network model with FORTRAN-functional subprograms. The inputs are also similar to those of CAN-Q. The output of SIM-Q is a self-documented network of a combined discrete-network SLAM simulation model. All the housekeeping

specification and statements needed to run the SLAM model are built into the network model.

SIM-Q enables the user to manipulate various system parameters, including part-mix ratio, processing time, machine breakdown, material handling, visit frequency, dispatching/priority rule, and routing, etc. Although, the running cost is more expensive than CAN-Q, it provides a variety of control which CAN-Q can not offer.

#### 2.3.1.3 PERTURBATION ANALYSIS

The traditional approaches to the FMS problems are computer simulation and queueing network modeling, which treat the problem from the viewpoint of probability theory and stochastic process. Queueing models are useful in deciding some system parameter values, particularly during the preliminary decision making stages for FMS design and operation, but these models ignore certain system details and are often not accurate enough for making final decisions while simulation usually appears expensive and time consuming.

In perturbation analysis, an FMS is viewed as a discrete event system which dynamically evolves in time. It is driven by the occurrence of discrete events, such as the arrival and the completion of a workpiece. These events further trigger

other events in other part of the system according to various rules of operation. As the system evolves in time, the interactions of these events become very complex and difficult to be modelled accurately.

Perturbation analysis has application potential in both simulation and real-time operations of FMS. It combines the advantages of both the queueing network models and simulation approaches, while minimizing their disadvantages (Ho and Cao,1983, Ho and Cassandras,1983). The basic idea is to observe the detailed behavior of the system for a set of decision parameters from simulation or an actual system. By doing some minor additional calculations, while the system is observed, perturbation analysis can predict the system behavior if these decisions were changed. The advantage is that it need not rerun the system (or simulation); all the predictions are obtained from one observation. This can save simulation time and improve manager's decisions without experimenting on the actual system. The modeling assumptions of perturbation analysis are minimal. It can directly work off real data and therefore has credibility with shop floor manufacturers. The disadvantage is that it can not predict accurately the effects of large changes in decisions. It can be used only as a tool for fine-tuning a design or operational decision (Ho,1984, Wallace,1985).

#### 2.3.1.4 PETRI NETS

Petri Nets is a tool newly applied to model FMS. It can provide a compact graphical representation of asynchronous, concurrent and non-deterministic event of any system. The main use of Petri Nets was to answer qualitative questions. Recent advances in timed Petri Nets can answer quantitative performance questions, popular for modeling asynchronous concurrent systems. Petri Nets models have the following merits:

1. graphical delineation of the system enables easier visualization,
2. systematic and thorough analysis of the system made possible by the virtue of the well-developed Petri Nets analysis technique, and
3. the existence of well-formulated top-down and bottom-up approaches for Petri Nets synthesis which facilitates system design and synthesis process.

One important question regarding analysis by Petri Nets is the efficiency of the resulting model after incorporating detailed system features such as machines with finite buffer sizes and real-time routing policies (Dubois and Stecke, 1983, Narahari and Viswanadham, 1984, Archetti, 1985).

### 2.3.2 THE ANALYSIS OF SYSTEM PARAMETERS

The operation and management of an FMS is more difficult than that of the conventional job shop or flow line, particularly in loading, scheduling, and control strategies because of the system versatility, the number of decision variables, and special constraints. Loading and scheduling typically involve the assignment of an operation to a machine and the balancing of the workload per machine while meeting due date or minimizing tardiness. A common objective is to maximize expected production. To take advantage of the machine versatility and system flexibility, many new loading and control strategies have been proposed and tested. Some "surrogate" objectives such as minimizing workpiece movement are often used for system optimization instead of directly maximizing expected production in order to simplify the problems.

Hutchinson and Wynne(1973) recognized the complexity of operational decisions of an FMS and developed a discrete simulation model using SIMSCRIPT to study the FMS performance and its sensitivity to many probable combinations of configuration designs and decision rules. The performance measures included parts completed by each machine, makespan, blocking time, material handling time, idle percentage, blocking percentage, and material handling system utilization. The decision variables are pallet number, cart speeds, number of

carts, and operation time distributions. The objective is to determine how each of the decision variables affects the FMS efficiency and effectiveness. A factorial design and F-tests were used to analyze the main effects and all first order interactions based on the results from 32 simulation runs.

The findings were that fast carts and more pallets cause production increase. Equal part operation time does not have positive effect on FMS output. Eliminating long individual operation times, however, is advantageous when interactions are taken into effect. Blocking time decreases when using faster carts or more shuttles.

The dependent variables selected in the study were closely related. More independent variables could be incorporated in the model. Interactions need to be more carefully examined. Larger sample should be taken to get more degree of freedom. Some covariates may be needed to reduce the error variance.

Following are some studies that analyze individual operating parameter from different aspects.

#### 2.3.2.1 PART MIX

Part mix issue in an FMS was addressed by Nof, Barash, and Solberg(1980). They compare the production rates resulted



from different number of part type mixes. It is concluded in the study that there exists some optimum set of part types to be run concurrently but it is dependent on the particular part types and processes used. It is believed that the optimum set generally consists of part types for which processing requirements are complementary to one another in such a way that processing requirements for the collection effectively matches the available system resources (Vaithianathan, 1982).

#### 2.3.2.2 PART MIX RATIO

Even when the part types and their processes are given, the machine loads in an FMS still heavily depend on the relative ratio of the various part types which will be produced. Two hypothetical process plans for two part types were simulated in the same study (Nof et al., 1980) to show how the separate and the total production rates vary as the relative product mix changes. The results indicated that the maximum rate is achieved when the products are mixed in nearly equal proportion. The production rate is about 37% greater than when either product is produced alone. But it does not mean the optimum ratio has to be around equal production. It actually depends on the relative machine loading.

### 2.3.2.3 PROCESS SELECTION

On process selection, Buzacott(1982) suggests that because of the inherent complexity of operation control, it is often advantageous to transfer the decisions from the operational level to the pre-release level. That is, if the constraints of operation sequence permit alternative routings, some specific routing should be chosen at the pre-release level in order to remove this decision burden from operational level.

However, Nof et al.(1980) contend that it is in general better to preserve the processing options for as long as possible. Even those process plans which seem to be clearly inferior when viewed statistically may prove to be superior in actual dynamic operation. Hence it may be advantageous to check the status of the system when a process is being decided.

Wilhelm and Shin(1985) investigate the influence of alternative operations on the performance of an FMS. A small example with 3 parts, each with four alternative routings, is simulated under different operating parameters. It is concluded that, within the experiment settings, the alternate operations can reduce flow time, in-process inventory, and increase machine utilizations.

Process selection is inextricably linked to the problems of part types, and part mix ratio. Ideally, one should present to the system a range of alternative process plans for each part type and let some algorithm select the parts and their processes, and determine the approximate mix ratio (Halevi,1981).

#### 2.3.2.4 CONTROL STRATEGIES

Control strategies were examined by Stecke(1977), Stecke and Solberg(1981), Nof, Barash and Solberg(1980), and Buzacott(1982a). Nof et al.(1980) proposed two rules to release parts to the system and concluded that the one which enters part type with higher ratio of production requirement remaining to their original requirements appears better than the other. Buzacott(1982a) also proposed one simple part release rule, called idle machine rule for deciding when to release a part. The rule only releases a part to the FMS when the machine for the first operation of the job becomes idle and there is no other part already in the FMS waiting for service at the machine. This is believed being able to improve FMS performance.

Several dispatching rules were tested by Nof et al.(1980). The results indicated that the rule which loads a part upon arrival, if it is behind schedule, is the best. Dispatching

rules were also extensively investigated by Stecke(1977) and Stecke and Solberg(1981). They used the CATLINE simulation model (developed by Mayer and Talavage(1976)) to test 16 dispatching rules against the Caterpillar's FMS . The result showed that SPT rule alone performed worse than the average rules but the combined SPT/TOT (shortest processing time for the operation divided by the total processing time for the part) is the best of the 16 dispatching rules. The production rate using this rule increased 24% over that achieved by the prevailing Caterpillar system.

The system performances shown in most simulation studies are highly dependent on the system loading level and other operational strategies, which, in turn, depend on many particular system parameters. Although it is suggested to always try SPT-related dispatching rules (Stecke and Solberg(1981)), yet which combination might be the best is highly system dependent. Each system deserves an individual study on various system parameters and real-time loading and control strategies.

#### 2.3.2.5 BUFFER AND PALLET NUMBER

Regarding the buffer problem, Buzacott and Shanthikumar (1980) have shown that common storage is superior to local storage. A common space automatically achieves control over

the number of parts in the system, where local storage can be used only if there is a close control over the release of parts to the system to avoid blocking. The only reason for providing local storage is to reduce delays while the material handling system moves parts between machines or between a machine and storage stations. It is likely that the local storage space for only one or two pallet is required (Runner, 1978).

Material handling operations create a certain amount of travel time. It seems that the production rate would increase if the material handling system is sped up or the transporter number increases. But, in general, transit time has a negligible effect on the production rate (Runner, 1978; Solberg, 1976). This effect increases significantly only with diminishing number of pallets allowed in the system and increasing ratio of mean transit time to mean processing time. Only when the transit time becomes comparable with processing time, the effect would become significant at low number of pallets.

An example of two machines and four parts system was studied by Buzacott and Shanthikumar (1980). It showed that the production rate decreased by less than 1% when the transit time increased from zero to one third of the operation time. How-

ever, it needs not be applied to any FMS in general. Further study is needed for each individual FMS.

The total number of pallets in the system is critical to the actual machine utilization but it is dictated by the number of machines, storage space, material handling capacity, and load/unload stations. Theoretically, the production rate increases when putting more pallets into the system but it can not continue to increase proportionately with increase in the number of pallets. There is some production rate which can not be surpassed no matter how many pallets are put into the system (Solberg,1976).

Dubois(1983) developed a queueing model to estimate the influence of the number of pallets in an FMS on production rate. It is showed that the production capacity is affected by a limitation of admissible work in process, especially when the FMS input is irregular. It helps to decide the minimal storage area which prevents blocking and congestion of an FMS.

### 2.3.3 CLOSING REMARK

In this section, four types of evaluative models are reviewed: (1) queueing network models, (2) simulation models, (3) perturbation analysis, and (4) Petri Nets. These modeling

techniques are frequently used to estimate various performances of an FMS. But it usually takes a long time to seek a good decision. Among the four techniques, simulation is the most widely applied in modeling FMS operations.

Studies pertaining to the analysis of system parameters are also reviewed in this section. These analyses are usually done by applying the evaluative modeling techniques. It is shown in general that performances of an FMS are highly dependent on the features of the individual system, job characteristics, and the applied control strategies.

In this research, a simulation model is developed to evaluate the validity of the optimal solution for machine loading and tool allocation, generated from the machine loading model(IM3) at different system parameter settings. The simulation model is also used to identify good operational strategies for a given set of parts.

#### 2.4 SUMMARY

In this chapter, FMS-related studies are reviewed under the topics of system selection and design, shop and machine loading, and system evaluation and the analysis of system parameters. There does not exist a comprehensive system selection model in the literature. Justification of an FMS is

suggested to be done by either economic or strategic analysis. Many FMS design procedures have been proposed and some have been implemented through computer packages.

The models for solving FMS operation problems fall into two types: generative or evaluative. Generative-type models generate good decision candidates under certain constraints, while evaluative models evaluate a given set of decisions. The models for shop loading and machine loading problems usually belong to the generative type. Integer programming is a major technique to solve these problems. It can model a complex system quickly and directly reaches an optimal solution. But, it is difficult to capture the dynamics and the uncertainties of a system. Large-size problems are not easy to solve. The mathematical programming approaches also remove the decision-makers from the decision-making process and thus they appear threatening to decision makers (Suri, 1984).

Evaluative models, on the other hand, can quickly measure performances of an FMS with a given set of decisions. But it takes much longer time to find good decisions. An evaluative model usually serves as a tool to effectively provide the decision-maker with insight of a system, rather than decisions.



In the following chapters, three mathematical models are formulated by applying integer programming technique for solving problems in system selection and design, multiple shop loading, and machine loading and tool allocation. Examples are given to illustrate the usage of these models. Simulation modeling technique is used to model an assumed FMS to evaluate the feasibility of the loadings assigned to the system and to investigate good operational strategies for the planning period.

### 3.0 A MODEL FOR MANUFACTURING SYSTEM SELECTION

In this chapter, a model for manufacturing system is developed. First, system characteristics are examined, and assumptions made in the development of the model are defined. This is followed by the presentation of a general design and selection procedure. System parameters required for the system selection procedure are then described. Cost factors are identified and finally a decision model is formulated to determine a mix of manufacturing systems which minimizes total annual manufacturing costs. Results are then presented regarding the use of the model under various operating conditions.

#### 3.1 SYSTEM CHARACTERISTICS

Typically, more than one production system can be chosen to satisfy given production demands. When the product demand is high and steady, the best system to use is the transfer line because (1) a transfer line is highly balanced, (2) it requires small setup time, (3) it involves low work-in-process inventory, (4) it requires short lead times and (5) machines have high utilizations. These characteristics lead to high productivity and relatively low flexibility in adjusting to product variations. Job shops on the other hand have high

flexibility in adjusting to product variations but they suffer from high WIP, long lead times, long setup times, low machine utilizations; and consequently low productivity. When the demands and product variety fall in between the two extremes, FMS becomes a viable alternative. An in-depth description of manufacturing systems can be found in the paper by Koenigsberg and Mamer(1982).

Rough ranges of demand and variety for system selection have been suggested by Kearney and Trecker(1983), Leimkuhler(1981), Hegland(1981) and Hutchinson and Holland(1983). However, this prevailing notion of system selection based on volume and variety alone is not precise. It is difficult, for example, to exactly specify the extent of demand volume and variety up to which a system ought to be adopted. A better system selection procedure is to consider in addition factors like system adaptability, routing flexibility, system controllability, part palletization, and material handling methods. System adaptability is the ability of a system to adapt to new product design or engineering changes. The routing flexibility means the capability to route a part from one station to another. System controllability is the dynamic capability of overriding the part routings to accommodate unscheduled events such as machine and tool breakdowns or the ability to optimize the real-time system performance (e.g. adaptive control). Part

palletization and handling methods indicate how the workparts are transported within the system.

These factors are important not only for system selection but also for the selection of their components. A system selection model based on these factors is presented next after a brief discussion about the assumptions.

### 3.2 ASSUMPTIONS

The system design model is developed based on the following assumptions. The production demands and engineering changes over the planning period are assumed known and furthermore the demand for each part family is assumed steady. That is, although the demand for a specific part type may fluctuate, the demand for that part family is expected to remain the same. The engineering variations are assumed to be so small that they can be accommodated in the existing system without a significant system modification. The initial setup time required to implement each system is assumed to be the same. The objective selected for decision making is to minimize total annual manufacturing cost consisting of annual depreciation cost and operating cost. The cost information are assumed to be available.

Only job shop, transfer line, and FMS types of system configurations are considered in this model. System mix is allowed (that is, more than one system can be selected) but no system expansion or system component replacements are taken into account within a planning period. Furthermore, the type, specifications, capabilities, life spans, and investment costs of available machine tools and other system components are assumed known. Knowledge about part specifications and their operation requirements are also assumed known up to the required level of detail.

### 3.3 A SYSTEM SELECTION/DESIGN PROCEDURE

A production facility typically produces a variety of products. These products vary in production quantity, shape, material, weight, fixturing requirements, desired tolerance, and/or operation processes. Usually there is no need to design a production system for each individual product. Due to their similarity in above attributes, some products can be grouped together and manufactured in a specialized production system, while others may be done in a job shop. A basic system selection/design procedure is as follows:

1. identify system configurations and system-compatible machine tools, material handling systems, and control systems

2. determine system capacity, system efficiency, and cost parameters for material handling systems, machine tools, machine operators, material handlers, and for overhead of each system at each system capacity level. The system capacity is defined here as the maximum number of machines available in a system.
3. group parts into families by applying Group Technology techniques (e.g. the cluster analysis discussed by King(1979), and King and Nakornchai(1982)) and by using prespecified criteria and thresholds. A threshold can be set, for example, on the number of part families desired. A criterion could pertain to one or more part characteristics. Processing requirements, for example, can be selected as a major criterion for this model.
4. estimate expected demands, setup times and costs, engineering changes (initial setup), batch size, and inventory levels and costs for each part family for each system configuration over the planning period.
5. estimate the operation contents of each part family in terms of broad processing requirements (e.g. turning, milling, grinding, etc.).
6. develop a model for the system selection problem.
7. solve the model.
8. select systems which result in the least overall annual manufacturing cost.

Similar steps for system selection/design procedure are also suggested by others. In this research, the focus is on steps 6, 7, and 8. For an in-depth discussion regarding data collection, the reader is referred to the FMS Handbook by Draper Lab.(1984). Before developing the model, system parameters to be used in the model are first briefly described.

### 3.4 SYSTEM PARAMETERS

The key system parameters for the model are part processing times, system capacity, system efficiency factor, inventory cost, machine cost, setup cost, control system cost, machine operator cost, material handling system cost, cost of material handler and machine operators, and factory overhead. The processing times are estimated in terms of general processing times for each part family. The processing time requirements of part families may be different for different systems because of variations in system's capability, control, setup, and inspection requirements. The processing requirements include among others operations of turning, drilling, milling, and grinding, etc.

The system capacity is expressed by the number of machines in a system. It is dictated by the MHS to ensure minimum machine blocking and system congestion. If the system capacity has to be increased, a larger MHS must be selected. System

efficiency (Cook,1979, Draper Lab.,1983) determines the actual availability of resources for processing needs. It is a factor used in the model to account for system congestion, blocking, routing inefficiency, machine breakdown, MHS breakdown, etc. These causes of system inefficiencies are difficult to be captured explicitly and make the analysis cumbersome. The system efficiency factor is assumed different for different production systems. In general, transfer lines have the highest operation efficiency (95-100%); and job shops have the least (40-50%), while FMS are in the middle (about 80%) (Barash,1980, Merchant,1983, and Hartly,1984).

Inventory costs are dependent on inventory level and carrying cost. Inventory level is based on manufacturing rate, demand rate, setup cost, and carrying cost, which in turn is determined by interest rate, material cost, and others. An FMS generally involves shorter makespan, smaller batch size and, therefore, leads to lower inventory levels and costs.

There are three types of setup considered in the model: initial setup, batch setup, and direct setup. The initial setup is required to introduce a part to the system and is usually caused by engineering changes or switching to other family of parts. It may cause machine remodification, MHS reajustment, and rewiring of control system. The cost is



determined by the frequency of changes and the extent of changes. The system usually has to be shut down for initial setup. The initial setup is relatively longer for a transfer line and shorter for a job shop.

Batch setup is the setup needed for processing a batch of parts. This requires setting up needed pallets, jigs, fixtures, cutting tools, lubricant, measuring tools, and machine accessories. Some preparations for this setup are done off-line but some require stopping of machines. The direct setup is the setup for each part in the batch. It includes both the machine and the part setups. Typically, the processing time of a part includes direct setup time. As a result the time it takes to process a part in a job shop is usually much longer than that in an EMS or a transfer line.

Overhead cost is the operating cost that is not related to direct labor and material costs. It includes cost of floor space, indirect labor, engineering support, maintenance, production control, utility, and others. Overhead cost is usually assumed to be a fixed multiple of direct labor cost. In the proposed model the overhead cost is determined based on system capacity and the capacity of the MHS.

### 3.5 THE MODEL

The proposed model consists of three sets of decision variables. The first set pertains to the assignment of part families to various systems. A part family may not be assignable to every system because of the inability of some systems to accommodate needed machine types.

The second set of decision variables pertain to the selection of machines for each system. If no part family is assigned to a system then no machine will be assigned to that system, which implies that the system is not selected for production.

The third set of decision variables is regarding the selection of the material handling systems (MHS). Material handling systems are classified according to their capacities and the handling method. Examples of MHSs include manual systems, programmable systems, and fixed automated systems. They can further be classified within each category. For example, a programmable system can be classified as a robot, conveyor, cart, or an AGV system. To be even more specific each of these types can be further classified. The cart system, for example, can be treated as one cart, two carts etc. The capacity of a MHS is defined as the number of machine tools that it can accommodate without causing excessive con-

gestion. The variables for MHS selection are treated as discrete variables in the model.

There are the following constraints and requirements.

1. part assignments

Each part family must be assigned to only one system.

$$\sum_n x_{in} = 1 \quad \text{for all } i$$

where

$i$  = part family number

$n$  = system number

$x_{in} = \begin{cases} 1, & \text{if part family } i \text{ is assigned to system } n \\ 0, & \text{otherwise.} \end{cases}$

2. resources constraints

The number of machines available in each system must be enough to finish all part families assigned to that system.

The constraints are as follows:

$$\sum_i u_{ikn} \cdot x_{in} \leq e_{kn} \cdot y_{kn} \cdot T \quad \text{for all } k \text{ and } n$$

where

$k$  = machine type

$u_{ikn}$  = processing time required by part family  $i$  on machine type  $k$  when assigned to system  $n$

$e_{kn}$  = efficiency factor (between 0 and 1) of machine type  $k$  in system  $n$

$y_{kn}$  = number of machine type  $k$  assigned to system  $n$ .

$T$  = planning period (units of time)

The efficiency factor is assumed to be in the same for all machines in a system.

### 3. MHS requirement constraints

A MHS must be assigned to a system, if a part family and consequently machines are assigned to it. Moreover, the number of machines that can assigned to a MHS must not exceed its capacity. Therefore, the corresponding constraints are:

$$\sum_k y_{kn} \leq \sum_m C_{mn} \cdot MHS_{mn} \quad \text{for all } n$$

where

$m$  = type of material handling system

$MHS_{mn} = \begin{cases} 1, & \text{when MHS type } m \text{ is assigned to system } n \\ 0, & \text{otherwise} \end{cases}$

$M$  = an arbitrary big constant

$C_{mn}$  = capacity of system  $n$  for MHS type  $m$ .

In reality, it is possible that a MHS may not be suitable for a manufacturing system. The above constraints are defined accordingly in that case. Also at most, one MHS is assigned to a manufacturing system; that is,

$$\sum_m \sum_{mn} \text{MHS}_{mn} \leq 1 \quad \text{for all } n$$

In case the maximum number of manufacturing systems to be considered are N, then

$$\sum_m \sum_n \sum_{mn} \text{MHS}_{mn} \leq N$$

The objective of minimizing total annual manufacturing cost can now be expressed as follows:

$$\begin{aligned} \text{Minimize } Z = & \sum_k MC_k \cdot \sum_n y_{kn} + \sum_k \sum_{n \in N1} MOC_{kn} \cdot y_{kn} \\ & + \sum_m \sum_{n \in N2} MOC_{mn} \cdot \text{MHS}_{mn} + \sum_m \text{MHSC}_m \cdot \sum_n \text{MHS}_{mn} \\ & + \sum_m \text{MHWC}_m \cdot \sum_n \text{MHS}_{mn} + \sum_m \text{CC}_m \cdot \sum_n \text{MHS}_{mn} \\ & + \sum_i \sum_n I_{in} \cdot x_{in} + \sum_i \sum_n \text{BSU}_{in} \cdot x_{in} \\ & + \sum_i \sum_n \text{ISU}_{in} \cdot x_{in} + \sum_m \sum_n \text{OH}_{mn} \cdot \text{MHS}_{mn} \end{aligned}$$

where

$MC_k$  = annual machine cost per unit of machine type k

$MOC_{kn}$  = annual labor cost for a machine type k in system n; N1 represents job shop and NC shop, while N2 indicates FMS and transfer line

$MHSC_m$  = annual cost of MHS type m

$MHWC_m$  = annual labor cost per unit time of the handler for MHS type m

$CC_m$  = annual cost of computer system needed by MHS type m

$I_{in}$  = annual inventory cost incurred by part family i assigned to system n

$BSU_{in}$  = annual batch setup cost of part family i in system n

$ISU_{in}$  = initial setup cost of part family i in system n

$OH_{mn}$  = annual overhead cost of system n containing MHS type m.

In this objective function the cost of machine tools is accounted for on annual basis using straight line depreciation. The labor cost of machine operators required for FMS and transfer line is determined based on the type of MHSs assigned to them while that required for job shops is determined based on the type of machine tools assigned to them. The cost of a MHS is assumed to be independent of the system

to which it is assigned and is also accounted for using straight line depreciation. The annual labor cost of material handlers and the annual control system cost of a manufacturing system are similarly determined based on the type of MHS assigned to it. The annual inventory cost is assumed different for different systems. The initial setup cost is assumed minimal for all systems except for a transfer line when more than one part family is assigned to it.

### 3.6 COMPUTATIONAL EXPERIENCE

The above model is a linear pure integer programming model, consisting of both general and zero-one types of integer variables. Pure zero-one type of linear integer programming models are easier to solve than the general integer programming models. Some well known computer codes for general integer programs are described in Loomba and Turban(1974). These are IPM1, 2, & 3, LIP1 & 2, IPSC, BBMIP, ILPH, CEIR LP90/94, IPLP6, Ophelie, and MPSX-MIP/370. PIPX developed by Crowder et al.(1983) is shown to be an effective procedure for 0-1 programs.

The revised IBM MPSX-MIP/370 programs were used to solve the model because of its availability, efficiency, and large capacity. In this routine the problem is first solved as a linear program by MPSX/370 and then searched for integer

solutions by MIP/370 using branch and bound type of search procedure. Other sophisticated features are used in the package to make it an effective procedure. A description of the MPSX-MIP/370 program is given in Appendix A. The proposed model was implemented on the following example problem. Further analysis was carried out to study system selection as a result of variations in system parameters.

### 3.7 AN EXAMPLE PROBLEM

In this example, the basic types of machines are classified as 1) turning and boring (M1), 2) drilling and reaming (M2), 3) planing, shaping, and slotting (M3), 4) milling (M4), 5) grinding (M5), 6) CNC turning and boring (M6), 7) vertical CNC machining center (M7), 8) horizontal CNC machining center (M8), and 9) CNC grinding (M9). The first five types are traditional job-shop types of machines, while the others are NC machines, which can be installed in job shops or automated systems. There are four types of production system configurations under consideration, namely conventional job shop (S1), NC job shop (S2), FMS (S3), and transfer line (S4). Some part families, for example, requiring non-NC types of machines may not be assigned to automated systems. The specific operation requirements for each part family and also the associated inventory cost, batch setup cost and initial setup cost are listed in Table 3.1.



Table 3.1 Data for the Example for System Selection Model

Part Family		1	2	3	4	5	6	7	8
Item									
Alternate machine Requirements for operation type	O1	M1 or M6 M2 or M7	M2 or M7 M3 or M7	M2 or M7 M4 or M8	M4 or M8 M5 or M9 or M8	M2 or M7 M4 or M8	M3 or M7 M5 or M9 or M8	M1 or M6 M2 or M7	M2 or M7 M3 or M7
	O3	-	M4 or M8	M5 or M9 or M8	-	-	-	M4 or M8	M4 or M8
	O4	-	-	-	-	-	-	-	M5 or M9 or M8
Systems in which part family can be operated on	S1	1	1	1	1	1	1	1	1
	S2	1	1	1	1	1	1	1	1
	S3	1	1	(1)	(1)	1	(1)	1	(1)
	S4	-	1	-	-	1	-	-	-
Processing time requirements of part families on machines in S1 (1 unit=200 hrs)	M1	20	0	0	0	0	0	40	0
	M2	16	12	24	0	32	0	18	0
	M3	0	18	0	0	0	24	0	16
	M4	0	16	12	12	16	0	20	22
	M5	0	0	12	22	0	28	0	14
Processing time requirements of part families on machines in S2 (1 unit=200 hrs)	M6	10	0	0	0	0	0	20	0
	M7	8	15	12	0	16	12	9	8
	M8	0	8	6	6	8	0	10	11
	M9	0	0	8	11	0	14	0	7
Processing time requirements of part families on machines in S3 (1 unit=200 hrs)	M6	10	0	-	-	0	-	20	(8)
	M7	8	15	(12)	-	16	(12)	9	(11)
	M8	0	8	(14)	(17)	8	(14)	10	(7)
Processing time requirements of part families on machines in S4 (1 unit=200 hrs)	M7	-	15	-	-	16	-	-	-
	M8	-	8	-	-	8	-	-	-
Annual inventory cost in system (1 unit=\$1000)	S1	20	18	20	36	42	22	24	32
	S2	20	18	20	36	42	22	24	32
	S3	10	9	(10)	(18)	21	(11)	12	(16)
	S4	-	5	-	-	10	-	-	-
Annual batch setup cost in system (1 unit=\$1000)	S1	4	4	4	4	4	4	4	4
	S2	2	2	2	2	2	2	2	2
	S3	2	2	(2)	(2)	2	(2)	2	(2)
	S4	-	-	-	-	0	-	-	-
Initial setup cost in system (1 unit=\$1000)	S1	3	3	3	3	3	3	3	3
	S2	3	3	3	3	3	3	3	3
	S3	15	15	(3)	(3)	15	(3)	15	(3)
	S4	-	210	-	-	210	-	-	-

In Table 3.1, columns correspond to part families while rows correspond to items pertaining to alternate machine requirements for part families, systems in which a part family can be operated on, processing time requirements of part families on machines in different systems and finally annual costs of inventory, batch setup, and initial setup for each system. For instance, operation type 1 of part family 1 can be done on machines M1 or M6. Manufacturing system type 1 (S1) can accommodate machine types M1 through M5. S2 can accommodate machine types M6 through M9. S3 can accommodate machine types M6 through M8, and S4 can accommodate machine type M7 and M8. Based on the processing requirements of part families, part family type 5 can be done in any of the four systems while part family type 7 can be done only in S1, S2 and S3. The processing time requirements of part family type 2 on M2 in S1, for example, is 12 units (one time unit = 200 hours). The processing time of a part family is composed of machining time, inspection time, and direct setup time. Because of different system characteristics processing time of the same set of operations is assumed to vary among systems. Initially, the processing time of a set of operations in job shop (S1) is assumed twice to that required in other systems. For example, part family type 3 needs 4800 hours of processing on M2 (drilling and reaming) in S1 while it needs 2400 hours on M7 to perform the same set of operations.

The efficiency factors of S1, S2, S3 and S4 are initially assumed to be 50%, 50%, 80%, 95% respectively. Assuming 250 working days per year and 2 shifts per day, the maximum availability amounts to 4000 working hours per year. Therefore the actual availability of each machine unit in each of the four systems is 2000, 2000, 3200, 3800 hours per year, respectively.

The annual machine cost and machine operator cost are depicted in Table 3.2. The annual machine cost is determined by dividing the initial investment cost by its estimated life span.

Data related to MHS are depicted in Table 3.3. There are six types of MHS under consideration. The first two types are truck systems used only in job shops (S1 and S2). The 3rd, 4th, and 5th types of MHS can be interpreted as cart, conveyor, and AGV systems respectively and can be used in an FMS (S3). The last type of MHS is dedicated for transfer lines. The remainder of Table 3.3 includes MHS related costs.

The following are some additional assumptions made in generating the basic data.

1. one operator handles two machines in the job shop and NC job shop

Table 3.2 Machine Cost and Operator Cost per Machine

Item	Machine	1	2	3	4	5	6	7	8	9
Annual machine cost (1 unit=\$1000)		15	10	15	24	23	75	80	90	85
Annual Operator cost (1 unit=\$1000)		20	16	19	21	20	20	21	21	21

Table 3.3 MHS related costs

MHS Item		1 (truck 1)	2 (truck 2)	3 (cart)	4 (conveyor)	5 (AGVS)	6 (for TL)
System in which a given MHS can be used	S1	1	1	-	-	-	-
	S2	1	1	-	-	-	-
	S3	-	-	1	1	1	-
	S4	-	-	-	-	-	1
MHS cost		5	10	40	85	120	50
Annual MH worker cost (1 unit = \$1000)		40	80	50	110	150	50
Annual System m/c operator cost		-	-	30	60	90	30
Annual Control System Cost		-	-	40	66	75	25
Annual System Overhead Cost (1 unit = \$1000)		50	100	50	100	150	50
System capacity (# of M/C)		30	70	6	12	24	9

2. the ratio of annual inventory costs for part families assigned to job shop, NC job shop, FMS, and transfer line is 4:4:2:1
3. the ratio of initial setup costs for job shop, NC job shop, FMS, and transfer line is 1:1:5:70
4. the ratio of batch setup cost for traditional job shop, NC job shop, FMS, and transfer line is 4:2:1:0

For this problem the model contains in all 80 zero-one and 36 general types of integer variables, and 100 constraints.

### 3.8 SYSTEM SELECTION STUDY

As a first study, the proposed model was run with the data presented in Tables 3.1, 3.2, and 3.3. The best system configuration obtained consists of job shop and FMS. The job and machine assignments are depicted in Table 3.4. The MHS selected for job shop is truck 1 and that for FMS is cart. The total annual cost of this system configuration is \$1,899,000. Results are also presented in Table 3.4 for the case when each of the individual systems is used alone for the production of the eight part families. The annual costs for job shop, FMS, and NC job shop are \$1,954,000, \$1,983,000, \$2,423,000 respectively. The optimal machine assignments and the MHS selected for each of these systems are depicted in Table 3.4. This example thus demonstrates that a mixed system

configuration can be better than using a system by itself to produce given part families.

This example is explored further to study system selection under various operating conditions. The following changes are made in the data presented in Tables 3.1, 3.2, and 3.3: (a) part families 3, 4, 6, and 8 can now be done in job shop and NC job shop only; that is, referring to Table 3.1, the entries within parentheses are now ignored, (b) the annual costs of traditional machines (namely M1, M2, M3, M4, M5) are doubled and (c) annual machine operator costs are increased by about 50%. The change in (a) is incorporated to represent a more realistic situation while changes in (b) and (c) are made for the sake of convenience. With these changes, the data of Tables 3.1, 3.2, and 3.3 will now be termed as the base case.

The results of this study are presented in Table 3.5. For the base case the optimal set of systems selected are NC job shop and FMS. Part family types 1, 5, and 7 are assigned to the FMS while the remaining part families are assigned to NC job shop. The NC job shop needs 5 vertical CNC machining centers, 4 horizontal CNC machining centers, and 4 CNC grinding machines with the first type of material handling system (truck 1), while the FMS needs 2 CNC turning machines, 2 vertical CNC machining centers, and 2 horizontal CNC machining centers

Table 3.4 A Mixed System Configuration Versus Individual Systems

System Configuration	MHS	Job Assignment								Machine Assignment								Total Annual Cost (106 dollar)	
		X1	X2	X3	X4	X5	X6	X7	X8	M1	M2	M3	M4	M5	M6	M7	M8		M9
Job Shop and FMS	Truck 1	1	0	1	0	0	0	1	1	6	6	2	6	3	-	-	-	-	1.899
	Cart	0	1	0	1	1	1	0	0	-	-	-	-	-	0	3	3	0	
Job Shop	Truck 2	1	1	1	1	1	1	1	1	6	11	6	10	8	-	-	-	-	1.954
FMS	AGVS	1	1	1	1	1	1	1	1	-	-	-	-	-	3	6	5	0	1.983
NC Job Shop	Truck 2	1	1	1	1	1	1	1	1	-	-	-	-	-	3	8	5	4	2.423



with the cart type of material handling system. The total annual manufacturing cost is \$2,566,000 dollars.

The first change studied is due to the variation of part family processing times in NC job shop. In the base case, the processing times at NC shop were assumed to be equal to that at FMS, and to be half of that at job shop. This may not always be true as the setup time at NC job shop, without palletized parts, may take longer than that at FMS. Assuming that the processing time in NC job shop is in the middle of that at job shop and FMS, the results are presented in Table 3.5. A greater number of part families (namely x1, x2, x5, x7), are now assigned to FMS while the rest are assigned to job shop. As a result more machines are allocated to FMS and a different MHS is selected to accommodate them.

In the base case, it was assumed that one operator handles two machines. If instead it is assumed that an operator can handle only one machine more part families are assigned to the FMS and while the remaining parts stay with NC job shop.

Next, consider variation in the cost of the MHS from the base case. In particular, the annual MHS cost, overhead cost and control system cost are doubled. In this case, all part families are assigned to NC job shop and the allocation of part families to FMS is no longer cost effective. If shop effi-

Table 3.5 System Selection at Various Operating Conditions

System Configuration	MHS	Job Assignment x1 x2 x3 x4 x5 x6 x7 x8	Machine Assignments Y1 Y2 Y3 Y4 Y5 Y6 Y7 Y8 Y9	Annual Manufacturing Cost (10 <sup>6</sup> Dollars)
<b>Base Case</b>				
NC Job Shop FMS	Truck 1 Cart	0 1 1 1 0 1 0 1	0 0 0 0 0 0 5 4 4 0 0 0 0 0 2 2 2 0	2.566
<b>50% Increase in Processing Times in NC Job Shop</b>				
Job Shop FMS	Truck 1 Conveyor	0 0 1 1 0 1 0 1 1 1 0 0 1 0 1 0	0 3 4 5 8 0 0 0 0 0 0 0 0 0 2 3 2 0	2.726
<b>One Operator Per Machine</b>				
NC Job Shop FMS	Truck 1 Conveyor	0 0 1 1 0 1 0 1 1 1 0 0 1 0 1 0	0 0 0 0 0 0 4 3 4 0 0 0 0 0 2 3 2 0	2.960
<b>Doubled MHS System Overhead and Control System Costs</b>				
NC Job Shop	Truck 1	1 1 1 1 1 1 1 1	0 0 0 0 0 3 8 5 4	2.691
<b>Decrease in the Efficiency Factor of Job Shops (from 50% to 40%)</b>				
NC Job Shop FMS	Truck 1 Conveyor	0 0 1 1 0 1 0 1 1 1 0 0 1 0 1 0	0 0 0 0 0 0 4 3 5 0 0 0 0 0 2 3 2 0	2.732
<b>Increase in NC Job Shop Efficiency Factor from 50% to 65% and Decrease in Number of Shifts (from two shifts to one shift)</b>				
NC Job Shop	Truck 1	1 1 1 1 1 1 1 1	0 0 0 0 0 5 13 8 7	3.653
<b>Increment in Inventory Cost</b>				
NC Job Shop FMS	Truck 1 Conveyor	0 0 1 1 0 1 0 1 1 1 0 0 1 0 1 0	0 0 0 0 0 0 4 3 4 0 0 0 0 0 2 3 2 0	2.848
<b>Increase in Demand and Inventory Cost and Decrease Initial Setup Cost</b>				
NC Job Shop FMS Transfer Line	Truck 1 Cart Special for Transfer Line	0 0 1 1 0 1 0 1 1 0 0 0 0 0 1 0 0 1 0 0 1 0 0 0	0 0 0 0 0 0 4 3 4 0 0 0 0 0 2 1 1 0 0 0 0 0 0 0 4 2 0	3.067

ciencies of job shop and NC job shop drop from 50% of the base case to 40% then, again, greater number of part families are assigned to FMS. However, if the NC job shop efficiency increase from 50 to 65% and the systems can only operate one shift then all part families are assigned to NC job shop.

The impact of the variation in inventory cost indicates that if inventory costs increase to 3 times the base case values, a greater number of part families are assigned to FMS. The rest of the part families remain assigned to NC job shop. However, if the inventory costs are doubled, costs for initial setup are reduced by half and demands for part family types 2 and 5 increase to 3 and 2 times, respectively, to their base case values then the best mix of systems selected consists of transfer line, NC job shop, and FMS. Part family types 2 and 5 are assigned to transfer line; part family types 1 and 7 are assigned to FMS and the rest are assigned to NC job shop.

For the next study consider three types of system configurations, namely job shop, NC job shop, and FMS of the base case and explore the conditions under which one system becomes better than the others. Only part family types 1, 2, 5, and 7 are considered for assignment so that all these part families are assignable to each individual system. The program is run for different values of labor costs, MHS related (in-

cluding MHS, control system, and system overhead) cost and system efficiency factors and the results are shown in Figures 3.1, 3.2, and 3.3.

Figure 3.1 depicts total cost of each system as a function of increment in labor cost. Job shop appears to be the one most sensitive to labor rate while FMS appears to be the least sensitive. FMS continues to cost the least in spite of increment in labor cost. However, when the labor cost is 12 dollars/hour or less, job shop appears to be better than NC job shop.

Figure 3.2 shows variation of total manufacturing cost with increase in the value of the system efficiency factor. Obviously total costs are extremely high when system efficiencies are low. They drop dramatically with increase in the value of the system efficiency factor. At lower efficiency values, FMS has the lowest production cost while job shop has the highest. At efficiency values near 0.6, total costs get relatively closer to each other. When the efficiency factor value is above 0.8 job shop appears more competitive and becomes the least cost alternative. Note that since system efficiency is only one of several system parameters considered in this model, the total cost does not drop proportionately to the efficiency factor.

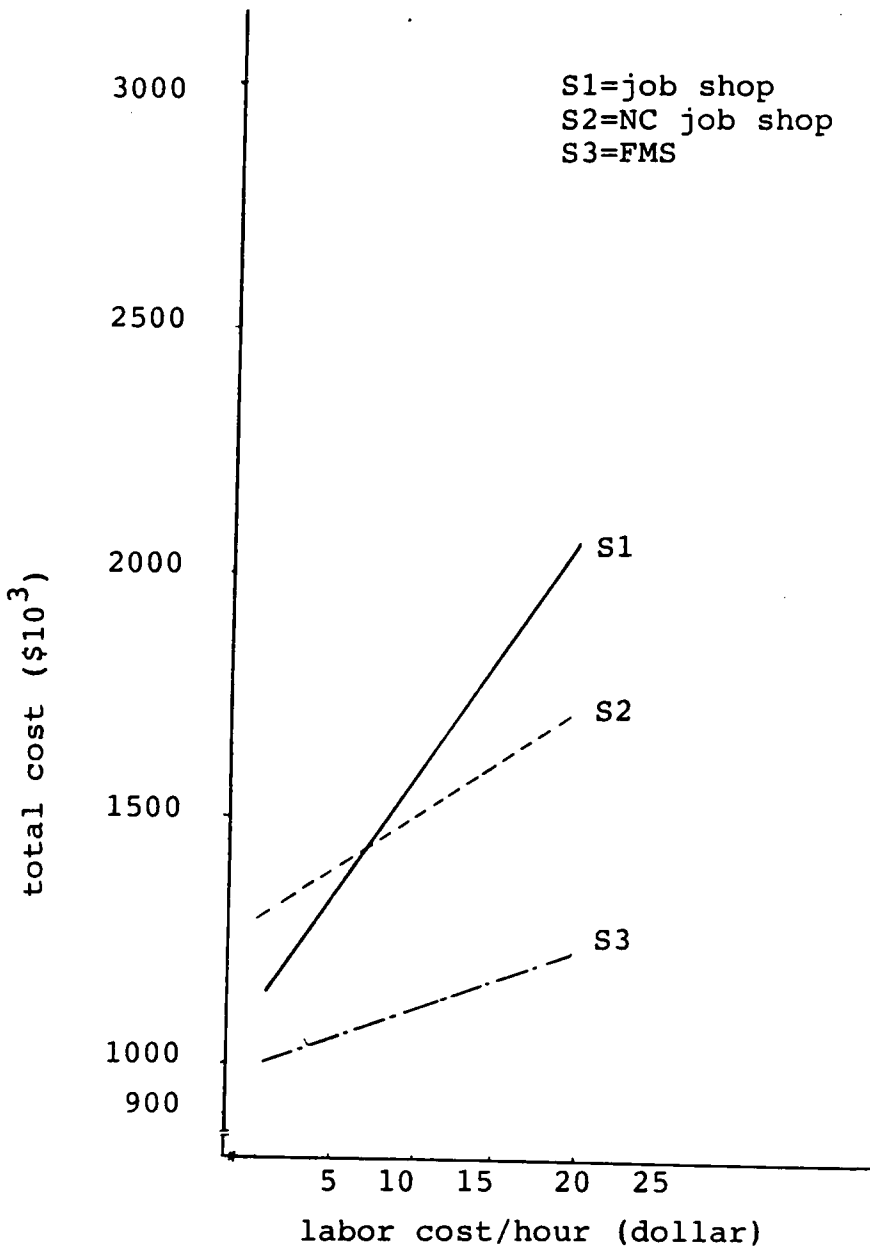


Figure 3.1 Total Cost Versus Labor Cost

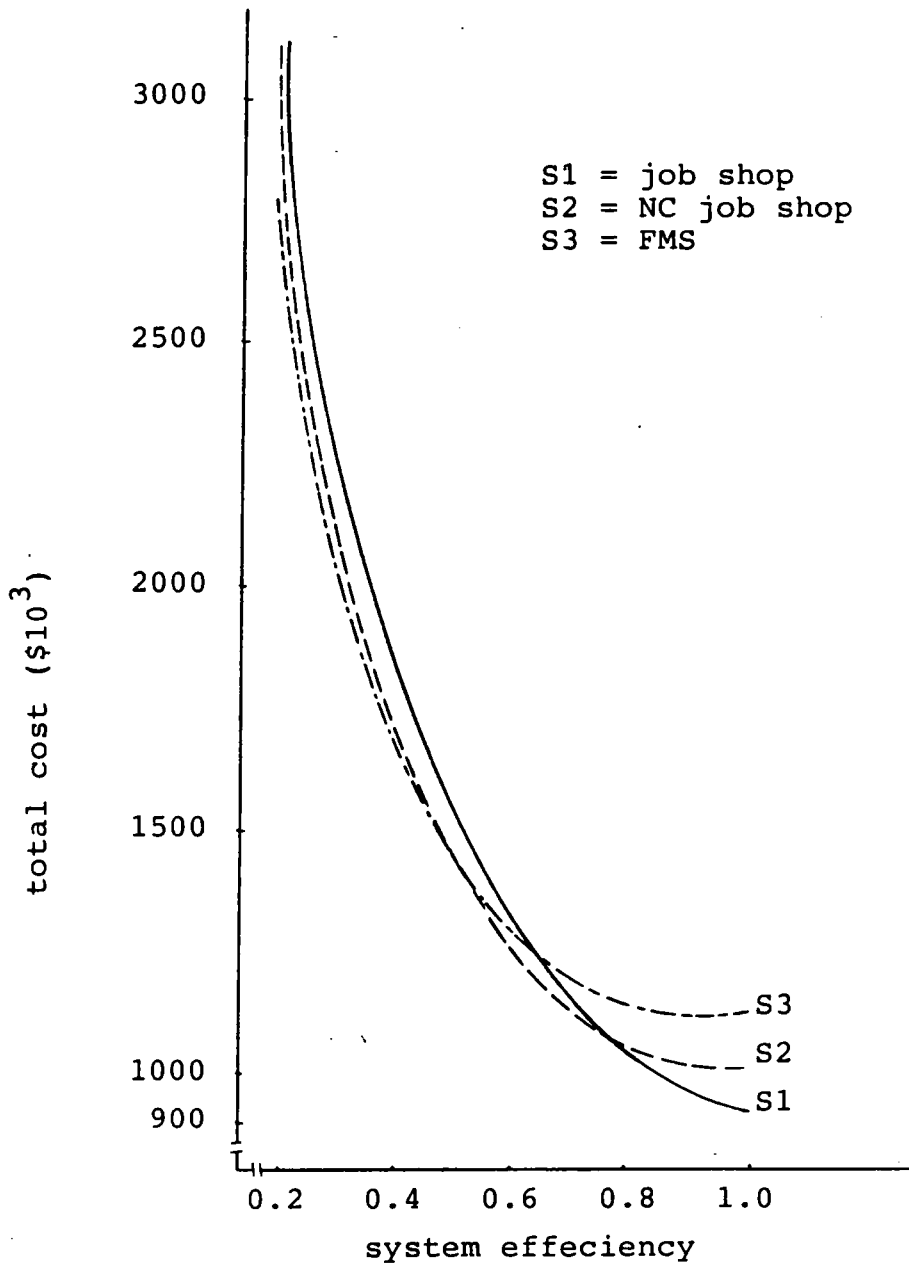


Figure 3.2 Total Cost Versus Efficiency Factor

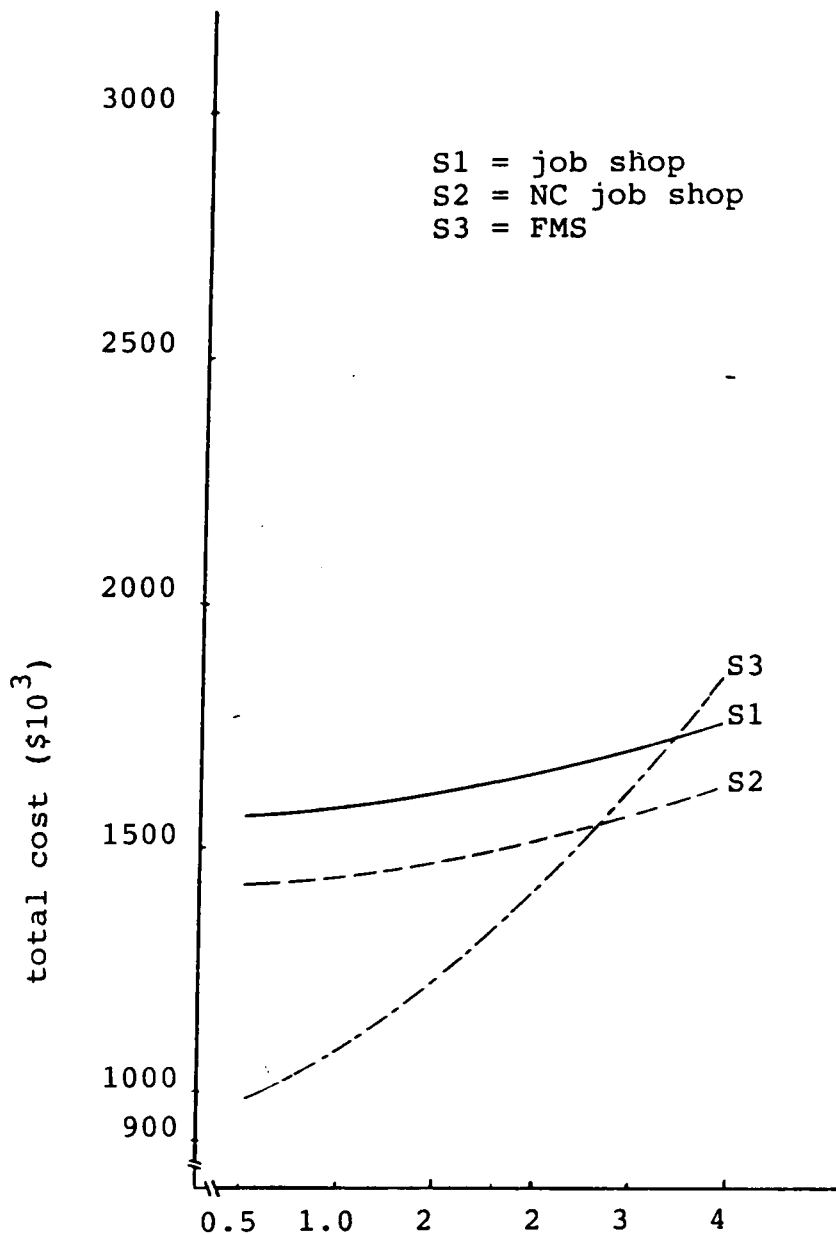


Figure 3.3 Total Cost Versus MHS & Control System Costs Expressed as Multiples of Base Value

Figure 3.3 depicts variation in total cost as a result of variation in MHS related costs. In the figure the base value of MHS related cost is represented by 1 and is varied as multiples of this value. FMS appears to be very sensitive in this regard compared to the other two systems because cost ratio for a MHS in the FMS is larger than in the other systems. At low MHS related costs, FMS is the best alternative, while NC job shop is a little better than the traditional job shop. When MHS related cost is increased three folds over the base value, NC job shop becomes the best alternative. For further increment of the MHS related cost the traditional job shop also becomes better than FMS.

### 3.9 SUMMARY

In this chapter an integer programming model was developed for selecting a mix of manufacturing systems to best suit management requirements. This model provides a practical approach and a precise tool for production system design, part assignments, machine selections, and material handling system selection. This model was used to show that a mixed system configuration can be better than one system alone to meet the desired production requirements. The system selection problem is also studied under various operating conditions and the superiority of one system over the others is demonstrated under these conditions.



## 4.0 MATHEMATICAL DEVELOPMENT OF THE LOADING MODELS

In this chapter we discuss the shop loading and the machine loading problems. The shop loading problem can also be designated as the capacity planning problem. Mathematical models are developed for the analysis of both of these problems. Computational experience with these models is presented. Sensitivity analysis is then carried out to further understand the system behavior.

### 4.1 DEVELOPMENT OF THE SHOP LOADING MODEL

#### 4.1.1 CAPACITY PLANNING

In production planning, two fundamental functions are performed in parallel: material requirement planning and capacity planning. Material requirement planning (MRP) converts the master schedule for end products into a detailed schedule for raw materials and components used in the end products. It identifies the amount, due date, and delivery dates of each item in order to meet master schedule of final products. It is a major input to production scheduling and material purchasing functions.

Capacity planning, on the other hand, is concerned with determining the labor and equipment resources needed to meet the production schedule. A master schedule can not exceed the plant capacity which is defined as the maximum output rate that a plant can achieve under a given set of assumed operating conditions. The assumed conditions may include the number of shifts, number of working days per week, employment levels, and overtime. When the output units of a plant are nonhomogenous, input units may be a better measure of plant capacity; a job shop, for example, may use labor hours or available machine hours to measure plant capacity. The available plant capacity is used to check the master schedule to make sure that it can be realized. If not, either the schedule or the plant capacity must be adjusted to balance them.

Typically, capacity planning is performed in terms of labor and/or machine hours available. The capacity adjustments can be accomplished in either the short-term or long-term strategies. The short-term adjustments would include decisions on the factors of employment levels, number of work shifts, labor overtime hours, inventory stock piling, order backlogs, or subcontracting while the long-term capacity requirements would include decisions on new machines, setting up of new plants, purchasing of existing plants, closing down or sell-

ing of existing facilities which will not be needed in the future.

#### 4.1.2 SHOP LOADING PROBLEM

Shop loading is related to the short-term capacity planning problem. It occurs when there are more than one production system available to perform a set of parts, no one system can handle all the parts, and/or no one system appears superior to the others to perform those parts. The objective is to finish all the parts within a specified time period and to incur the least manufacturing cost. More specifically, the problem is to assign each of the parts to one of the systems so that the parts can be finished within the planning horizon, while minimizing the overall costs.

The shop loading problem is considered at the beginning of each planning period. At this stage, the in-coming parts are usually grouped into families by their manufacturing processes. The machines in each system are also pooled by their major functions, such as milling, turning, drilling, etc. so that the problem could be simplified and reduced to a practical and manageable size, and setup time, lead time, and other costs could be reduced. The machining requirements are expressed by each part family instead of by individual part. The setup time and machining times are estimated at part

family level for each machine type in each system. Manufacturing costs are then estimated accordingly. Specific routings of each part are not taken into account at this stage. They are left for the next level of production planning. An efficiency factor is adopted to handle these routing and system congestion effects as well as effects due to machine breakdown, tool/material availability, machine idleness, operator absenteeism, etc. Although each system faces similar problems, they still differ in the level of utilization. The efficiency factors can be obtained from historical data or through system simulation. The determination of efficiency factor is discussed in Chapter 5. For this model, it is assumed to be known and given for each system as a parameter to calculate the upper resource limits.

For this analysis, the manufacturing requirements are dictated by MRP and are assumed to be known. The due dates of the parts are assumed to be the end of the planning period. The processing time, the setup time, and the utility needs for each part are different for different manufacturing systems, thereby resulting in different manufacturing costs for each part and system combination. These differences are due to the differences in production efficiency of systems and system-part compatibilities. Each system may have been designed to satisfy special needs. The system, however, can not be reserved only for those pre-determined part types or

most beneficial groups of parts, because in that case the systems would be underutilized as demand fluctuates.

The production systems in consideration could be any types of identifiable production units such as job shop, flow shop, FMS, etc. Second shift of a system can be treated as another system because of different unit cost. Subcontracting work can also be treated as a production system with corresponding purchasing costs and unlimited capacity.

#### 4.1.3 DIFFERENCES BETWEEN SYSTEMS

Before the shop loading model is actually developed, an example is given here to illustrate how systems differ in their functions and performances. Assume that a set of identical machine tools are arranged into two systems: (1) job shop and (2) FMS. The major differences between these two systems are due to MHS, part palletization, and central computer control system.

The material handling system of an FMS provides random and independent movements of workpieces between machine tools in the system. The carts (or conveyors) are ready to move the parts to their next destinations for which decisions are already made. Therefore, it reduces both part idle time and machine blocking time. Furthermore, the handling speed is

greater for this system than that for the other part transportation systems and the material handling system is more reliable thereby reducing delays and congestion effects. Because all the parts in an FMS are palletized, the direct setup time is considerably reduced.

The setup of work at each workstation involves two phases: (1) adjustment of the workholding fixture and (2) preparation of the raw material required for processing at that workstation. The workpieces on FMS are fixed on standard pallets and transported from station to station. At each station, a transport mechanism (e.g. shuttle) transfers the pallet and the part automatically between the material handling system and the work station. The transport mechanism automatically locates and orients the part at each workstation for processing so that the handling time, the setup time, and the readjustment time for a part are considerably reduced. As a result, the lead time is reduced, the mean flow time of a part is shortened, and the machine utilization (machine time in cut) is increased because it takes less time to stop a machine for direct setup. As the parts spend a relatively shorter length of time in an FMS, the in-process inventory is significantly lower than their corresponding levels in a job shop. The central computer control system provides FMS with dynamic system controllability (i.e. the ability to randomly launch parts into the system and to reroute them),

which can easily adjust to the changes in production schedules which further reduces in-process inventory. Because of the above features an FMS is preferable to job shop with respect to the criteria of part flow time, part tardiness, work-in-process inventory, production rate, and machine utilization.

It has been reported (Barash,1980, Dwivedi,1983, Merchant,1983) that an FMS is better than a system consisting of an identical set of stand-alone NC machines for medium volume production. The proportion of machine time in-cut is reported to be 80% for FMS vs. 45% for stand-alone NC machines. Similarly, significant differences of production cycle times and lead times are also reported for these systems. For the cases of extremely low demand quantity and very high part variety, an FMS may suffer from limited tool slots, tool settings, pallet types, and would be less attractive.

When the production systems are different in their components, however, the system selection is not so obvious. The situation is further complicated by the fact that manufacturing costs are different in different systems because of particular part characteristics, system features, loading conditions and the amount of money invested in them.

#### 4.1.4 SHOP LOADING PROCEDURE

For shop loading, parts are first grouped by their manufacturing attributes, such as major manufacturing processes, major dimensions, length/dimension ratio, surface finish, operation sequence, machine tool requirement, due date, processing time, batch size, demand rate, fixtures needed, cutting tools, or a combination of the above. For production purposes, manufacturing processes and operation sequences are usually selected to be the primary grouping criteria for FMS because of their impact on cutting tools and fixtures requirement and effort required in changing tools. The part setup times and material handling requirements are typically selected as criteria for job shop. The main steps of a shop loading procedure are as follows:

1. screen out those parts which can be assigned to only one system
2. group parts according to their manufacturing processes
3. pool machines into groups by their major functions
4. estimate setup time and machining time for each machine type in each system for each part family
5. calculate cost of manufacturing each part family in each system
6. assign parts to systems by applying the shop loading model.



Next, we describe the development of the mathematical model used in step 6.

#### 4.1.5 DEVELOPMENT OF THE MODEL

There are the three types of parameters needed for this model and they are classified as: part-related, cost-related, and system efficiency-related . The part-related parameters pertain to the processing times (or resource consumption) requirements for each part family in each system. It is assumed that the production needs of each part family are known at the planning stage so that the resource consumptions of each part family can be estimated for each system. Consequently, the production cost incurred for each part family can also be estimated in advance. The cost-related parameters include direct manufacturing cost and fixed costs. Direct manufacturing cost includes material cost and operation cost, which is in turn a function of the handling, machining, and the assembly operations of the parts, and the tool changing, and the tool costs. The costs corresponding to maintenance, heat, light, power, engineering support, depreciation, QC personnel, are assumed fixed and are classified as fixed costs. These costs are constant, and are independent of the level of operation of a system. However, no such costs are incurred for a system if it is not in operation. For more information about manufacturing costs and their estimation,

the reader is referred to Ostwald(1984), Malstrom(1981), and Malstrom(1984).

The following assumptions are made in the development of the model:

1. all parts are available at the beginning of each planning period.
2. each part family can be assigned to one of several production systems.
3. all parts of a family should be performed together on only one system. no splitting of part families and transfer between systems is allowed.
4. each part family must be completed within the planning period.
5. manufacturing needs and costs of all part families are known at each system.
6. manufacturing needs and costs of each part family is calculated based on the most cost-effective machine.
7. the result and product quality is assumed to be identical, regardless of which system the part family is assigned to.

The proposed model consists of two sets of decision variables. The first set of variables pertains to the assignment of part families to various systems. A part family may not

be assigned to a system if it can not perform all the operations required by the part family. The second set of variables pertains to the decision regarding the selection of a system for operation in the planning period. There are the following constraints that must be satisfied:

1. resource constraints

The availability of each machine type in each system is estimated by the available machining time. The total resource availability is therefore determined by multiplying the length of the planning period and the number of machines in that system. The constraints to ensure that each machine type in each system is not overloaded, are as follows:

$$\sum_i u_{ikn} \cdot x_{in} \leq T \cdot m_{kn} \cdot y_n \quad \text{for all } k \text{ and } n$$

where

- i = part number
- k = machine number
- n = system number
- u<sub>ikn</sub> = the operation time on machine type k in system n for processing part i, if assigned
- m<sub>kn</sub> = number of machines type k at system n
- x<sub>in</sub> = 1, if part i is assigned to system n  
0, otherwise
- y<sub>n</sub> = 1, if system n is selected for production  
0, otherwise

$T$  = nominal available machining time per machine over the planning period

The operation time accounts for all the machining time needed by a part including direct setup, machining, and on-machine inspection.

## 2. part assignment constraints

A part can be assigned only to one system.

$$\sum_n x_{in} = 1 \quad \text{for all } i$$

If a part can be done only by one system, the problem is modelled accordingly.

## 3. system efficiency constraints

A system efficiency factor is used to account for system's machine non-productive time, such as machine breakdown, system congestion, etc. so that realistic estimates of available resources are actually used for assigning parts. Accordingly, the constraints are as follows:

$$\sum_i \sum_k u_{ikn} \cdot x_{in} \leq T \cdot \left( \sum_k m_{kn} \right) \cdot e_n \quad \text{for all } n$$

where

$e_n$  = the efficiency factor for system n

Note that the efficiency factor,  $e_n$ , is assumed here for a system as a whole, rather than for each individual machine type because of the fact that some machines may be fully loaded and operated all the time while other machines often stay idle or breakdown more often. If this is the case, imposing the same factor on each machine will actually hinder the utilization of efficient machines in this system. Also, note that the variables  $y_n$ 's are omitted in the above set of constraints. It is possible to do so because the first set of constraints (the resource constraints) are more restrictive. They ensure that no part will be assigned to a system if it is not in operation.

The objective for the shop loading problem is to minimize the overall manufacturing and purchasing costs. This can be expressed as:

$$\text{minimize: } Z = \sum_i \sum_n c_{in} \cdot x_{in} + \sum_n f_n \cdot y_n$$

where

$c_{in}$  = the cost for part family i if produced in system n

$f_n$  = the fixed cost for system  $n$ , if it is in operation.

The manufacturing cost for each part family is either the direct manufacturing cost when manufactured in plant, or the direct purchasing cost if purchased from a vendor. The shop loading model can now be summarized as follows:

$$\text{minimize } Z = \sum_i \sum_n c_{in} \cdot x_{in} + \sum_n f_n \cdot y_n$$

subject to

$$\sum_i u_{ikn} \cdot x_{in} \leq T_{kn} \cdot y_n \quad \text{for all } k \text{ and } n$$

$$\sum_n x_{in} = 1 \quad \text{for all } i$$

$$\sum_i \sum_k u_{ikn} \cdot x_{in} \leq T_n \cdot \left( \sum_k m_{kn} \right) \cdot e_n \quad \text{for all } n$$

$$x_{in} = 0 \text{ or } 1 \quad \text{for all } i \text{ and } n$$

$$y_n = 0 \text{ or } 1 \quad \text{for all } n.$$

#### 4.1.6 SOLUTION OF THE SHOP LOADING MODEL

The shop loading problem has been formulated as a pure integer linear programming model, involving decision variables for part assignments and system selections. Both sets of variables are binary types of integer variables and are relatively small in size; so fairly large problems can be solved within a reasonable computation time. Therefore it is a practical approach to solve shop loading problems involving large number of parts.

The IBM MPSX-MIP/370 package is used to solve the example problem for this study. The description of the IBM package is given in Appendix A.

#### 4.1.7 THE EXAMPLE PROBLEM AND COMPUTATIONAL EXPERIENCE

Next, we present an example problem to demonstrate the applicability of the shop loading model. For this example problem, five systems are assumed available for part assignments. They are traditional job shop, the second shift of job shop, NC job shop, FMS, and subcontracting.

The planning period is assumed to be of one month duration with 4 weeks in a month and 5 working days per week. The number of machines of each type in each system is given in

Table 4.1. Assuming that each machine can operate 8 hours a shift, the available resources are also given in Table 4.1. Note that the system efficiency factor is assumed equal to 1 for each system to simplify the example. But this assumption will be relaxed later when we consider variations of this problem.

The unit of time used in Table 4.1 is 20 hours; therefore, for example, 800 machine hours of type one machine are available at system S1. There is no limit on the amount of work that can be subcontracted.

On the other hand, there are 15 part types to be assigned. All parts can be manufactured at systems S1 and S2, or can be subcontracted. But the part types 2, 6, and 15 can not be assigned to NC job shop and FMS, and part types 7, 11, 13 are incompatible with FMS. The manufacturing costs and resource consumptions of each part at each system are given in Table 4.2. One unit of processing time is equal to 20 machine hours. It is assumed that the processing time and cost are smaller at FMS than at NC job shop, which in turn is superior to the traditional job shop in costs and efficiency. The job shop overtime system is superior only to subcontracting. For example, part type 1 takes 280 hours on machine type 1, 60 hours on machine type 2, 260 hours on machine type 3, and costs 30 dollars if it is assigned to system 1, while it takes 40 hours on machine type 1, 140 hours on machine type 2, 120



Table 4.1 Available Resources and Fixed Cost of Each System in The Planning Period

item	system	S1	S2	S3	S4	S5
number of machine of each type in each system	M1	5	5	3	3	*
	M2	5	5	3	4	*
	M3	5	5	3	2	*
	M4	5	5	3	3	*
available machine time of each type in each system (1 unit=20 hours)	M1	40	40	24	24	*
	M2	40	40	24	32	*
	M3	40	40	24	16	*
	M4	40	40	24	24	*
fixed cost of each system (dollar)		10	20	15	30	2
* = infinite						

hours on machine type 3 at FMS, and costs 20 dollars. Nevertheless, these parameters do not have to remain in this fashion. Whatever their actual values are, the model should be able to generate an optimal solution.

The model for this example problem contains 71 binary integer variables and 32 linear constraints. It was solved using the MPSX-MIP/370 package on a IBM/370 computer and took less than a minutes of CPU time. In addition to this example, several similar runs were also performed to demonstrate the sensitivity of the model and to investigate the changes in decisions as a result of variations in parameter values. The results are summarized in Table 4.3.

The first run is made using the data given above and is designated as the base case. It shows that part types 4 and 6 are assigned to system S2; part types 7, 12, 13 are assigned to system S3, part types 1, 3, 5, and 14 are assigned to system S4, and the rest of the parts are assigned to system S1; no part is subcontracted. The optimal cost is \$508 dollars. The second run assumes that the 2nd shift of the job shop can operate only at half the capacity. Then part types 4 and 6 are switched to system S1, while part type 2 is assigned to system S2 and part type 8 is now assigned to system S3. The rest of parts and cost remain unchanged. That is, under the current demands the cost will not increase even if

Table 4.2 Mfg. Costs and Processing Time Requirements of Part Families on Machines in Each System

Job Number Item		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mfg. cost of part in system: (dollar)	S1	30	54	37	18	61	41	25	19	13	22	14	34	28	46	26
	S2	35	59	42	23	56	46	30	24	18	27	19	39	33	51	31
	S3	25	0	32	25	56	0	20	24	19	29	17	30	32	43	0
	S4	20	0	27	22	51	0	0	21	24	26	0	26	0	36	0
	S5	55	79	62	43	76	66	50	44	38	47	39	59	53	72	51
Proc. time req't of parts on machines in S1(1 uni =20 hrs.	M1	14	20	17	2	11	21	3	7	3	5	0	3	0	10	3
	M2	3	14	10	4	15	0	11	4	6	0	10	4	12	10	3
	M3	13	14	0	2	25	10	6	2	3	5	4	12	4	10	12
	M4	0	6	10	10	10	10	5	6	0	12	0	15	12	16	8
Proc. time req't of parts on machines in S2	M1	14	20	17	2	11	21	3	7	3	5	0	3	0	10	3
	M2	3	14	10	4	15	0	11	4	6	0	10	4	12	10	3
	M3	13	14	0	2	25	10	6	2	3	5	4	12	4	10	12
	M4	0	6	10	10	10	10	5	6	0	12	0	15	12	16	8
Proc. time req't of parts on machines in S3	M1	5	-	7	1	10	-	4	6	2	10	0	0	3	10	-
	M2	4	-	3	3	5	-	4	1	4	0	6	5	6	5	-
	M3	5	-	7	2	0	-	4	5	0	4	4	7	2	0	-
	M4	6	-	7	6	5	-	4	0	4	0	0	12	7	15	-
Proc. time req't of parts on machines in S4	M1	2	-	4	0	7	-	-	2	2	0	-	6	-	10	-
	M2	7	-	7	5	6	-	-	4	4	4	-	4	-	2	-
	M3	6	-	5	2	0	-	-	3	0	2	-	4	-	4	-
	M4	0	-	4	3	3	-	-	0	0	5	-	6	-	8	-

the available capacity of the second system decreases by  $1/2$ . If one of the third type of machines in the FMS breaks down, the difference from the base case is that part types 1 and 3 are now assigned to system S3, which was previously underloaded, and the cost increases to \$514. This is shown as the third run in the table. The fourth run depicts the results under the conditions that both of the third type of FMS machines are out of order. No part is assigned in this case to FMS and part type 5 is subcontracted.

In the fifth run the processing times of parts are doubled. In this case part types 2, 6, 10, 13, and 14 are subcontracted, part types 1, 4, and 9 are assigned to system S2, part types 11 and 12 are assigned to NC job shop, part types 3 and 5 are assigned to FMS and the rest are assigned to job shop. The optimal cost is \$665. If the processing times remain doubled and the second system can operate only at half the capacity, then the second system can manufacture only the fourth part type, the 3rd system produces part types 3 and 7, the FMS produces part types 1 and 5, while the job shop and subcontracting share the rest of the parts. As shown in the seventh run, if one of the third machine types at FMS breaks down and the second system can operate at only half its capacity, subcontracting is still not needed. But if, in addition, the processing time doubles and the fixed costs increase as above, then (refer to the last run) most parts

Table 4.3 Assignments of Part Families to System Under Various Conditions

Run No.	Systems chosen	Part Family															Mfg. cost
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
1	S1		1					1	1	1	1					1	508
	S2				1	1											
	S3						1					1	1				
	S4	1	1		1										1		
2	S1				1	1		1	1	1						1	508
	S2		1														
	S3						1	1				1	1				
	S4	1	1		1										1		
3	S1		1					1	1	1						1	514
	S2				1	1											
	S3	1	1				1						1				
	S4					1		1				1		1			
4	S1	1			1	1		1		1			1				543
	S2		1					1						1	1		
	S3			1				1		1		1					
	S5					1											
5	S1						1	1								1	665
	S2	1			1				1								
	S3										1	1					
	S4			1		1											
5	S5		1			1				1			1	1			
	S1							1	1	1	1						671
	S2				1												
	S3			1				1									
S4	1				1												
5	S5		1			1						1	1	1	1		
	S1							1	1	1	1						528
	S2		1									1					
	S3	1		1				1			1		1				
S4				1	1				1					1			
8	S1							1	1	1	1						759
	S3	1						1									
	S5		1	1	1	1	1						1	1	1	1	

are subcontracted and the second shift and FMS are not used. The optimal cost increases to \$759.

These computational runs indicate that the best mix of production systems required to meet production requirements for a planning period is different for different operating conditions and production demands. One mix of production systems may not be cost effective always. Also it may not be the best policy to maximize the utilization of only one production system. One ought to look at all available production systems and then choose the best mix, which may, in fact, result in the selection of only one system.

## 4.2 MACHINE LOADING AND TOOL ALLOCATION MODEL DEVELOPMENT

### 4.2.1 MACHINE LOADING PROBLEM

The machine loading and tool allocation problem is the lowest level of production planning problem. The loading can be done weekly, daily, or during each shift. Usually the loading decisions are made by the system manager. At this stage, the parts to be processed, due dates, available tools, fixtures, pallets, machine types and number, and other system and part characteristics are all known to the decision maker. The problem is to load the parts and the tools to the workstations. Specifically the problem is to assign every opera-

tion of the parts and the needed tools to each workstation. Once these decisions are made, the tools stay with the assigned machine tool for the planning period. The parts are then routed through the machine stations where the needed tooling and NC programs are already loaded.

Two types of direct costs are incurred as a result of assigning tools to machines: (1) the cost due to cutting tool wear and tear, and (2) the cost due to machine usage. Typically, these costs depend upon the tool-machine combination. Some machine and tool combinations are more efficient for some types of parts than for others. However, the availability of machine tools and cutting tool types are usually limited and it is not possible to assign parts to the most efficient machines and tools, and a compromise between cost efficiency and machine utilization has to be made.

As in the previous models, the real time operation decision making capabilities are not considered directly in this model. The problems like machine breakdowns, cutting tool failures, machine blocking, etc. are left for the real-time operational control stage. Instead an efficiency factor is used to capture their aggregate impact on system availability. As mentioned in the previous section, this factor is different from machine to machine and from system to system. Its value is dictated by the system and part characteristics,

control strategies applied to the system, loading level, system reliability, and their interactions.

#### 4.2.2 DEVELOPMENT OF THE MODEL

The input to the model includes estimates of tool life, operation time, number of tool slots, efficiency factor, resource availability, and associated costs. The estimates of tool life are used to determine when a tool ought to be unloaded, checked, and resharped before using for more machining. Tool life estimates can be different for different machines because of different cutting speed and feed used at different machines. The estimates of operation time include machining time and setup time. It is assumed that an operation may need different operation times at different machines, even for the same tool. Each workstation is equipped with a tool drum which provides a fixed number of tool slots. Due to its size and weight, a tool may occupy several slots of a tool magazine in order to accommodate the tool and to balance the tool drum.

The cost is estimated based on tool wear and tear and machine usage (Groover, 1980, Whitney and Suri, 1984). Other costs such as material handling and power consumption costs are not considered. Additional input information for this model is the operation-tool and tool-machine compatibility, which in-



icates the tools that can be used to perform an operation of a part and the machines that a tool can be assigned to.

The following assumptions are made for the development of the machine loading and tool allocation model:

1. all parts are available at the start of the planning period.
2. batching is not necessary.
3. all parts must be finished within the planning period.
4. each operation of a part can be performed at least by one cutting tool on one machine but one operation is assigned only to one tool and performed on only one machine.
5. the number of pallets and their types are assumed to be sufficient.
6. processing times and costs are known for every operation of all parts.

There are two types of decision variables. One indicates the assignment of an operation of a part to a machine and the other indicates the allocation of a tool to a machine. No alternate tool or routing considerations are included in this formulation. Specific constraints and requirements are as follows:

1. machine resource limits

The availability of a machine is expressed as the available machining time of that machine. In order that the machine usage does not exceed its availability we have:

$$\sum_i \sum_j \sum_t u_{ijtk} \cdot x_{ijtk} \leq e_k \cdot T_k \quad \text{for all } k$$

where

- i = part number
- j = operation number of a part
- t = tool number
- k = machine number
  
- $u_{ijtk}$  = processing time of operation j of part i using tool t at machine k
- $x_{ijtk}$  = 1, if operation j of part i is assigned to machine k with tool t  
0, otherwise
  
- $T_k$  = available machining time of machine k
  
- $e_k$  = upper utilization limit of machine k. it is assumed to be 100% availability at this planning stage.

## 2. tool life constraints.

The tool life constraints here simply state that the parts assigned to a tool can not exceed its tool life. They are expressed as:

$$\sum_i \sum_j \sum_k u_{ijtk} \cdot x_{ijtk} \leq (TL)_t \quad \text{for all } t$$

where

$(TL)_t$  = the tool life limit for tool  $t$ .

### 3. tool assignment constraints

Each tool is given a number and each tool number can be assigned to only one machine. If there are several tools of the same type, each is given a different number and treated separately. Therefore it is possible that more than one machine can be installed with the same type of tool, which alters system to have the potential of rerouting or have alternative routings for real-time operational control. These constraints can be expressed as:

$$\sum_i \sum_j x_{ijtk} \leq M \cdot y_{tk} \quad \text{for all } t \text{ and } k$$

$$\sum_k y_{tk} = 1 \quad \text{for all } t.$$

where

$y_{tk} = \begin{cases} 1, & \text{if an operation of a part is assigned} \\ & \text{to machine } k \text{ using tool } t \\ 0, & \text{otherwise} \end{cases}$

$M =$  a big number, indicating an upper limit on the number of operations that can be assigned to a tool. This can be tool dependent and can be set at a reasonable value depending upon the number of candidate operations for that tool in a given problem situation.

#### 4. tool magazine constraints

The capacity of each tool magazine is limited. Typically, some tools are bigger and heavier and, therefore, need more tool slots than the others. We assume here that the tool magazine is unchangeable and is fixed to the workstation. The slot constraints are expressed as:

$$\sum_t s_t y_{tk} \leq TS_k \quad \text{for all } k$$

where

$TS_k$  = the limit on tool slot at machine  $k$

$s_k$  = number of tool slots needed for tool  $t$ .

#### 5. operation assignment constraints

Each operation is assigned to only one machine. This limits the part flexibility, but saves tool slots and therefore increases machine utilizations. If system is reliable and congestion is minimal, this would result in better system performance. The corresponding constraints are:

$$\sum_t \sum_k x_{ijtk} = 1 \quad \text{for all } i \text{ and } j.$$

These constraints can, however, be easily relaxed to allow alternate routings for each part by simply changing the RHS to equal to the number of desired alternate routings.

#### 6. system efficiency constraint

An efficiency factor,  $e$ , is imposed on the system to account for machine breakdown, system congestion, etc. It should be of sufficient value to cover the loss of machining time but should not be so large that the system is underutilized. The values of these factors can be obtained from experience or they can be estimated using simulation. The constraint is as follows:

$$\sum_i \sum_j \sum_t \sum_k T_{ijtk} \cdot x_{ijtk} \leq e \cdot \sum_k R_k$$

#### 7. Binary integer constraints

Each operation and tool is assigned to exactly one machine; therefore the values of these variables must be either one or zero. No fractional values are allowed. Therefore,

$$x_{ijtk} = 0 \text{ or } 1 \quad \text{for all } i, j, t, \text{ and } k$$

$$y_{tk} = 0 \text{ or } 1 \quad \text{for all } t \text{ and } k.$$

The objective of this loading model, as discussed previously, is to minimize the total processing costs corresponding to cutting tools and machine usages. If  $c_{ijtk}$  = machining cost incurred by operation  $j$  of part  $i$  using tool  $t$  on machine  $k$ , then the mathematical model (IM3) can be summarized as follows:

$$\text{Minimize } Z = \sum_i \sum_j \sum_t \sum_k c_{ijtk} \cdot x_{ijtk}$$

subject to

$$\sum_i \sum_j \sum_k u_{ijtk} \cdot x_{ijtk} \leq (TL)_t \quad \text{for all } t \quad (1)$$

$$\sum_i \sum_j \sum_t u_{ijtk} \cdot x_{ijtk} \leq e_k \cdot T_k \quad \text{for all } k \quad (2)$$

$$\sum_i \sum_j \sum_t \sum_k u_{ijtk} \cdot x_{ijtk} \leq e \cdot \sum_k T_k \quad (3)$$

$$\sum_i \sum_j x_{ijtk} \leq M \cdot y_{tk} \quad \text{for all } t \text{ and } k \quad (4)$$

$$\sum_k y_{tk} = 1 \quad \text{for all } t \quad (5)$$

$$\sum_t s_t \cdot y_{tk} \leq (TS)_k \quad \text{for all } k \quad (6)$$

$$\sum_t \sum_k x_{ijtk} = 1 \quad \text{for all } i \text{ and } j \quad (7)$$

$$x_{ijtk} = 0 \text{ or } 1 \quad \text{for all } i, j, t, k \quad (8)$$

$$y_{tk} = 0 \text{ or } 1 \quad \text{for all } t \text{ and } k \quad (9)$$

#### 4.2.3 THE EXAMPLE PROBLEM AND THE COMPUTATIONAL RESULTS

The machine loading and tool allocation problem has been formulated as a pure integer linear programming model, consisting of only binary integer variables. In an FMS, the number of work stations is fairly small, usually between 4 to 10 machines. The number of part types are also very limited in this planning period. But, the number of operations and tools can be so large that the model becomes unsolvable within a reasonable computation time. A small problem, for example, of 4 parts, 4 machines, 10 operations, and 200 available tools, needs 32,000 zero-one integer variables, which is quite large for all known integer programming packages. Fortunately, because of the nature of the problem, many tool and operation, and tool and machine are not compatible with each other; and therefore they do not have to be incor-

porated in this model. This reduces the size of the model tremendously and facilitates the input and execution process. Furthermore, many operations of similar type can be grouped together to form a larger operation, which is then assigned to one machine as a unit and so can the similar tools. For example, drilling operations and reaming can be grouped together and similarly drills of different sizes can also be grouped together because of their similarity in order to simplify the solution process. At the planning level, operation grouping is considered reasonable and practical for real applications (Mayer and Talavage, 1976). This further reduces the size of the problem and makes the model manageable.

Nevertheless, this model is still too big to be solved manually because of the number of variables and constraints in spite of its special structure. Fortunately, since all the variables are binary, it needs relatively less computer working storage space and execution time, so most of available integer programming packages should be able to solve this problem of a practical size. For this research, though, the IBM MPSX-MIP/370 is used to solve the example problem.

The example problem consists of four parts, each with 4 operations. There are 4 machines in the FMS; each machine has a tool drum with a capacity of 60 tool slots. In addition,



20 types of tools are available for processing parts. These are designated as 1, 2, 3, ..., 19, and 20; each representing a set of tools. The operation-tool and tool-machine compatibility are specified in Table 4.4. For example, operation 3 of part 2 can be machined by tool type 10 and 17, and tool type 10 can be assigned to machine 1 or 2. The number of slots needed by each tool set is also given in Table 4.4. The tool type 10, for example, needs 11 tool slots.

The operation times and the associated machining costs are shown in Table 4.5, which specifies the processing time and cost for each operation of each part on each machine using a different tool. The operation 3 of part 2, for example, need 66 minutes of operation time on the second workstation, if using the tenth type of tool, and it costs \$39 if operation 2 of part 4 is assigned to machine 2 containing tool type 20. All these operation times, the associated costs, and the compatibilities are arbitrarily assigned so that the model will exhibit its adaptability to all kinds of input fluctuations.

The model for this example problem contains 1240 integer variables and 145 constraints, but by deleting infeasible operation-tool and tool-machine combinations, the model can be tightened containing only 78 binary integer variables with 95 constraints. As a result, the tightened model with reduced number of variables and number of constraints larger

Table 4.4 Tool-operation and Tool-machine Comptability

Item/Tool Set No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Tool-operation Compatibility of part 1 on operation:	OP1	1	1																	
	OP2			1			1													
	OP3					1				1			1							
	OP4										1			1						
Tool-operation compatibility of part 2 on operation:	OP1	1		1																
	OP2							1								1				
	OP3									1							1			
	OP4			1								1						1		
Tool-operation compatibility of part 3 on operation:	OP1											1			1					
	OP2								1									1		
	OP3										1								1	
	OP4			1										1						1
Tool-operation compatibility of part 4 on operation:	OP1		1		1															
	OP2					1														1
	OP3						1						1	1						
	OP4						1	1												
Tool-machine compatibility for machine	M1	1		1		1		1			1		1			1				
	M2	1		1	1	1	1			1		1		1					1	1
	M3		1		1	1		1	1		1		1					1		
	M4					1			1		1		1		1				1	
Required tool slots for each tool set	10	14	8	12	13	6	5	18	12	11	4	13	12	15	4	4	5	5	5	4



than the number of variables makes the problem easier to converge to an optimum, saving computation times and computer working storage space. Seven runs were made and all these example problems were solved within half a minute of CPU time on an IBM/370 computer. The results are summarized in Tables 4.6 and 4.7.

The first run is the base case, which takes on all the input data as described in the example problem. Then by changing some input parameters, additional runs were performed for comparison with the base case to demonstrate the sensitivity of the model and to show how the decision is affected by the variations of these system parameters.

Table 4.6 shows, for each run, the part loadings at each machine, associated tool assignments, and the optimal machining costs. The solution for the base case is as follow: machine one is loaded with operation 2 of part 1, operation 1 of parts 2 and 3, operation 4 of parts 3 and 4, and is equipped with tool types 1, 3, 7, 12, and 16; machine two is loaded with operation 4 of parts 1 and 2, operation 3 of parts 2 and 3, and is equipped with tool types 4, 10, 11, 14, 19, and 20; machine 3 is loaded with operation 1 of parts 1 and 4, operation 3 of part 1, and operation 2 of part 2 and is equipped with tool types 2, 6, 8, and 17; while machine 4 is loaded with operation 2 of parts 3 and 4, operation 3 of part 4, and

is equipped with tool types 5, 9, 13, 15, and 18, resulting in an optimal machining cost of \$302. Since the system efficiency constraint at the base case is not binding at optimum, the values of decision variables and the optimal cost would not change by increasing the efficiency factor.

The second run is made with the tool slot capacity at each machine reduced from 60 to 50. The tool assignments as well as the machine loadings are different. The optimal cost increases to \$336. The third run is made with the value of the system efficiency factor reduced from 80% to 70%. The fourth run shows that if the 7th type of tool is not available, the optimal cost significantly increases along with the changes of tool assignments and machine loadings. The fifth run shows that if tool life for each set of tool decreases from 150 to 120 minutes, then the optimal machining cost will increase. In the sixth run the tool slot capacity is reduced from 60 to 50, system efficiency drops from 80 to 70%, and the tool life decreases to 120 minutes. The system can still finish all the parts within the planning period but the optimal cost is up to \$413 and the assignments and loadings are also different.

The seventh run shows that when the tool slot capacity and the system efficiency factor drop as in the above run and the 7th type of tool is out of stock, all the parts can still be

finished in time although the loadings and the assignments are different and the cost increases to \$397. However, if, in addition, the tool life also drops to 120 minutes, then the problem becomes infeasible; that is, the parts can not all be finished within the planning period. Even when the system efficiency factor is increased to 80% or the tool slot capacity is back to 60, the problem remains infeasible.

Table 4.7 gives details of the part routings and the needed tools for each part for each run. The sequences are expressed in terms of machine numbers. The decisions for the base case are that the routing for part 1 is 3-1-3-2 (in terms of machine number), and the needed tools for each operation are 2, 7, 6, and 10, respectively. As is shown in Table 4.7, the part routings and the tool allocations change with changes in system parameters and part characteristics.

#### 4.2.4 THE EFFECT OF LOWER UTILIZATION LIMIT

Since an FMS is expensive, one major effort in operating an FMS is to maximize the utilization of the expensive equipment (Mayer and Talavage, 1976, Suri, 1984, Sarin and Dar-El, 1984, Dar-El and Sarin, 1984, Co, 1984). Also, it is believed that the maximum production rate and system utilization can be achieved by minimizing the difference between machine utilizations (Solberg, 1976, Steckel, 1983). To study the impact on

Table 4.6 Tool Assignments and Machine Loadings

Run No.	Machine No.	Operator assigned to each machine	Tool Set No. Assigned to each machine	Machining cost(dollar)
1	M1	*OP12,OP21,OP31,OP34,OP44	1,3,7,12,16	302
	M2	OP14,OP23,OP24,OP33	4,10,11,14,19,20	
	M3	OP11,OP13,OP22,OP41	2,6,8,17	
	M4	OP32,OP42,OP43	5,9,13,15,18	
2	M1	OP21,OP24,OP34	1,12,3,5,16	336
	M2	OP13,OP14,OP23,OP33 OP42,OP44	6,10,11,20,7,14,19	
	M3	OP11,OP12,OP22,OP41	2,4,8,17	
	M4	OP31,OP32,OP43	15,9,13,18	
3	M1	OP12,OP21,OP31,OP34,OP44	7,1,12,3,16	337
	M2	OP14,OP23,OP24,OP33,OP42	10,4,19,20,11,14	
	M3	OP11,OP13,OP22,OP41	2,6,8,6,9,17	
	M4	OP32,OP43	18,13,4,15,5	
4	M1	OP21,OP22,OP24,OP34	1,16,12,3	363
	M2	OP14,OP23,OP33,OP43	10,11,14,19,20	
	M3	OP11,OP12,OP13,OP41,OP44	2,4,6,8,17	
	M4	OP31,OP32,OP42	15,9,5,13,18	
5	M1	OP11,OP12,OP21,OP22 OP31	1,7,3,16,12	383
	M2	OP14,OP24,OP33,OP34	10,4,11,14,19,20	
	M3	OP13,OP23,OP41,OP44	6,17,2,8	
	M4	OP32,OP42,OP43	9,5,13,15,18	
6	M1	OP11,OP12,OP22,OP31	1,7,16,12,5	413
	M2	OP13,OP14,OP21,OP33, OP34,OP42	6,10,3,19,14,20	
	M3	OP23,OP24,OP41,OP44	17,4,2,8	
	M4	OP32,OP43	9,13,11,15,18	
7	M1	OP21,OP22,OP24,OP34	1,16,12,3,5	397
	M2	OP12,OP14,OP23,OP33, OP42	10,4,19,14,20	
	M3	OP11,OP13,OP41,OP44	2,6,8,17	
	M4	OP31,OP32,OP43	15,18,13,9,11	

\*OP12 means operation 2 of Job 1.

Table 4.7 Job Routings and Required Tools for Each Part

Run No.	Part No./OP-Sequence Routings and toolings of each part	1				2				3				4			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	1. Routings (in terms of machine no.)	3-1-3 -2				1-3-2 -2				1-4-2 -1				3-4-4 -1			
	2. Required tools (tool number)	2 7 6 10				1 8 10 4				12 9 11 3				2 5 13 7			
2	1. Routings	3-3-2 -2				1-3-2 -1				4-4-2 -1				3-2-4 -2			
	2. Required tools	2 4 6 10				1 8 10 12				15 9 11 3				2 20 13 7			
3	1. Routings	3-1-3 -2				1-3-2 -2				1-4-2 -1				3-2-4 -1			
	2. Required tools	2 7 6 10				1 8 10 4				12 18 19 3				2 20 13 7			
4	1. Routings	3-3-3 -2				1-1-2 -1				4-4-2 -1				3-4-2 -3			
	2. Required tools	2 4 6 10				1 16 10 12				15 9 11 3				2 5 14 8			
5	1. Routings	1-1-3 -2				1-1-3 -2				1-4-2 -2				3-4-4 -3			
	2. Required tools	1 7 6 10				3 16 17 4				12 9 11 14				2 5 13 8			
6	1. Routings	1-1-2 -2				2-1-3 -3				1-4-2 -2				3-2-4 -3			
	2. Required tools	1 7 6 10				3 16 17 4				12 9 19 14				2 20 13 8			
7	1. Routings	3-2-3 -2				1-1-2 -1				4-4-2 -1				3-2-4 -3			
	2. Required tools	2 4 6 10				1 16 10 12				15 18 19 3				2 20 13 8			



machining cost of minimizing the difference between utilizations of machines in an FMS, we use the machine loading and tool allocation model. In particular, the problem of interest is to study the impact on total machining cost at various system efficiency levels of imposing a lower utilization limit on each machine. We use the example of Section 4.2.3 for illustration purposes.

To perform this study, a set of lower utilization limit constraints is added to the mathematical model (IM3). The constraint set is expressed as follows:

$$\sum_i \sum_j \sum_t u_{ijtk} \cdot x_{ijtk} \geq \alpha \cdot T_k, \quad \text{for all } k$$

where  $\alpha$  = a permissible lower utilization level.

By increasing the lower utilization limit toward the system efficiency factor, the difference in machine utilization is minimized. Note that the lower utilization limit can not exceed the system efficiency level. Theoretically, by adding new constraints the problem is tightened and the objective function value would increase for the minimization objective. The machining cost would further increase with increase in the value of  $\alpha$ . This is due to the shrinkage of solution space as the lower utilization limit gets closer to the system efficiency level. The results of this study are summarized in

Table 4.8 and plotted in Figure 4.1. The following observations can be made from these results:

1. the machining cost is relatively lower at higher system efficiency level;
2. the machining cost increases with increase in lower utilization limit;
3. the rate of increment of machining cost is higher at lower system efficiency levels; and
4. it becomes difficult to obtain feasible solution when the difference between the lower utilization limit and the system efficiency level gets smaller than 5%.

#### 4.2.5 STUDY OF OPERATION-TOOL ASSIGNMENT LIMITATION

Since the machine loading model (IM3) is designed to apply on a daily basis, it may be worthwhile to explore the effect of adding a constraint that allows only one operation to be assigned to a tool. The advantages of adding this constraint are:

1. it reduces the size of the problem in both the number of constraints and the number of variables,
2. it reduces the modeling and the computation time, and

Table 4.8 Machining Costs for Same Set of Parts  
at Different System Efficient Factors  
and Lower Utilization Limits (dollar)

System efficiency level	lower utilization level (%)							
	50	55	60	65	70	75	80	85
70%	343	347	404	inf.	-	-	-	-
75%	312	314	326	326	343	-	-	-
80%	302	302	302	302	302	313	-	-
85%	302	302	302	302	302	313	333	-
90%	302	302	302	302	302	313	333	inf.

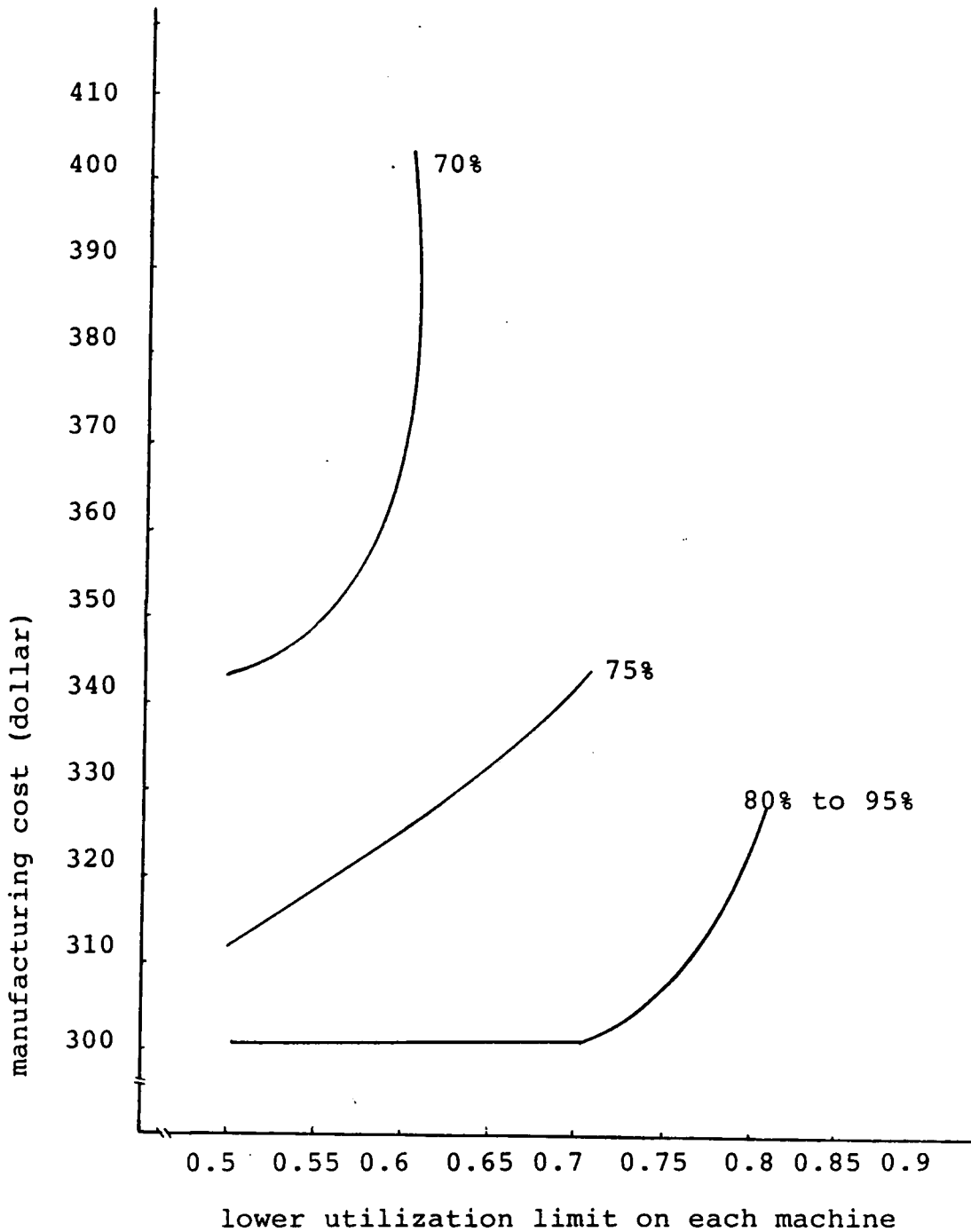


Figure 4.1 The Impact of Lower Utiliation Limits of Manufacturing Cost at Various System Efficiency Levels

3. it provides a model with a better structure to deal with from the computational point of view.

The disadvantages are:

1. it may require more tools and subsequently more tool slots, and
2. it may increase machining cost since some operations may not be assigned to the most efficient tool.

If operations are different from each other and do not use common tools or common tool slots and the cutting tools are not active constraints (Stecke, 1983, Koren, 1983) then tighter formulation will be obtained by adding the new constraint set which will be easier to solve. If this is not the case then a tradeoff can be sought between the ease of the solution process and the increase in machining cost.

This section explores this issue by solving an example with two formulations: the original machine loading model (IM3) with the lower utilization limit constraints on machines. The revised model is the original model with the following constraints replacing the constraint sets (5), (6), and (9) of model (IM3):

$$\sum_i \sum_j \sum_k x_{ijtk} \leq 1 \quad \text{for all } t$$

$$\sum_i \sum_j \sum_t s_t x_{ijtk} \leq (TS)_k \quad \text{for all } t$$

This model is tighter than the original model. Since it eliminates  $t \cdot k$  decision variables and  $t \cdot k$  constraints, the size of the revised model is much smaller.

In order to compare these models, they were used to solve the example problem of section 4.2.3. The revised model has 38% less variables and 30% less constraints. The computational times of both formulations are presented in Table 4.9. The machining costs obtained from the revised model at various system efficiency levels and lower machine utilization limits are listed in Table 4.10 and plotted in Figure 4.2.

Table 4.9 shows that for a 70% lower utilization limit on each machine, the computational time for the revised model are smaller than those for the original model for all system efficiency levels. The computational times for the revised model are half to those for the original model at high system efficiency values. When the system efficiency level gets closer to the lower utilization level (i.e. the differences in the utilizations of machines values), the computational time for the original model increases dramatically while the time for the revised model increases moderately.

Table 4.9 Computational Times for The Original and The Revised Models for The Example Problem at The 70% Lower Utilization Limit of each machine (in seconds)

Item	system efficiency level (%)					
	75	77.5	80	85	90	100
the original model	39	6.6	1.2	1.2	1.2	1.2
the revised model	4	3	0.6	0.6	0.6	0.6

Table 4.10 Machining Costs for The Revised Model at Different System Efficiency factors and Lower Utilization Limits (in dollars)

system effic.	lower utilization levels (%)									
	0	50	55	60	65	70	72.5	75	77.5	80
80%	377	377	377	378	379	379	386	394	425	-
85%	368	368	368	368	369	369	374	374	374	391
90%	368	368	368	368	369	369	374	374	374	391



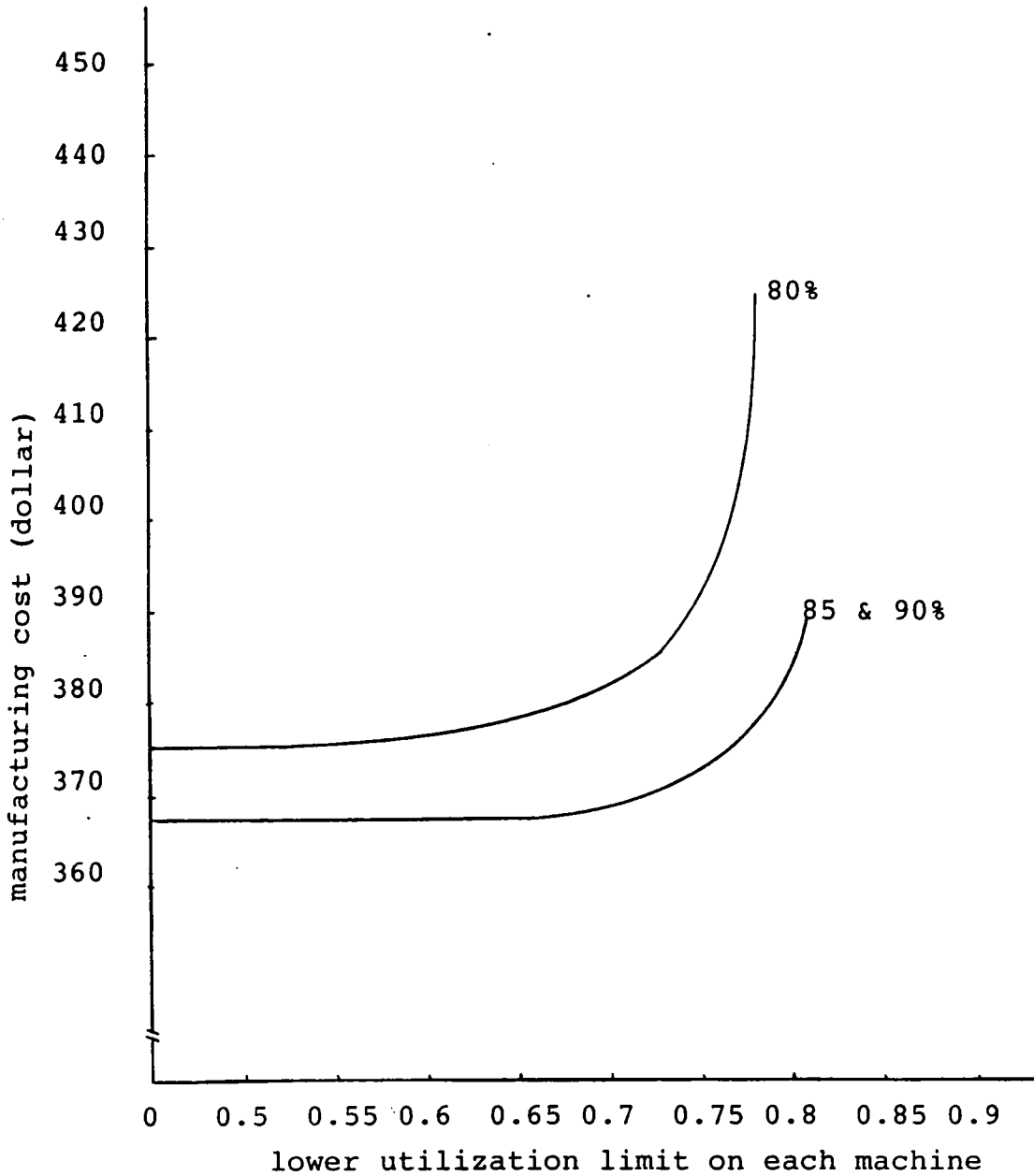


Figure 4.2 The Impact of Lower Utilization Limits on Manufacturing Cost at Various System Efficiency Levels, When A Tool Can Be Used for at Most One Operation

Figure 4.2 shows that the optimal machining costs remain stable at lower utilization limits and increase rapidly when the machine utilization differences get closer. The machining costs at high system efficiency levels are always lower than those at lower levels. By comparing Tables 4.8 and 4.10, it is obvious to conclude that the revised model consistently causes higher machining costs at the optimum (e.g. \$302 vs. \$368 in the case of 70% lower utilization limit and 85% system efficiency level). A tradeoff can be made between the savings in computational time and machining costs. Note that, if computations are run for a fixed amount of time the revised model is most likely to achieve its optimal solution and may have objective function value close to that of the original model.

### 4.3 SUMMARY

In this chapter, two production planning problems were addressed, namely the shop loading problem and the machine loading and tool allocation problem. The first one is related to the short-term capacity planning problem while the second one involves routing of parts. Both problems were formulated as integer programming models, and were illustrated on example problems by the IBM MPSX-MIP/370 package. Computational experiences were presented. Sensitivity analyses were also performed for both models by varying some system and part

parameters to show how the decisions change with changes in parameter values.

## 5.0 SIMULATION MODEL DEVELOPMENT AND PARAMETERS ANALYSIS

In the previous chapter, two mathematical models were formulated for part loading and tool allocation problems. Because of the inability of these models to capture system dynamics a system efficiency-factor was incorporated in these models to compensate for decrease in utilization due to congestion, machine blocking, components failure, and other factors. However, the measurement of these coefficients was not discussed in detail because these coefficients are contributed by many factors and are different from system to system. Therefore, a generally-applicable factor can not be obtained and every individual system needs an experiment in this regard (Stecke and Solberg,1981). In this chapter a simulation-based approach is presented for determining such a factor.

While an experiment on a real system is often very expensive, time-consuming, and even impractical, fortunately, a simulation model can serve this purpose inexpensively and without interrupting a real system operation. It can seize in detail the dynamic features of a system and can accurately measure various system performances in a single run. Simulation technique is, therefore, used to test the feasibility of the optimal loading solution obtained by the mathematical models

discussed in Chapter 4, and to measure the actual system efficiency for a given set of operation parameters. The simulation model is also used to study the interactions among these parameters and their effects on system performances. The best operational strategies for the given set of parts is also studied with this model for a given planning period.

To summarize, the purposes of this simulation model are (1) to evaluate the feasibility of the optimal assignments obtained from the mathematical model(IM3), (2) to identify the best set of control policies for the set of parts within the planning period and (3) to statistically analyze the interaction effects of system parameters on system performances.

## 5.1 SIMULATION PROCESS

The simulation model is a mathematical-logical representation of the manufacturing system which can be implemented in an experimental fashion on computer. It is used as an analysis vehicle to determine the critical system elements, decision issues, and to evaluate proposed solutions. The simulation model can be viewed as a description of the manufacturing system, or as an abstraction of the system. The success of the simulation model depends on how well the significant system elements and the relationships between these elements are defined. Next, we describe the simulation model after a

brief discussion of discrete simulation, simulation languages and their logic.

### 5.1.1 DISCRETE SIMULATION

Simulation models are generally classified as discrete and continuous, regarding to the behavior of the dependent variables (e.g. queue length). In discrete simulation, the state of the system can change only at event times. So a complete dynamic portrayal of the state of the system can be obtained by advancing simulated time from one event to the next. This timing mechanism is referred to as the next event approach and is used in most discrete simulation models.

Instead of defining the changes in state that occur at each event time (event oriented), a discrete simulation model can also be formulated by describing the process through which the entities in the system flow (process oriented). This concept is employed in most simulation languages to ease modeling efforts. A user can simply model the flows of entities through the system without knowing the actual sequence of events because they are already defined and automatically executed by the simulation language as the entities move through the process. It is relatively easy to develop a simulation model in this case since the event logic associated with the program statements is contained within the simu-

lation language. Process oriented simulation is less flexible, while the event oriented discrete simulation is more difficult to learn but provides a highly flexible modeling framework.

### 5.1.2 SIMULATION LANGUAGES

The widespread use of simulation as an analysis tool has led to the development of a number of languages specifically designed for simulation. These languages provide specific concepts and statements for representing the state of a system at a point in time and for moving the system from state to state.

GPSS, GASP, Q-GERT, SLAM, SIMAN, and MAP/I are some of the simulation languages often applied in modeling manufacturing systems. They are process-oriented, FORTRAN-based, discrete event simulation languages. Some of them also possess functions for event-oriented and continuous simulation. Ideally, a simulation language should be evaluated by the features such as ease of learning, coding, documenting, debugging and data gathering, and computation/execution speed (Pritsker and Pegden, 1979). The selection of a simulation language, nevertheless, is frequently based on user's knowledge and its availability as opposed to a formal comparison of language features.

SIMAN (Pegden,1982) is selected as the simulation language in this study to perform system simulation because of the ease in achieving the prespecified purposes by its use. SIMAN has most of the features listed above. In addition, it contains a number of characteristics which make it particularly applicable to modeling a manufacturing system.

SIMAN is a FORTRAN-based, primarily process-oriented discrete simulation language. It can run a program on micro computers as well as on main frames. The data structure is specially designed to allow the problem size, in terms of entities, attributes, files, statistical variables, etc. to be specified at run time without the need to recompile the SIMAN program. Another advantage of this language is its ability to model MHS elements which reduces the modeling process and makes it very attractive to manufacturing environment.

A SIMAN simulation model contains two portions: system model and experimental frame (experimental frame specifies the conditions under which the model is run to generate output data). For a given model there can be many experimental frames resulting in many sets of output data. By separating the model structure and the experimental frame into two distinct elements, different simulation experiments can be run by changing only the experimental frame, where the system model remains the same.



An example system will be proposed and described in SIMAN block diagram model following a discussion of the operational parameters and objectives in next section.

## 5.2 OPERATIONAL PARAMETERS AND OBJECTIVES FOR AN FMS

### 5.2.1 SYSTEM OBJECTIVES

In operating a manufacturing system, the problems first confronted are: (1) to select a performance measure for this system and (2) to optimize the system performance. At operational level, the system configuration is fixed. Many system parameters can not be altered. The parts and process requirements are also fixed in the proposed decision logic. The selection of a performance measure depends on its operational objectives, which can be different for different systems because of their system parameters and part characteristics. The common-used performance measures include operating cost, throughput, makespan, average flowtime, machine utilization, machine idle time, machine blocking time, congestion, and length of queue. When part type and part ratio are fixed, however, the direct objective is usually maximization of throughput. If a set of parts to be finished is given, the objective should be to minimize makespan. If more than enough parts are given in a planning period, the primary objective would be that of maximizing the

profit or minimizing the operating cost by selecting the most beneficial set of parts to be made. The performance measures of interest in this study are makespan and the mean flow time in the system.

### 5.2.2 THE FACTORS THAT AFFECT SYSTEM PERFORMANCE

The factors that decrease system utilization and hinder productivity are from at least one of the four sources: machine blocking, machine starving, system components breakdown, and inefficient machine usage.

Blocking happens when a workstation finishes all the operations of a part assigned to the station and the part can not be removed off the station. Consequently, the part stays on the machine table and the machine has to stay idle. The problem can be solved by adding out-going local buffers, adding material handling carts, or increasing the material handling system speed. Increasing the speed is often the easiest way to do it.

Starving happens when a workstation finishes a part and no part waits at the in-coming queue waiting to be processed by this workstation. It happens probably because of inefficient material handling system, insufficient in-coming queue space, or limited work-in-process. A solution to this problem can

be to add pallets in the system, add carts, increase material handling system speed, add in-coming queue capacity, increase number of parts in the system, and increase machine flexibility.

Breakdowns are caused by mechanical or electronic component failures or tool breakdowns. It is a problem of system reliability and can not be controlled much by system management. However, by reinforcing preventive maintenance, by having more alternative routings, and by machine flexibility, the effects can be reduced to a minimum.

Inefficient use of machines is a cumbersome problem and difficult to trace. Since the system is very expensive, we would like to fully utilize the system resources; in other words, we try to keep machines busy all the time. However, due to the part mix and scheduling problems, a multifunctional machine could be assigned to work on a less efficient part rather than on a more efficient part coming in a few seconds later. This problem needs an independent study and is not covered in this chapter.

### 5.2.3 SYSTEM PARAMETERS

The parameters at the operational level can be categorized as part-related, control-related, and system-related. The

part-related parameters include part type, part mix ratio, part routing flexibility, and processing time distribution. Since these are dictated by the mathematical model analysis, these part-related parameters are assumed to be known and fixed at this stage.

The control-related parameters are those associated with system control policies such as initial part release rule, part release rule, part dispatching rule, cart request rule, cart selection rule, and shop loading level. In this study, part dispatching rules and cart request rules are the two control-related parameters of interest. The other parameters are assumed fixed.

The system-related parameters include maximum pallet number allowed in the system, cart number, cart speed, component breakdown distribution, repair time distribution, number of load/unload worker, local queue capacity, part transport and transfer time, among others. In this study, part transfer time is assumed to be constant. Part transport time is proportional to the distance it travels. The cart breakdown and repair times are assumed to follow known distributions. Each station is assumed to have a certain size of queue capacity. The number of pallets in the system and the cart speed are control variables and vary within a prespecified range.

## 5.3 MODEL DEVELOPMENT

### 5.3.1 THE EXAMPLE

A layout of the example manufacturing system is shown in Figure 5.1. There are 4 workstations, each containing one machine which is connected by a cart-type material handling system. Station 5 is designated as the load/unload station. Each part enters and leaves the system from this station. Station 6 is the central storage area, which temporarily stores all the work-in-process. A local queue of size two is provided in front of every machine so an in-coming part which can not seize the machine stays in the local queue; otherwise, it is transported to the central storage area waiting for a change in status. The relative distances among stations are listed in Table 5.1.

There are 4 types of parts, each containing 4 operations. The part type, operation requirement, and routings are generated from the mathematical model(IM3). The routings and the corresponding processing times are listed in Table 5.2. A total of 40 parts, 10 of each part type, are to be finished within a planning period of 480 minutes. The second type of part, for example, must be transported to STATION(1) for its first operation which takes 11 minutes to process.

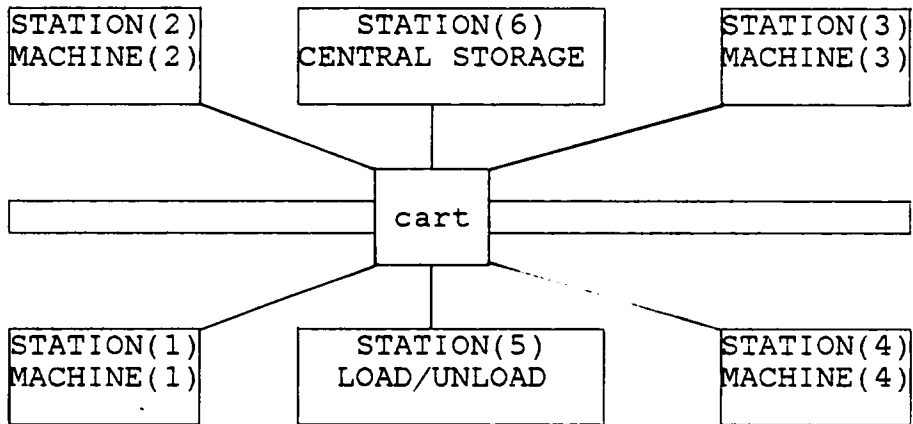


Figure 5.1 Layout for The Example System

Table 5.1 Relative Distances Between Stations (in feet)

from to		station number					
		1	2	3	4	5	6
station number	1	-	0	32	32	16	16
	2	0	-	32	32	16	16
	3	32	32	-	0	16	16
	4	32	32	0	-	16	16
	5	16	16	16	16	-	0
	6	16	16	16	16	0	-

Table 5.2 Routings and Processing Times for Each Part Type

Item	Sequence Number	1	2	3	4
Routing for Part Type:	1	M3	M1	M3	M2
	2	M1	M3	M2	M2
	3	M1	M4	M2	M1
	4	M3	M4	M4	M1
Corresponding Machining times of part: (in Minutes)	1	10	4	12	8
	2	11	12	7	12
	3	7	12	12	8
	4	5	12	12	7



The following conditions and limitations are assumed for this simulation model:

1. system configuration is fixed as shown in Figure 5.1
2. a limited number of pallets are allowed in the system
3. a limited size queue in-coming parts is allowed at each machine station
4. no queue for out-going parts is provided at each machine station
5. all the processing time and station breakdown time distributions are known
6. machine breakdown takes place only after the completion of the current operation
7. travel time is proportional to traveling distance
8. no alternative routing is considered for a part
9. proportional amount of each part type is initially released to the system
10. the part mix ratio remains the same, i.e. one part of the same type is released to the system, when one of that type leaves.
11. each part movement between different stations is carried out by a cart
12. a requested transporter unit (cart) is allocated to the entity having the highest priority with ties broken based on the shortest travel distance between the cart and the

requesting entity. If ties remain, they are broken based on the order that the requests are made.

13. if the cart is busy at the time that its scheduled failure occurs, it remains operational until the completion of the current task.

### 5.3.2 THE SIMULATION MODEL DESCRIPTION

A basic part-flow diagram for this simulation model is depicted in Appendix F. The listings of SIMAN variables, queues, system parameters, and entity attributes are given in Appendix G, H, I, and J, respectively. The simulation program is listed in Appendix K and L. The simulation model is described in terms of part flow in the following paragraphs.

The model initially generates a number of parts of each type for the system. After assigning each part with a part-type attribute, and marking it with creation time (arrival time), the parts are routed to STATION(5) waiting for a loader to be palletized. After served by a loader, the palletized part is moved to STATION(6), waiting for a cart to be routed to a workstation for its first operation; meanwhile the operation sequence, workstation number, processing time and other attributes are assigned.

When a part waits at STATION(6), the queue status at its destination station is scanned each time an event happens. If the queue length falls below its maximum capacity, a part is released from the central storage area to its outgoing (dummy) queue and waits for a cart. The system variable which indicates the number of waiting parts in that queue is increased by one. A request signal is then sent for a cart and the status of the specified transporter is tested to determine if it is both operational and idle. If it is, the status of the unit is changed from idle to busy and the travel time of the unit to the station of the requesting entity is computed. The station number of the specified transporter unit is reset to the station number of the requesting entity. The entity departs STATION(6) after a delay equal to the computed travel time for the transporter. If the requested transporter unit has either failed or is busy, the requesting entity waits in the dummy queue preceding the REQUEST block for a change in status.

Once an entity is allocated to a transporter unit at a REQUEST block, it is transported from the current station to its next workstation using the TRANSFER block. The transport time is computed based on the distance between stations and the transporter speed. At the end of the required transport time, the transporter entity enters its destination STATION block. The transporter is then released by using FREE block

after a delay of transfer time. The FREE block changes the status of the specified transporter from busy to idle.

After being transported to its prescribed workstation, the part waits in the queue for in-coming parts along with other waiting parts for the machine to become idle. When the machine becomes idle, the parts waiting in that queue are searched for the rank of the entity meeting a prescribed condition. Once the rank is determined, the entity is removed from the queue by the REMOVE block. The entity then seizes the machine for a period of its processing time. And the system variable which indicates the number of waiting entities in that queue decreases by one.

After the operation is finished, a cart request signal is sent. But the machine can not be released until the part is removed off the machine by a transporter. During this waiting time, the machine stays idle.

Before a part leaves a workstation, the status of the incoming queue at its next destination station is checked. If the queue length is less than its maximum capacity, the system variable indicating the current queue length is increased by one and a cart request signal is made to send this part to this station with updated attributes. Otherwise, the part is transported to the central storage area, waiting for a change

in status. If the next station of a part is STATION(5), the part is said to be finished with all required operations, and is de-palletized and released from the system.

Transporter and machine breakdowns are generated randomly and separately. The operational status of a transporter is changed using HALT and ACTIVATE operation blocks. At the beginning of a simulation run, one entity is created to trigger a breakdown event. After a time delay, the cart unit is set idle for a period of repair time. Then, it is reset to active by using ACTIVATE block. If the transporter unit is busy at the time that its operational status is changed to inactive, the transporter device remains operational until the next release at a FREE block. At that time, it will remain idle until its operational status is reset to active. Machine breakdowns are manipulated by ALTER block. Initially, all machines are set to be operational and an entity is generated to create a machine breakdown. After a time of delay, a randomly selected machine is set to failure and reset to be operational by ALTER block after a delay of repair time.

When a part arrives at STATION(5), the cart is released but the part waits at the QUEUE(12) for a material handler to unload it. After being unloaded, the part is split into two entities. One is routed to collect statistics, including a count on the number of parts finished, time spent in system,

and time between parts leaving the system. The other is branched to check the current system status and causes an introduction of a new part to the system. In this case part type is first identified, and then the total number of parts of that type which have entered the system is checked. If the number of this part type is less than a predetermined number, then the entity is re-routed back to the system as a new coming part of that type.

The parameters in the experimental frame are set as follows for the base case:

1. a maximum of 12 pallets are allowed in the system
2. the cart stays at STATION(5) at the beginning of a simulation run
3. cart speed is set at 64 ft/min
4. there is one cart, one material handler, and one machine at each station
5. load/unload time is exponentially distributed with a mean of 3.0 minutes
6. transfer time between cart and station is constant being equal to 0.1 minutes
7. time intervals for cart and machine breakdown are exponentially distributed with a mean of 240 minutes
8. repair times are exponentially distributed with a mean equal to 5 minutes

9. each machine has equal failure probability
10. there are two in-coming queues at each workstation

The simulation session is terminated when: (1) no part exists in the system, (2) preset simulation time is reached, or (3) the counter equals or exceeds the count limit specified in the experimental frame.

### 5.3.3 COMPARISON WITH CAN-Q

The simulation model is compared with the CAN-Q model. In order to compare the two models, the simulation model is revised to comply with the assumptions of CAN-Q which are as follows:

1. exponentially distributed activity times
2. infinite queue capacity at each workstation
3. no blocking at each station
4. a fixed number of pallets allowed for use in the system
5. the transportation operation is inserted between each pair of consecutive ordinary operation
6. the average time of transport is the same regardless of the item type, the distance between destinations, and the sequence of operations performed on the workpiece completion

7. the storage space for in-process items is treated implicitly, no particular assumption on the location of the storage is made
8. the mathematical model used in CAN-Q implicitly assumes FCFS as queue discipline
9. each raw material is transformed into a single finished part
10. no scrap and rework are allowed
11. the workload of a station is equally shared by all of the servers of that station.

With these changes, the revised model was run 10 times for a total period of 7,000 minutes. The sample value collected up to 1,000 minutes are discarded to reduce the startup effect and consequently reduce the bias of the output estimators, which are production rate and mean flow time. The startup policies employed here include a pilot run for setting up the truncation point, and initial introduction of equal number of each part type, at various completion stage, to the system for more easily reaching "steady state" (Gafarian, Ancker and Morisaku, 1978, Pritsker and Pegden, 1979). The results are presented in Table 5.3. The production rate for the CAN-Q model is 4.853 parts/hour and the mean flow time in system is 148.38 minutes. On the other hand, the production rate for the revised simulation model is 4.793 parts/hour with a standard deviation of 0.0892 and the mean flow time is



148.077 minutes with a standard deviation of 2.6356. At both 99% and 95% significance levels, the null hypotheses are accepted, thereby implying that there is no significant difference between the two models in terms of production rate and mean flow time for this set of parts. This comparison serves as a validation of the simulation model.

#### 5.4 FEASIBILITY TEST FOR THE OPTIMAL SOLUTION

The optimal solution of machine loading and part routing problem obtained from the mathematical model (IM3) presented in Chapter 4 must be tested for feasibility with respect to the makespan value before it is actually released for implementation. There are two approaches to do that: (1) simple feasibility check and (2) detailed feasibility test. When system reliability is high and the variation in each operation time is negligible, the simple feasibility check would be very efficient and accurate enough to use. Otherwise, the detailed test has to be performed.

##### 5.4.1 SIMPLE FEASIBILITY TEST

In the simple feasibility test the program is run under the assumptions of no system components breakdown, constant processing time, fixed part transfer time, fixed transport time, and fixed part load/unload time. Therefore, the esti-

Table 5.3 t-test on The Means from CAN-Q and The SIMAN Model

item measure	SIMAN model		sampl size (N)	hypo- thesis mean (u)	Stati- stics  t	Signi- ficance level	
	Mean (x)	Standard Deviation (s)				95%	99%
Comparison with CAN-Q							
Prod. rate(the revised SIMAN model)	4.793	0.089	10	4.85 (mean for CAN-Q)	-2.127	NS*	NS
Mean Flow Time(from the revi- sed SIMAN model)	148.1	2.64	10	148.38 (mean for CAN-Q)	-0.364	NS	NS
Feasibility Test							
Makespan (from the SIMAN model)	478.60	11.41	25	480**	-0.5977	NS	NS
* NS = Non-Significant **length of planning period							

mation of makespan is deterministic and only one simulation run is needed to conclude the feasibility of the optimal solution.

As an illustration of this test consider the input data of the example of Section 5.4.1. The makespan value of 473.4 minutes is obtained, while the planning period is 480 minutes. This indicates that the optimal solution generated by the mathematical model is feasible. However, the assumptions made for this test may not be quite realistic. For example, machines and cart as well as other system components do indeed fail and load/unload processing times may not remain the same. So, it is usually more reasonable to perform the feasibility test incorporating these uncertainties in the simulation model.

#### 5.4.2 DETAILED FEASIBILITY TEST

In the detailed feasibility test, the situation is run under all the assumptions and conditions described in the previous sections, including system components breakdown, and probabilistic load/unload times. It is assumed that variations within 5% of the makespan value are acceptable. The minimum sample size for 5% makespan variation is 4 following the procedure to determine the sample size described in Appendix M. However, for the example problem, 25 simulation runs were

made. In each run, the makespan value was determined for the completion of 40 parts. The results are shown in Table 5.3 (in the third row). The mean makespan value is 478.68 with a standard deviation of 11.479. The difference from the prescribed makespan (value of 480 minutes) is within the acceptable limit of 5%. Furthermore, the t-test with 99% and 95% significance levels revealed that the true makespan has no significant difference from the given planning period of 480 minutes. Therefore, the optimal solution is feasible and acceptable.

In testing the feasibility various system parameters and control strategies can also be applied to obtain better system performances. The procedure to do this is depicted in the flow chart in Figure 5.2. The effects of system parameters and control strategies on makespan and mean flow time are studied in the next section.

In case the actual makespan is outside the acceptable range (of 5% in this case), the optimal solution is infeasible. Therefore a new set of system parameters described in Section 5.3.3 is selected to resume a simulation run. If an acceptable solution is still not obtained after all system parameters are tested, an adjustment to the utilization limit on the bottleneck station is made. If feasible solution is still not found then the system efficiency factor is reduced. A

5% decrement in the machine utilization limit and system efficiency factor is suggested per trial. With these changes the appropriate mathematical models are solved once again to obtain a new solution which is then tested for feasibility. The adjustment procedure is depicted in Figure 5.2. If the simulated makespan is significantly shorter than the prescribed makespan, an adjustment of system efficiency factor could also be made to further improve system performance. In case, the estimated makespan is significantly shorter but the system efficiency constraint is not binding then no change is needed in the efficiency constraint and the optimal solution is the best.

## 5.5 PARAMETRIC ANALYSIS

### 5.5.1 FACTORIAL DESIGN

The parametric analysis is done here to identify the best strategies for the operational control of parts through the system. The factors of operational control studied are (A) part dispatching rule (queue discipline), (B) cart request rule, (C) maximum number of pallet allowed in the system, and (D) cart speed. A factorial experiment was designed to study their effects and interactions. The measures of interest include makespan and mean flow time. The levels of each factor considered are summarized in Table 5.4.

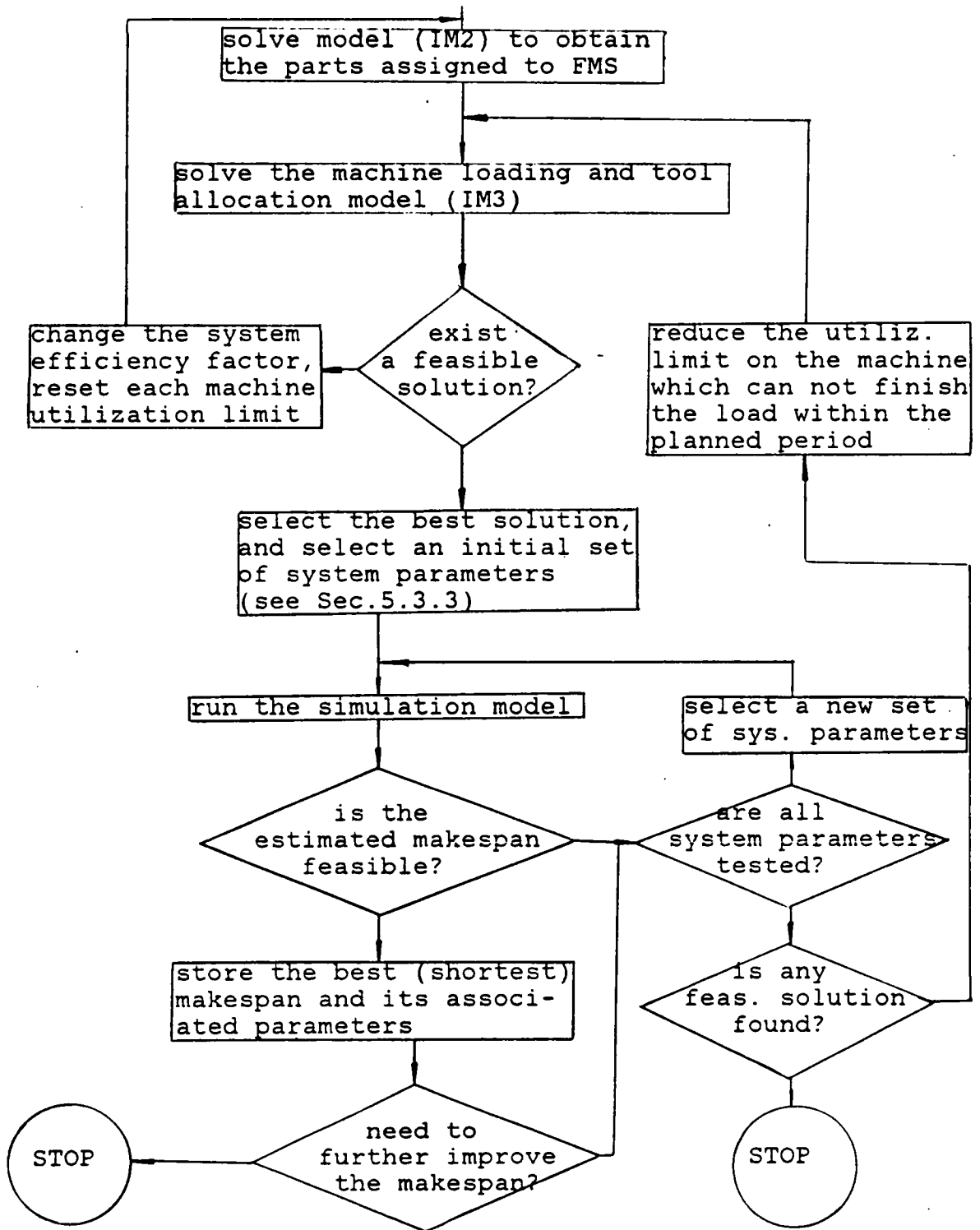


Figure 5.2 The Feedback Process for IM2, IM3 and IM4

Table 5.4 Levels of 4 Factors Used in The Factorial Design Experiment

Treatment Factor	Level 1	Level 2	Level 3
Dispatching Rule (A)	FCFS	SPT	WINQ
Cart Request Rule (B)	FCFS	SPT	HAMUF
Maximum Number Pallets in The System (C)	8	12	16
Cart Speed (ft/min) (D)	32	64	128

Regarding factor A, FCFS rule selects that part which arrives first at a station; SPT rule selects a part to process next that has the shortest processing time; while WINQ rule selects a part with the smallest queue length at its next destination station. For factor B, FCFS and SPT rules are the same as that for factor A, where HAMUF assigns a cart unit first to a requesting station with nominally the highest average machine utilization. Machine utilizations can be obtained from the input information because part routings and processing times are both known.

Eighty one experiments were required for each response based on the complete factorial design. These experiments were replicated 4 times each with different random number seeds. Thus, a total of 324 simulated experiments were conducted for analyzing the effects of these four factors with respect to the two system responses of interest.

### 5.5.2 ANALYSIS OF THE RESULTS

The analysis of variance (ANOVA) and the Duncan multiple range tests were used to analyze results of the simulation experiments. The results of the ANOVA test for the makespan criterion are presented in Table 5.5. The significance of the source of variations is statistically tested using the F-statistics at 95% and 99% levels of significance.



Table 5.5 ANOVA-Test Results for The Makespan Criterion

Source of variation	df	ANOVA SS	Statistic F-value	Significance level	
				95%	99%
A	2	29588.33	97.18	S	S
B	2	14.52	0.05	NS	NS
C	2	6281.31	20.63	S	S
D	2	86294.25	283.42	S	S
AB	4	354.24	0.58	NS	NS
AC	4	1754.30	2.88	S	S
AD	4	919.31	1.51	NS	NS
BC	4	381.96	0.63	NS	NS
BD	4	219.23	0.36	NS	NS
CD	4	876.81	1.44	NS	NS
ABC	8	847.00	0.90	NS	NS
ABD	8	1000.08	0.82	NS	NS
ACD	8	316.41	0.26	NS	NS
BCD	8	231.21	0.19	NS	NS
ABCD	16	1063.29	0.44	NS	NS

S = Significant  
 NS = Non-Significant  
 df = degree of freedom  
 SS = sum of squares

The The Duncan multiple range test is used to test mean differences among the treatments of each factor. The Duncan test is performed when the null hypothesis on that factor is rejected. The test procedure is as follows:

1. rank sample means from the largest value to the smallest
2. draw a bar under any pair of means for which the null hypothesis is accepted
3. start by comparing the lowest and the highest means (i.e. t-mean difference when there are t levels within a factor)
4. if the difference is significant, then test the t-1 mean difference (i.e. the lowest vs. the second highest, and the second lowest vs. the highest)
5. next test the t-2 mean difference and so on
6. at any point, if we have a non-significant result, draw a bar under the pair and stop testing any pair contained within this range.

The Duncan test results for factors A, B, C, and D on makespan are presented in Table 5.6. Similarly, the results of the ANOVA test for the mean flow time criterion are presented in Table 5.7. The results of the Duncan test for the mean flow time are presented in Table 5.8. The significant relationships and effects are described in the following paragraphs.

Table 5.6 Duncan Tests for The Makespan Criterion

Factor	Item	highest value	Treatment second value	lowest value
A	1. dispatching rule	SPT	FCFS	WINQ
	2. mean value	492.78	486.73	470.17
	3. grouping	—	—	—
B	1. cart request rule	SPT	FCFS	HAMUF
	2. mean value	483.53	483.10	483.06
	3. grouping	—		
C	1. max. no. of pallets	16	8	12
	2. mean value	486.63	483.22	477.84
	3. grouping	—	—	—
D	1. cart speed	32ft/min	64ft/min	128ft/min
	2. mean value	505.10	478.68	465.91
	3. grouping	—	—	—
<p>Note . the tests control the type I comparisonwise error rate</p> <p>. <math>\alpha = 0.05</math></p> <p>. <math>df = 243</math></p> <p>. <math>MSE = 152.237</math></p>				

Table 5.7 ANOVA-Test Results for Mean Flow Time Criterion

Source of variation	df	ANOVA SS	Statistic F-value	Significance level	
				95%	99%
A	2	435.07	77.40	S	S
B	2	6.41	0.35	NS	NS
C	2	332599.18	17939.15	S	S
D	2	6284.00	338.94	S	S
AB	4	9.72	0.26	NS	NS
AC	4	675.47	18.22	S	S
AD	4	82.94	2.24	NS	NS
BC	4	11.27	0.30	NS	NS
BD	4	25.83	0.70	NS	NS
CD	4	322.31	8.69	S	S
ABC	8	18.50	0.25	NS	NS
ABD	8	34.11	0.46	NS	NS
ACD	8	61.52	0.83	NS	NS
BCD	8	49.91	0.67	NS	NS
ABCD	16	56.89	0.38	NS	NS

S = Significant  
 NS = Non-Significant  
 df = degree of freedom  
 SS = sum of squares

Table 5.8 The Duncan Test Results for Mean Flow Time

Factor	Item	Treatment		
		highest value	second value	lowest value
A	1. dispatching rule	FCFS	SPT	WINQ
	2. mean value	130.44	127.36	125.31
	3. grouping	—	—	—
B	1. cart request rule	HAMUF	SPT	FCFS
	2. mean value	127.87	127.71	127.53
	3. grouping	—	—	—
C	1. max. no. of pallets	16	12	8
	2. mean value	167.26	127.07	88.78
	3. grouping	—	—	—
D	1. cart speed	32ft/min	64ft/min	128ft/min
	2. mean value	133.60	126.50	123.01
	3. grouping	—	—	—
<p>Note . the tests control the type I comparisonwise error rate</p> <ul style="list-style-type: none"> <li>. <math>\alpha = 0.05</math></li> <li>. <math>df = 243</math></li> <li>. <math>MSE = 152.237</math></li> </ul>				

### 5.5.2.1 INTERACTION EFFECTS

There are no significant 3-way or 4-way interactions for makespan and mean flow time. But factors A and C have significant interaction effects for makespan and mean flow time. In addition, factors C and D also have significant interaction effects for the mean flow time at both 95% and 99% significance levels.

In the presence of significant interactions, we must be very careful in interpreting the results of the F-test for the main effects of factors A, C, and D on the mean flow time and the makespan values because the interactions may mask the main effects (Ott, 1984). In order to study the characteristics of the interactions, the sample means of associated groups are calculated in Table 5.9 and then plotted in Figures 5.3, 5.4, and 5.5 to graphically exhibit the relationships between factors A and C for the makespan and the mean flow time criteria and between factors C and D for the mean flow time criterion. Since these are all orderly interactions (e.g. in Figure 5.3, the order of the mean makespan values for levels of factor C is always the same even though the magnitude of the differences of the mean makespan values for levels of factor C may change with respect to levels of factor A), therefore the F-tests for the main effects of factors

A, C, and D for the mean flow time and the makespan are appropriate.

Furthermore, Figure 5.3 shows that WINQ with 12 pallets outperforms all other combinations with respect to the makespan criterion, while SPT with 16 pallets results in the longest makespan. In addition, SPT is very sensitive to the change in the maximum number of pallets allowed in the system while WINQ is the least sensitive. If FCFS is chosen as the dispatching rule with 16 pallets in the system the makespan value becomes significantly larger than that with 8 and 12 pallets. If WINQ is employed as the dispatching rule with 12 pallets in the system the makespan value becomes significantly shorter than that with 8 and 16 pallets. In case, at most 8 pallets are allowed in the system, WINQ is the best dispatching rule and SPT is the worst. In case a maximum number of 16 pallets are allowed in the system, then WINQ is still the best dispatching rule. However, a better decision is to keep 12 pallets in the system because it gives shorter makespan.

Figure 5.4 shows that WINQ with the smallest number of pallets in the system gives the best mean flow time value, while FCFS with the largest number of pallets (16) results in the largest mean flow time value. If, at most, eight pallets are allowed in the system, then there is no signif-

Table 5.9 Mean Makespan Values of Number of Pallets vs. Dispatching Rule, Mean Flow time values of Dispatching Rule vs. Number of Pallets and Cart Speed vs. Number of Pallets

1. mean makespans on AC cells				
factor A	factor C	number of pallets		
		8	12	16
dispatching rule	FCFS	483	482	495
	SPT	495	485	499
	WINQ	472	466	473
2. mean flow times on AC cells				
factor A	factor C	number of pallets		
		8	12	16
dispatching rule	FCFS	89.5	129.7	172.3
	SPT	89.5	125.9	166.5
	WINQ	87.2	125.3	163
3. mean flow times on CD cells				
factor D	factor C	number of pallets		
		8	12	16
cart speed (ft/min)	32	93	132.4	175.8
	64	87.9	124	167.6
	128	85.5	122	161.5



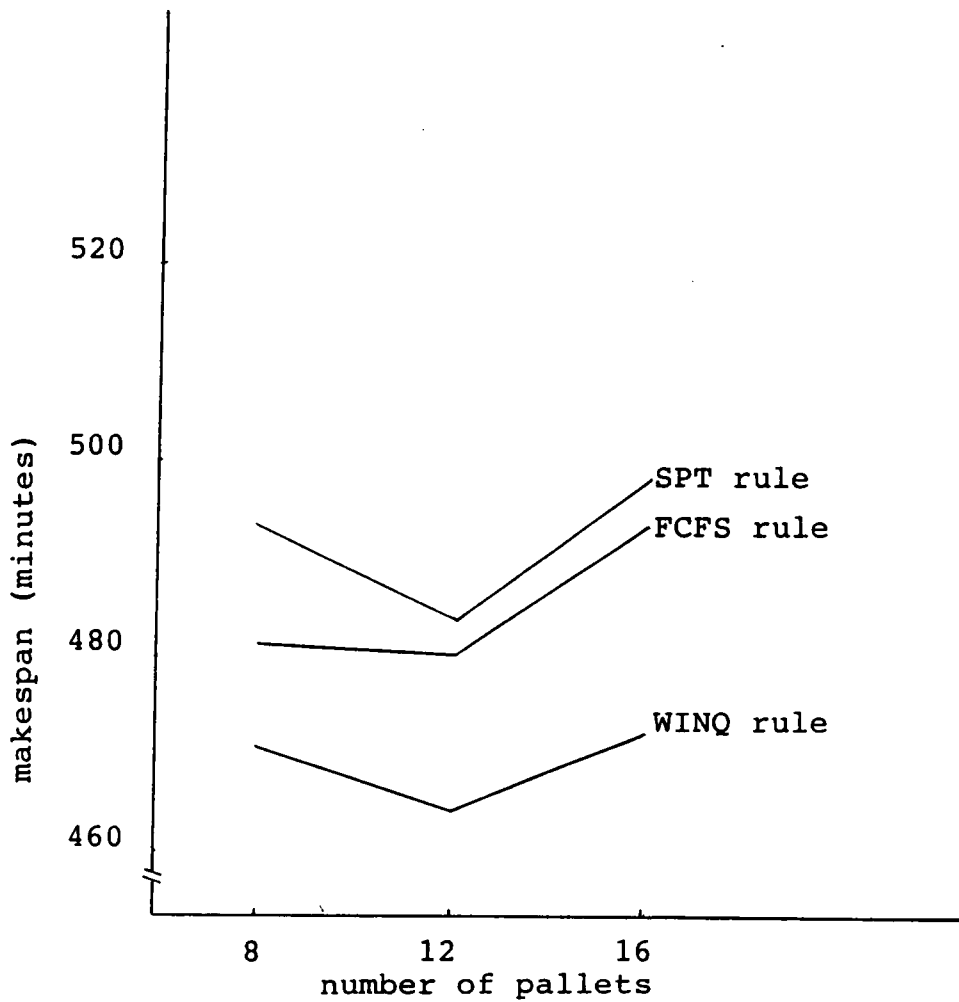


Figure 5.3 Interactions of Dispatching Rule Versus Maximum Number of Pallets in System on Makespan

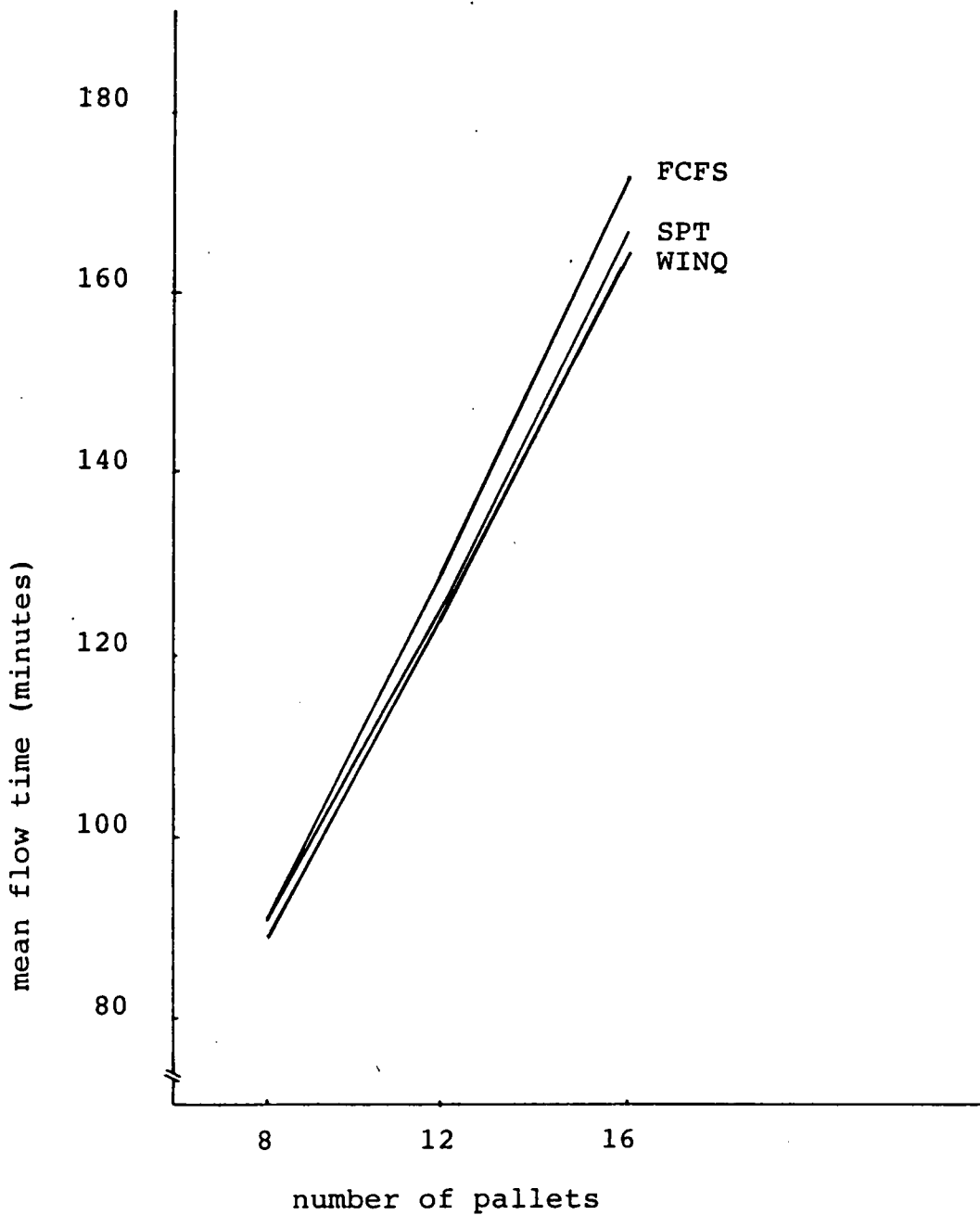


Figure 5.4 Interactions on Mean Flow Time of Dispatching Rule Versus Maximum Number of Pallets in System

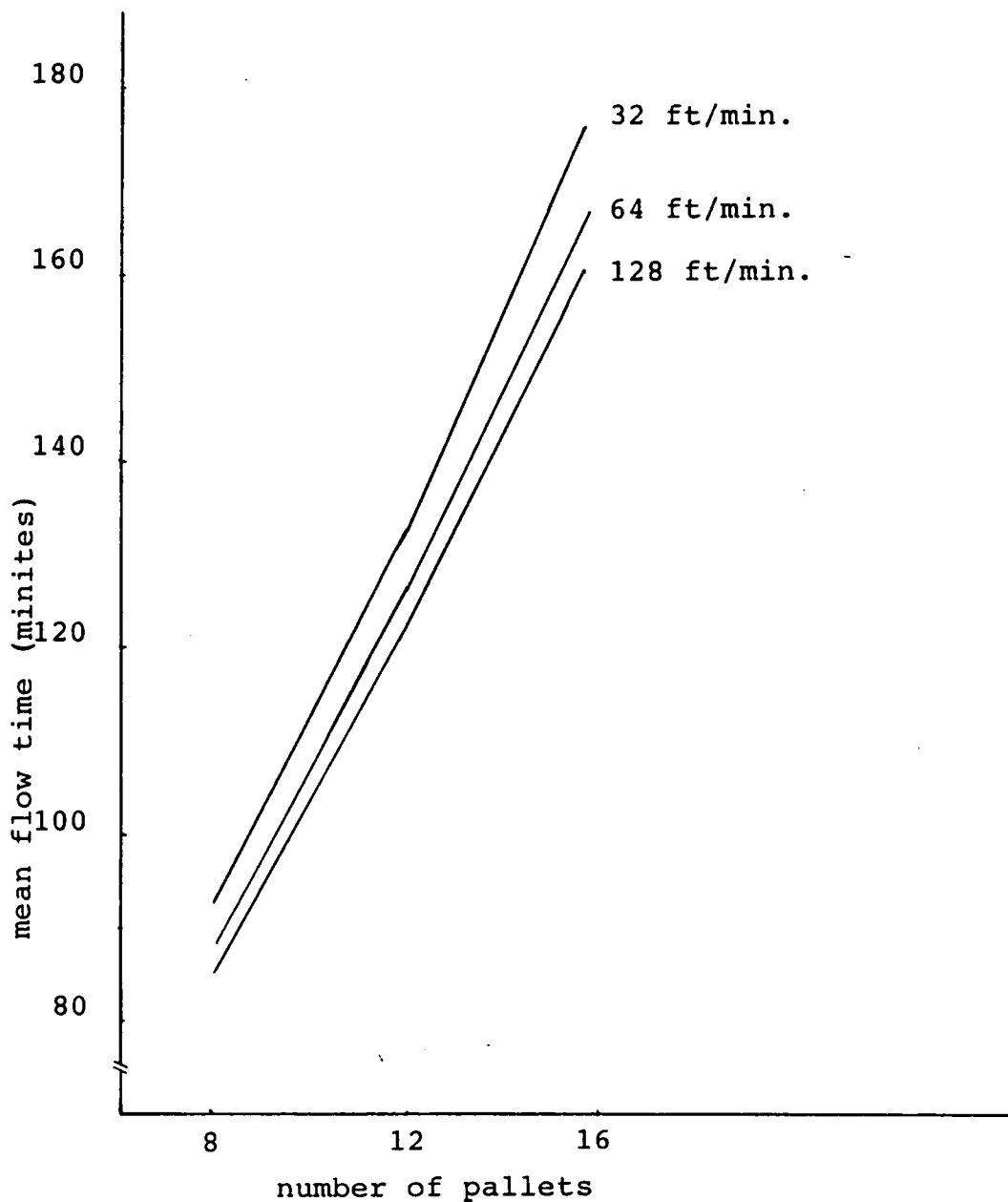


Figure 5.5 Interactions on Mean Flow Time of Cart Speed Versus Maximum number of Pallets in System

icant difference among the dispatching rules regarding the mean flow time criterion. When a maximum of 12 pallets are allowed in the system, SPT is as good as WINQ for the mean flow time criterion, while FCFS is the worst.

Figure 5.5 indicates that a combination of the smallest pallet number (8) in the system and the highest cart speed (128 ft/min) results in the lowest mean flow time value while the largest pallet number in the system (16) at the slowest cart speed (32 ft/min) gives the largest mean flow time. It also shows that the mean flow time consistently increases with an increment in the maximum number of pallets in the system and consistently decreases with an increment in cart speed.

#### 5.5.2.2 MAIN EFFECTS

The following conclusions are drawn based on the ANOVA and the DUNCAN tests presented in Tables 5.5, 5.6, 5.7, and 5.8.

##### (A) dispatching rule

In general, the effect of the dispatching rules is highly significant with respect to the makespan and the mean flow time criteria. The WINQ rule is the best dispatching rule for both the makespan and the mean flow time criteria. SPT

is the worst dispatching rule for makespan, but it appears better than FCFS for mean flow time.

(B) cart request rule

The cart request rule has no significant effect on makespan and mean flow time. This is probably because of no serious system congestion, no large variation in machine utilizations, and relative equal distance between workstations.

(C) maximum pallet number

The number of pallets in the system have a very significant effect on both the makespan and the mean flow time criteria. The lowest mean flow time value is obtained for the smallest number of pallets (8) in the system. But, the minimum makespan value is obtained for the medium number of pallets (12) in the system. This is because of the congestion phenomenon when there are too many pallets in the system, and the starvation phenomenon when there are too few parts in the system.

(D) cart speed

Cart speed also has a significant effect on both the mean flow time and the makespan values. As expected, higher cart

speed reduces makespan and also reduces mean flow time significantly. If the cart speed decreases from 64 ft/min to 32 ft/min, average makespan increases from 478.29 to 505.10 minutes, while mean flow time increases from 126.5 minutes to 133.6 minutes. Note that, the rates of decrement of the makespan and the mean flow time values decrease with an increase in cart speed, and at sufficiently high cart speeds, the transport time becomes negligible for the two system criteria.

## 5.6 SUMMARY

In this chapter, the simulation approach was briefly reviewed. Operational parameters and objectives of an FMS were then discussed before the example system and its simulation model were presented. The simulation model was first compared with the CAN-Q model under similar operational conditions. It was then used to validate the feasibility of the optimal solution obtained using the mathematical model(IM3). Feedback process was also discussed for the given set of parts.

A factorial experiment was designed to evaluate the effects of the dispatching rules, the cart request rules, cart speed, and the maximum number of pallets on the makespan and the mean flow time criteria over a given planning period (480 minutes in this example). Within the selected experimental

region of factorial design, results and findings were summarized and conclusion were drawn.

It was found that there is no significant effect of higher-level interactions among the factors on the makespan and the mean flow time values. For the mean flow time criteria, the smallest number of pallets and the highest cart speed together result in the shortest mean flow time. The WINQ rule with medium (12) number of pallets in the system results in the shortest makepan. WINQ is also the best dispatching rule for the makespan and the mean flow time criteria. SPT is the worst rule for the makespan criterion, while FCFS is the worst rule for the mean flow time criterion.

No significant differences exist among cart request rules on both the makespan and the mean flow time values in this study. Medium number of pallets (12 in this study) in the system can reduce makespan but more pallets in the system always cause larger mean flow time values. Higher cart speed reduces both the makespan and the mean flow time values.

## 6.0 CONCLUSIONS

In this research a hierarchical methodology was developed for the overall design of manufacturing systems. The methodology consists of solutions to the following four levels of problems: (1) manufacturing system selection, (2) shop loading, (3) machine loading and tool allocation, and (4) testing feasibility of a schedule and determining strategies for the operational control of the system. Although these problem levels are developed in a hierarchical sense, they can be applied independently by assuming appropriate inputs to the problem level under consideration. The third and the fourth level problems are addressed in this research for the flexible manufacturing system. Similar approach can be developed to solve these problems for other production systems.

The hierarchical methodology and the models are concluded in Section 6.1, which also summarized some general results obtained based on the experimentation conducted. Also, some findings that are specific to the FMS configuration and operating conditions considered in this research are summarized in Section 6.1. Possible extensions of this research are then suggested in Section 6.2.



## 6.1 THE HIERARCHICAL METHODOLOGY AND THE MODELS

The hierarchical approach for the overall design of manufacturing systems was initially proposed by Sarin and Wilhelm(1983). This research has further developed that hierarchical approach and has provided a quantitative tool for its implementation. The resulting hierarchical methodology is new and useful, and is easy to implement.

There is no comprehensive model available in the literature for the manufacturing system selection problem, the first level problem of the hierarchical methodology. The system selection mathematical model developed in this research provides a basic and an integrated relationship among the systems, system components, production requirements, and costs. The relationship enables an overall production cost to be analyzed during the initial design stage of a manufacturing system. Thus, the model provides a precise tool for simultaneously selecting manufacturing system(s), machines, material handling system, and for assigning each part family to the selected system(s). Several studies have been published in the literature for shop loading, scheduling, and sequencing problems. However, only a few are related to the multiple shop loading problem that the second level of the hierarchical methodology addresses. Those that are related are not computational efficient to use for problems of reasonable

size. See Section 2.2 for a review of some related work. The shop loading model developed in this research considers a system efficiency factor to account for factors like system congestion, blocking, and machine breakdown, and is very effective from the computational point of view.

Regarding the third level problem of machine loading and tool allocation in an FMS, several models have been suggested in the literature with little computational experience. The model developed in this research is a comprehensive model which provides part routings, and selects a cutting tool for each operation, taking into considerations tool life, system congestion, and tool magazine capacity limitation. The computational experience with this model indicates that it can be applied to solve relatively large size loading problems. At the fourth level of the hierarchical methodology a simulation approach was adopted to evaluate the feasibility of the predetermined system efficiency factor, machine loadings, and part routings. If the solution is infeasible, the mathematical models of appropriate levels are re-solved by adjusting system efficiency factor.

All the mathematical models developed in this methodology are linear in objective functions and constraints and are, therefore, relatively easier to solve than the non-linear models. By collecting sufficient manufacturing information

related to tooling, machining, part specification, and associated costs and implementing these models, this methodology can be repetitively and efficiently used to obtain optimal solutions, especially to cope with the ever-changing manufacturing environment.

Based on the experimentation conducted using the mathematical models, the following results can be concluded. The implications of some of these results have also been observed by other researchers, but this research has further justified them through the use of the proposed methodology and the models.

1. system selection

- a. each system can be the best choice under certain production requirements and cost values;
- b. the decision for the selection of a manufacturing system should be based not only on production demand but also on various cost factors;
- c. an overall minimum manufacturing cost may be achieved by using an integrated approach;
- d. system selection and system component requirement problems can be solved simultaneously;
- e. a mix of production systems can be better than any single production system for given production requirements;

2. shop loading
  - a. the multiple shop loading problem should be (and can be) formulated and solved as an overall minimization model;
  - b. some systems should not be operated under certain operating conditions and production demands in order to reduce overall operating costs;
  - c. it may not be the best policy to maximize the utilization of only one system, like FMS, if the manufacturing system consists of several production systems;
3. machine loading and tool allocation in an FMS
  - a. part scheduling problem is dramatically simplified by using a system efficiency factor and by leaving the sequencing problem to real-time control;
  - b. machining costs, part routings, and tool allocations are sensitive to changes in system and operation parameters such as tool slot limitation, system efficiency level, tool life, and tool availability;
  - c. machining cost increases by imposing a lower utilization level on each machine, that is, by minimizing the difference between machine utilizations;
  - d. the rate of increment of machining cost appears to be higher at lower system efficiency level.

The following findings relate to the operational control of an FMS and are specific to the FMS configuration and operat-

ing conditions considered in this research. Several similar types of findings have been reported in the literature, as discussed in Section 2.3.2.

1. system performances (corresponding makespan and mean flow time) are sensitive to system parameters and control rules applied;
2. for the given set of parts in the example problem, WINQ was found to be a better dispatching rule than SPT and FCFS for the makespan and the mean flow time criteria;
3. there exists some optimal number of pallets for an FMS, which results in the minimum makespan value; the makespan is generally prolonged because of machine starvation (less pallets in the system) or because of system congestion (too many pallets in the system). But the mean flow time value always increases with increase in the number of pallets in the system; and
4. the higher speed of the material handling system the greater reduction in the makespan and the mean flow time because system congestion and machine idleness are reduced in an FMS. But at sufficiently high speed and with sufficient queue and pallet capacity, the makespan and the mean flow time become insensitive to the speed of a material handling system.

## 6.2 POSSIBLE EXTENSIONS

The following recommendations can be made for further research in this area:

1. one possible extension is to link the hierarchical methodology to a manufacturing information system, part grouping system, and a process planning system to further facilitate the decision process;
2. the mathematical models were solved in this research using the MPSX-MIP/370 packages; some computation refinements for the solutions of these models were developed in Appendix B; the proposed algorithmic structure for these models can be further developed to obtain more efficient solution procedures;
3. a feedback procedure was proposed to link the mathematical models (IM2) and (IM3) with the simulation model to obtain an optimal (from the mathematical models) and feasible (from the simulation model) solution; the procedure can be implemented in a software package incorporating potentially good control strategies and system parameters to facilitate the solution process;
4. the system selection model is currently developed for a known and fixed demand over the planning horizon; this model can be extended to incorporate demand fluctuations for each part family over the planning horizon; this

would result in a model which is a better representation of reality;

5. several operational strategies can be further explored under various performance criteria for an FMS (e.g. maximization of system utilization(s) and minimization of material flow) by using the shop loading, the machine loading, and the simulation models; various dispatching rules, cart request rules, and part release rules, can be tested under various system and job parameter values (such as MHS speed, pallet number, queue capacity, system layouts, and part mixes) for different system performance measures; also, it is believed that some covariates can be incorporated in the statistical analysis model to identify the control rules which are generally good for any mix of parts; some candidates in this regard include: the differences in workstation utilizations, variations of distances among workstations, material flow pattern, and ratio of cart to station utilizations; and
6. lastly, this research has been devoted to the development of a methodology; this methodology can next be tested for implementation on a real-life situation.

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## APPENDIX A. MPSX/370 AND MIP/370

The MPSX/370 and MIP/370 packages are selected for this model because of their availability, efficiency, and large capacity. The Mathematical Programming System Extended/370 (MPSX/370) and the Mixed Integer Programming/370 (MIP/370) were developed by IBM. These were originally released in 1974 and were revised in 1979. They are composed of a set of procedures, all operating under the direction of a user control program. Each procedure has a specific function, such as input data conversion, building of a starting solution, primal optimization, solution editing, and others.

A user control program is a sequence of operations used to solve a given mathematical programming problem. It is specified in the form of control language statements which perform such functions as procedure calling, arithmetic statement evaluation, logical testing, titling, etc. Problem processing is done in two job steps; first, the control program is compiled; it is analyzed and transformed into an efficient executable program; and second, the program, containing the operations specified by the control program, is executed.

Two control languages are available with which to write control programs: MPSCL and ECL. MPS control Language (MPSCL)

is a language specific to MPSX/370 and MIP/370. It can be used by applications personnel who are not professional programmers. An MPSCL control program is compiled by a special compiler and executed by a special executor. Both compiler and executor are supplied to users as part of MPSX/370. MPSCL is specifically oriented towards the solution of simple mathematical programming problems which require neither sophisticated logical or arithmetical handling nor interfacing with other techniques.

Extended control language (ECL) is a language that has greater capacity than MPSCL. ECL is based on a multi-purpose high-level programming language, PL/I, and permits ECL processing of advanced mathematical programming applications. ECL facilities are part of MPSX/370, but the PL/I optimizing or checkout compiler is needed to compile ECL programs.

#### A.1 MPSX/370 PACKAGE

In MPSX/370, the MPSCL common procedures are initialization, problem file maintenance/startup, optimization, and output/solution analysis. The system macro INITIALZ in MPSCL sets parameters to standard values and establishes standard processing for demands that can be set by MIP/370 procedures. Although it is optional in an MPSCL control program, all of its functions must be provided by user before execution of

the first procedure, if it is not used as the first statement in the control program.

A problem file is a file that contains LP models and is created by the insertion of data describing the models. Once the problem file has been created, the original input data need not be processed again. Certain problem file maintenance procedures modify the data contained on the problem file and copy selected problems from one problem file to another. The most common procedure which performs problem file maintenance is CONVERT, which reads binary coded decimal (BCD) data and creates a machine independent problem file in packed binary format, while the problem file is being generated, comprehensive error checks are made, and statistics of the model are calculated for use by SETUP.

SETUP is one of the startup procedures, which accomplishes the second stage of data insertion and prepare a problem on the problem file for a specific optimization. SETUP prepares for the optimization, taking into account the particular problem and system environment. It reads a problem from the problem file, analyzes the problem statistics, the I/O device configuration, and the solution strategy. It then dynamically allocates available storage and builds the working files so that the optimization procedures can most efficiently solve the problem.

OPTIMIZ is one option of the optimization procedures, which take their input data from the work files and optimize the model. OPTIMIZE (an MPSCL macro) automatically performs all functions required when optimizing a problem.

SOLUTION is one of the procedures which put out printout solutions computed during the optimization and/or by postoptimal procedures and create reports for model formulation, debugging, and analysis. Solution produces in output form, the solution (activity levels, reduced cost, original cost coefficients, right hand side elements, and dual activities) determined by a preceding iterative procedure.

## A.2 MIP/370 PACKAGE

The Mixed Integer Programming/370 (MIP/370) is an extended package of MPSX/370 for studying mixed integer linear programming problems. An integer programming problem must first be optimized by considering all integer variables as being continuous. It is, therefore, an ordinary linear programming problem, whose optimization is performed by the linear programming procedures of MPSX/370. The optimal solution obtained is called an optimal continuous solution.

The problem is then searched for integer solutions; that is, feasible solutions satisfying the constraints and giving in-

teger values to the integer variables. The integer variables are forced to take on integer values using a branch and bound technique with heuristic rules. The search for integer solutions is performed by MIP/370 procedures. The MIP/370 has the following features:

1. automatic and flexible search for integer solutions. The user can decide which of the MIP/370 heuristic rules are to be followed.
2. freezing of an integer solution, that is, fixed integer variables at their current values. This allows post optimal studies on the continuous variables
3. options for provisional stops and different ways of resuming the search
4. extensive, automatic survey of the search
5. no any extra rows or variables are generated in a model.

The search for integer solution is aimed at finding an optimal integer solution. A straightforward strategy leads to a series of integer solutions tending towards the optimal integer solution. When an integer solution is found, it is not immediately known whether it is optimal. The search must therefore continue until either a better solution is found or it is proved that no better solution exists. For problems with many integer variables and relative loose constraints or many equivalent coefficients, good solutions are quickly



found, but it takes a long computation time to either improve them slightly or prove their optimality, generating a lot of equivalent solutions and large searching tree.

However, the Models requiring too long a run for a complete solution, can still be studied within a reasonable computation time. For such models, the user can evaluate the results of a partial search and then decide whether to stop the study or continue a restricted search. The information produced by the run may help indicate whether better integer solutions exist. Since a MIP control program is a program consisting of MPSX/370 statements supplemented by specific MIP/370 statements, knowledge of MPS control language is indispensable.

Three MIP/370 levels of use are available, corresponding to 3 levels of increasing capability and complexity. The levels are called straightforward, advanced; and sophisticated use. In straightforward use, OPTIMIX is the MPSCL system macro which provides an automatic search for integer solutions according to a standard strategy. The search starts from the continuous optimal solution and leads to a series of integer solutions directed towards an optimal solution and to the proof of the optimality of the last integer solution. It provides for interrupting the search and resuming it later. This allows for analyzing integer solutions already obtained

in order to decide whether it is advantageous to continue the search.

In advanced use, a number of procedures can be called to take advantages of all their capabilities. MIXSTART is the procedure which initiates the search for integer solutions or resumes a search that was previously interrupted and saved. MIXFLOW performs the search. MIXSAVE saves all elements necessary to resume the search later. MIXSTATS prints an extensive survey of the current status of the search. MIXFIX freezes an integer solution by fixing the activities of the integer variables to their current integer values in the work-matrix, thus allowing for postoptimal studies of the continuous variables.

In sophisticated use, a certain number of parameters can be used to define search strategies. MIP/370 offers two levels of options: either a number of built-in search strategies or facilities to build our own search strategy by defining which rules of the branch and bound technique are to be used in the search for integer solutions.

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## APPENDIX B. REFINEMENT OF THE SOLUTION METHODOLOGY FOR THE MATHEMATICAL MODELS

### B.1 INTRODUCTION

Three integer programming models have been formulated and demonstrated through example problems. These models can be solved to a moderate size of practical problems in a feasible computation time by using a MPSX-MIP/370 package. If the problems are big and computational efficiency becomes a major concern, it may be worthwhile to explore special structures existing in each model and to develop a specialized code to solve them more efficiently. Obviously, the three models (IM1, IM2, and IM3) possess special structures in constraint sets and decision variables. The second model (IM2) can be viewed as a fixed charge uncapacitated location problem, while the first and the third models are close to a generalized assignment problem.

Many approaches and algorithms have been proposed in the literature to solve these two types of problems, taking advantages of the special structure in the formulation.

The shop loading model (IM2) determines the systems to operate as well as the job allocations such that the total operation cost is minimized. Solution procedures for solving a fixed charge location problem have been proposed in the literature. Efroymsen and Ray(1966) presented a branch and bound algorithm to solve this problem. This algorithm was improved upon by Khumawala(1972). Spielberg(1966) also developed implicit enumeration algorithms for the location problem with some side constraints. Bilde and Krarup(1977) and Erlenkotter(1978) devised similar multiplier adjustment methods for the Lagrangian relaxation for solving the location problem. Cornuejols, Fisher, and Nemhauser(1977) also proposed a subgradient method with the Lagrangian relaxation to solve this type of problem.

The system selection model (IM1) can be viewed as a quasi-generalized assignment problem by expressing the general-type integer variables,  $y_{kn}$ , in terms of 0-1 integer variables. A generalized assignment problem, usually, is considerably large in terms of variables and constraints and is often hard-to-solve. For this type of problems, Beale and Tomlin(1970) and Forrest et al.(1974) proposed branching rules for exploring the special ordered set(SOS) of constraints. The basic idea is to fix at zero or one as many integer variables as possible, such that a subproblem is

easier to be fathomed. Based on this concept, Martin and Sweeney(1983) and Martin et al.(1985) implemented two similar solution strategies called ideal column algorithm and reduced cost branch and bound algorithm for integer models with SOS constraints and 0-1 integer variables. The proposed methods restrict a large portion of the integer variables to zero on one branch. The advantage is that the original integer program is solved by optimizing a series of smaller, more tightly restricted, integer problems. Another approach called Lagrangian relaxation, on the other hand, is more often applied to solve generalized assignment problems. Successful experiences were reported in Fisher(1973, 1975), Ross and Soland(1975), and Chalmet and Gelders(1976), among others.

Following this discussion, a solution approach for solving these models is proposed. In particular, a method based on the Lagrangian relaxation and the subgradient method will be proposed. The machine loading and tool allocation model (IM3), with minor variation, is used to illustrate the solution procedure.

## B.2 THE FORMULATION

An illustrative integer program, designated as (P), is constructed as below:

$$Z = \min \sum_i \sum_j \sum_t \sum_k c_{ijtk} \cdot x_{ijtk}$$

subject to

$$\sum_i \sum_j \sum_k u_{ijtk} \cdot x_{ijtk} \leq (TL)_t \quad \text{for all } t \quad (1)$$

$$\sum_i \sum_j \sum_t u_{ijtk} \cdot x_{ijtk} \leq T_k \quad \text{for all } k \quad (2)$$

(P)

$$\sum_i \sum_j \sum_t \sum_k u_{ijtk} \cdot x_{ijtk} \leq e \cdot T_k \quad (3)$$

$$\sum_i \sum_j \sum_k x_{ijtk} \leq 1 \quad \text{for all } t \quad (4)$$

$$\sum_i \sum_j \sum_t s_{t} \cdot x_{ijtk} \leq (TS)_k \quad \text{for all } k \quad (5)$$

$$\sum_t \sum_k x_{ijtk} = 1 \quad \text{for all } i \text{ and } j \quad (6)$$

$$x_{ijtk} = 0 \text{ or } 1 \quad \text{for all } i, j, t, \text{ and } k \quad (7)$$

This formulation is a variation of the model (IM3) in Chapter 4 but appears tighter than that model. Since it eliminates  $t \cdot k$  constraints and  $t \cdot k$  decision variables, the problem size in terms of variables and constraints is much smaller. It possesses a better structure that can be explored. The limitation added to the new model, in practical term, is that one

tool can be used for only one operation. Therefore, the new model is advantageous in the situation that a large number of tools are available and the problem size and computation time are major concerns. This example problem is used to illustrate how the Lagrangian relaxation and subgradient methods are applied for these types of models.

### B.3 THE LAGRANGIAN RELAXATION PROBLEM

The Lagrangian relaxation procedure is to include a set of complicated constraints of a general mixed integer programming (MIP) model into the objective function in a Lagrangian fashion (with fixed multipliers) (Geofrion, 1974). Dualizing the set of constraints produces a Lagrangian problem that is easy to solve (comparing with the case of solving the original problem or the linear programming (LP) relaxation), and the value of the optimal solution is a lower bound (for a minimization problem) on the optimal value of the original problem. A Lagrangian problem is usually used in place of a linear programming relaxation to provide bounds in a branch and bound algorithm. The Lagrangian approach offers the following advantages over LP relaxation.



1. It provides a stronger lower bound in a branch and bound algorithm for (P) than LP relaxation (Geofrion, 1974, Fisher, 1981).
2. The Lagrangian problem is easier to solve.
3. It provides a medium for selecting branching variables and for choosing the next branch to explore.
4. Lagrangian minimization may yield optimal or good feasible solution to the primal (Fisher, Northup and Shapiro, 1975).

Therefore, a candidate problem for applying Lagrangian relaxation is a problem which has a special structure in constraint sets and for which the Lagrangian relaxation problem becomes readily solvable after dualizing the complicating constraints so that the original model can be solved more efficiently. For solving the model (P), a Lagrangian approach implemented in a branch and bound algorithm will be proposed after a discussion of the following important issues:

1. selection of constraint sets to be relaxed
2. solution of the Lagrangian problem with fixed multiplier values
3. adjustment of multiplier values to improve bounds

4. use of the Lagrangian relaxation to obtain a feasible solution for (P).

Decisions on these issues must be made before the development of a branch and bound algorithm using the Lagrangian relaxation approach to solve the problem.

#### B.4 SELECTION OF A CONSTRAINT SET TO BE RELAXED

Two criteria are commonly used in choosing between competing relaxations. They are: (1) the sharpness of the bounds produced and (2) the amount of computation required to obtain these bounds. Usually, the selection of a relaxation involves a tradeoff between these two criteria.

For the integer programming model (P), there are two natural Lagrangian relaxations. The first one is obtained by dualizing constraints (1) to (5). That is,

$$\begin{aligned}
 Z_D(v) = \min & \sum_i \sum_j \sum_t \sum_k c_{ijtk} \cdot x_{ijtk} + \sum_t v^1 \left( \sum_i \sum_j \sum_k u_{ijtk} \cdot x_{ijtk} \right. \\
 & \left. x_{ijtk} - (TL)_t \right) + \sum_k v^2 \left( \sum_i \sum_j \sum_t u_{ijtk} \cdot x_{ijtk} - T_k \right) \\
 & + v^3 \left( \sum_i \sum_j \sum_t \sum_k x_{ijtk} - e \sum_k T_k \right) + \sum_t v^4 \left( \sum_i \sum_j \sum_k x_{ijtk} - 1 \right)
 \end{aligned}$$

$$+ \sum_k v^5 \left( \sum_i \sum_j \sum_t s_{ijtk} \cdot x_{ijtk} - (TS)_k \right)$$

subject to (6) and (7)

Further simplification gives,

$$Z_D(v) = \min \sum_i \sum_j \left( \sum_t \sum_k c_{ijtk} + \sum_t \sum_k v^1 u_{ijtk} + \sum_t \sum_k v^2 u_{ijtk} + \sum_t \sum_k v^3 u_{ijtk} \right. \\ \left. + \sum_t \sum_k v^4 + \sum_t \sum_k v^5 s_{ijtk} \right) x_{ijtk} - \sum_t v^1 (TL)_t - \sum_k v^2 (T)_k \\ \text{(LR1)} \\ + v^3 e \sum_k T_k - \sum_t v^4 - \sum_k v^5 (TS)_k$$

subject to (6) and (7).

This Lagrangian problem, designated (LR1), is defined for all  $v \geq 0$ . This is a necessary condition for  $Z_D(v) \leq Z$  to hold.

This problem can be easily solved by determining  $\min_{tk} (c_{ijtk} + \sum_t \sum_k v^1 u_{ijtk} + \sum_t \sum_k v^2 u_{ijtk} + \sum_t \sum_k v^3 u_{ijtk} + \sum_t \sum_k v^4 + \sum_t \sum_k v^5 s_{ijtk})$  for each  $i$  and  $j$  and setting the associated  $x_{ijtk} = 1$ .

Remaining  $x_{ijtk}$  are set to be zero.

The second relaxation is obtained by dualizing constraint (6). That is,

$$Z(q) = \min_D \sum_i \sum_j \sum_t \sum_k c_{ijtk} \cdot x_{ijtk} + \sum_i \sum_j q_{ij} \left( \sum_t \sum_k x_{ijtk} - 1 \right)$$

subject to constraints (1) to (5) and (7),  
 which upon further simplification gives

$$Z_D(q) = \min \sum_t \sum_k \sum_i \sum_j (c_{ijtk} + q_{ij}) x_{ijtk} - \sum_i \sum_j q_{ij}$$

subject to (1)-(5) and (7).

This Lagrangian problem, designated (LR2), is more difficult to solve than the first one since it is not readily separable over  $t$  and  $k$ . So, it can not be directly transformed into a multiple 0-1 knapsack type of problem and, therefore, will take longer computation time to solve.

Although, in general, the second Lagrangian relaxation problem requires more computation time, it is difficult to know how many times each Lagrangian problem must be solved in optimizing the dual. It is also impossible to know analytically the time required to solve the LP relaxation of (P) (Fisher, 1981).

To compare the relative sharpness of the bounds produced by the two Lagrangian relaxation (LR1 and LR2) and the LP relaxation, assume

$$Z_D(V) = \max Z_D(v)$$

$$Z_D(Q) = \max Z_D(q), \text{ and}$$

$Z_{LP}$  = optimal value of the problem (P) with integrality relaxed.

$Z_D(Q)$  is generally better than  $Z_D(V)$ , which is equal to  $Z_{LP}$ . This relationship is analytically proved in Geoffrion(1974) and Fisher(1981). The reason is that the first problem (LR1) has the integrality property and the second (LR2) does not .

Nonetheless, empirical results show that many successful Lagrangian problems have had integrality property. For these applications, Fisher(1981) attributed their success to the fact that:

1. the LP relaxation closely approximated the original problem, and
2. the method used to optimize the dual (usually subgradient method) was more powerful than methods available for solving the (generally large) LP relaxation.

For this proposed model, the first relaxation (LR1) is adopted. That is, the dualization of the resource constraints for which the Lagrangian problem is easy to solve.

## B.5 SOLUTION TO THE LAGRANGIAN PROBLEM WITH FIXED MULTIPLIER VALUES

The Lagrangian multipliers are fixed values used for the problem (P) to dualize the resource constraints, thus forming a Lagrangian problem in which the operation assignment constraints appear explicitly, while the resource constraints appear only in the Lagrangian function. Because the remaining constraints do not interact among operations, the problem of minimizing the Lagrangian decomposes into a subproblem for each operation, and appears much easier to solve. The solution process was previously discussed. Minimization of the Lagrangian with fixed multiplier values yields a lower bound on the optimal solution to the original problem (P). The multiplier values are then adjusted iteratively to strengthen the value of this bound and to tighten the problem. The initial values for the multiplier vectors are usually set to zero to quickly obtain a lower bound.

## B.6 ADJUSTMENT OF MULTIPLIER VALUES TO OBTAIN A STRONGER LOWER BOUND

Three approaches are commonly used in the Lagrangian relaxation method to adjust the multiplier values to improve on the bound; namely, (1) the subgradient method (Held, Wolfe and

Crowder,1974, Bazzara and Serali,1981), (2) applications of simplex method implemented by using column generation technique (Fisher,1973, Fisher, Northup and Shapiro,1975), and (3) the multiplier adjustment method(Held and Karp,1970, Erlenkotter,1978). Since the subgradient method is easy to program and has been proved effective on many practical problems(Fisher,1981), it is adopted in the proposed algorithm to adjust multiplier values to improve the bounds.

The subgradient method is an adaptation of gradient method in which gradients are replaced by subgradients. Given initial multiplier values  $v^0$ , a sequence  $(v^k)$  can be generated by the rule(Fisher,1981):

$$v^{k+1} = v^k + t_k (Ax^k - b),$$

where  $x^k$  is an optimal solution to the Lagrangian problem (LR1),  $(Ax-b)$  correspond to the dualized constraints, and  $t_k$  is a positive scalar step size, which is commonly determined by the formula:

$$t_k = (\alpha_k(Z^* - Z_D(v^k)))/|Ax^k - b|^2,$$

Where  $\alpha_k$  is a scalar satisfying  $0 \leq \alpha_k \leq 2$  and  $Z^*$  is an upper bound on  $Z_D(v)$ , frequently obtained by applying a heuristic

to the original problem (P). The sequence  $\alpha_k$  is often determined by setting  $\alpha_0 = 2$  and taking half of it whenever  $Z_D(v^k)$  can not increase in some fixed number of iterations. Fisher (1981) summarized empirical results and concluded that this rule worked well although it is not guaranteed to satisfy the sufficient condition (complementary slackness) for optimal convergence. It was also concluded in the same paper that the bounds provided by Lagrangian relaxation are usually extremely sharp. The bounds are typically very close to the optimal value of the original problem like (P). An analytical evidence to this effect is given in the paper by Cornuejols, Fisher, and Nemhauser(1977).

In searching for a feasible solution to (P), if a solution vector  $x$ , for a given  $v$ , satisfies the three conditions:

1.  $x$  is optimal to  $(LR1_v)$
2.  $Ax \leq b$ , and
3.  $v(Ax - b) = 0$ ,

then  $x$  is an optimal solution to the original problem. If  $x$  satisfies (1) and (2) but not (3), then  $x$  is a suboptimal solution of P with  $d = v(b - Ax)$  (Geofrion, 1974). In other words, if the dualized terms  $(Ax - b)$  in the objective function of LR1 are equalities, this solution is also optimal to



(P). If the terms contain some inequalities, the solution is then a feasible solution to (P).

However, a solution obtained from the Lagrangian problem (LR1) is rarely feasible to the original problem (P). On the other hand, it often happens that a solution to LR1 obtained while optimizing the dual will be nearly feasible for (P) and can be made feasible by tinkering with the variable values using a method called Lagrangian heuristic. Successful applications of the Lagrange heuristic method to construct primal feasible solution by using Lagrangian solutions were reported in the studies by Fisher(1973) and Cornuejols, Fisher, and Nemhauser(1977). For the problem (P), some heuristic rules considering the special relationship between the variables  $x_{ijtk}$  and  $y_{tk}$  are to be developed. In addition, the active node with the smallest lower bound on the subproblems will be selected to branch from. The  $y_{tk}$  variable with  $\min_{tk} (\sum_i \sum_j c_{ijtk} / \sum_i \sum_j x_{ijtk})$  may also be chosen to branch from (by assigning the associated  $y_{tk}$  with 1). Other criteria can also be devised and tested for implementation in the algorithm.

## B.7 SOLUTION PROCEDURE

The Lagrangian relaxation method and the issues discussed in the preceding paragraphs are implemented in a branch and bound algorithm. Closely referring to the steps proposed by Fisher, Northup, and Shapiro(1975), the solution search procedure is suggested in Figure B.1. The branch and bound procedure used for the Lagrangian problem is exactly the same as that used for the LP relaxation. The search process at each node decomposes the problem into collective and exhaustive (in IP sense) subproblems.

With this approach the initial Lagrangian relaxation problem is formulated and solved with a set of selected initial multiplier values to get a lower bound. A series of checks are then performed to test: (1) if the subproblem can be fathomed, (2) if a feasible solution to (P) is obtained, (3) if any heuristic rule should be applied to search for a primal feasible solution, and (4) if further search for tighter bound on this subproblem is needed. When neither of these answers is positive, a new subproblem (an active node) is selected to branch according to some decision rule.

If a Lagrangian solution is feasible to the original problem, the possibility of updating the incumbent solution and

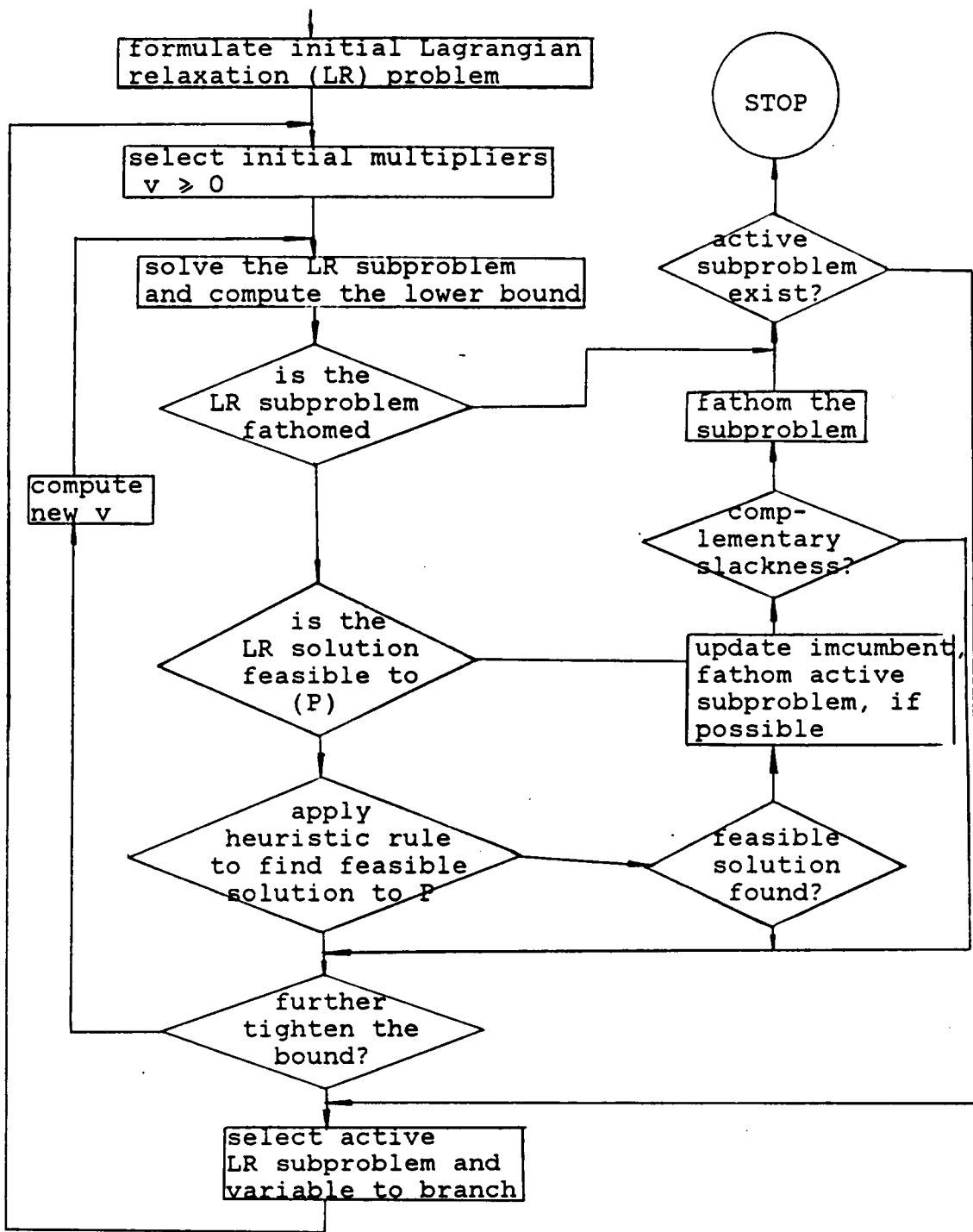


Figure B.1 A Branch and Bound Algorithm for The Lagrangian Relaxation Problem

fathoming some active subproblems (nodes) is checked. Furthermore, if the complementary slackness also holds, then the subproblem is fathomed. The process stops when no active node exists. For the subgradient method, the number of iterations required to get to a tight lower bound depends on the type of node being explored. At higher-level nodes of the tree, a larger number of iterations are commonly used to get a stronger lower bound. In addition, initial multiplier values for each subproblem are usually set to the terminal multiplier values at its preceding node.

APPENDIX C. COMPUTER CODE FOR THE SYSTEM SELECTION MODEL

```

0
//B023CHEN JOB 40495, INUD87, MSGLEVEL=(2,1), REGION=1500K, TIME=2
/*JOBPARM CARDS=10000, LINES=10
/*PRIORITY IDLE
/*ROUTE PRINT MV51.LOCAL
//MPSCL PROC ACT='A43CB0.', VOL=USER07
/*DEFAULT MOD1
/*1A, 2A, 3A, 4A, 5A, 6A, 7A
//*****
//*
//* MPSX/370
//*
//* CATALOG PROCEDURE FOR RUNNING MPSCL.
//*
//* APS SPD 12/07/84 PTL
//*
//*****
//MPSCOMP EXEC PGM=DPLCOMP
//STEPLIB DD UNIT=SYSDA, VOL=SER=&VOL, DISP=SHR,
// DSN=&ACT.DPL.MPSX370
//SCRATCH1 DD UNIT=SYSDA, SPACE=(TRK, (2,2))
//SCRATCH2 DD UNIT=SYSDA, SPACE=(TRK, (2,2))
//SCRATCH3 DD UNIT=SYSDA, SPACE=(TRK, (2,2))
//SCRATCH4 DD UNIT=SYSDA, SPACE=(TRK, (2,2))
//SYSMLCP DD UNIT=SYSDA, DISP=(NEW, PASS), SPACE=(TRK, (2,2))
//SYSPRINT DD SYSOUT=A, DCB=(RECFM=FBA, LRECL=133, BLKSIZE=133)
//MPSEXEC EXEC PGM=DPLEXEC, COND=(0, NE, MPSCOMP), PARM='TASK'
//STEPLIB DD UNIT=SYSDA, VOL=SER=&VOL, DISP=SHR,
// DSN=&ACT.DPL.MPSX370
//ETA1 DD UNIT=SYSDA, SPACE=(CYL, (25))
//ETA2 DD UNIT=SYSDA, SPACE=(CYL, (25))
//MATRIX1 DD UNIT=SYSDA, SPACE=(CYL, (25))
//SCRATCH1 DD UNIT=SYSDA, SPACE=(CYL, (25))
//SCRATCH2 DD UNIT=SYSDA, SPACE=(CYL, (25)), SEP=(SCRATCH1)
//PROBFILE DD UNIT=SYSDA, SPACE=(CYL, (25))
//MIXWORK DD UNIT=SYSDA, SPACE=(CYL, (25))
//*REWORK DD UNIT=SYSDA, SPACE=(CYL, (25))
//*REFILE DD UNIT=SYSDA, SPACE=(CYL, (25))
//*FORTFILE DD UNIT=SYSDA, VOL=SER=&VOL, DISP=(NEW, KEEP),
//* DSN=&ACT.FORTFILE, SPACE=(CYL, (25,25)),
//* DCB=(RECFM=VBS, LRECL=204, BLKSIZE=10204)
//SYSMLCP DD DSN=* .MPSCOMP.SYSMLCP, DISP=(OLD, DELETE)
//SYSPRINT DD SYSOUT=A, DCB=(RECFM=FBA, LRECL=133, BLKSIZE=133)
//SYSPUNCH DD SYSOUT=B
//END PEND

```

```

//          EXEC  MPSCL
//MPSCOMP.SYSIN DD  *
PROGRAM
INITIALZ
MOVE(XDATA, 'TEST1')
MOVE(XPBNAME, 'PBFILE')
CONVERT('SUMMARY')
XNODES=8000
SETUP('BOUND', 'BOUD', 'NODES', XNODES)
MOVE(XOBJ, 'Z')
MOVE(XRHS, 'RH')
OPTIMIZE
SOLUTION
XMXFNLOG=0
OPTIMIX
EXIT
PEND

```

```

/*
//MPSEXEC.SYSIN  DD  *
NAME  TEST1  FREE
ROWS
N  Z
E  R1
E  R2
E  R3
E  R4
E  R5
E  R6
E  R7
E  R8
L  R9
L  R10
L  R11
L  R12
L  R13
L  R14
L  R15
L  R16
L  R17
L  R18
L  R19
L  R20
L  R21
L  R22
L  R23
L  R24
L  R25
L  R26
L  R27
L  R28

```

L R29  
 L R30  
 E R31  
 E R32  
 E R33  
 E R34  
 E R35  
 E R36  
 E R37  
 E R38  
 L R39  
 L R40  
 L R41  
 L R42  
 L R43  
 L R44  
 L R45  
 L R46

COLUMNS

	DEBE	'MARKER'	'INTORG'
X11 R1	1	R9	20
X11 R10	16		
X11 Z	27		
X12 R1	1	R14	10
X12 R15	8		
X12 Z	25		
X13 R1	1	R18	10
X13 R19	8		
X13 Z	27		
X21 R2	1	R10	12
X21 R11	18	R12	16
X21 Z	25		
X22 R2	1	R15	15
X22 R16	8		
X22 Z	23		
X23 R2	1	R19	15
X23 R20	8		
X23 Z	26		
X24 R2	1	R21	15
X24 R22	8		
X24 Z	215		
X31 R3	1	R10	24
X31 R12	12	R13	16
X31 Z	27		
X32 R3	1	R15	12
X32 R16	6	R17	8
X32 Z	25		
X41 R4	1	R12	12
X41 R13	22		
X41 Z	43		

X42	R4	1	R16	6
X42	R17	11		
X42	Z	43		
X51	R5	1	R10	32
X51	R12	16		
X51	Z	49		
X52	R5	1	R15	16
X52	R16	8		
X52	Z	47		
X53	R5	1	R19	16
X53	R20	8		
X53	Z	38		
X54	R5	1	R21	16
X54	R22	8		
X54	Z	220		
X61	R6	1	R11	24
X61	R13	28		
X61	Z	29		
X62	R6	1	R15	12
X62	R17	14		
X62	Z	27		
X71	R7	1	R9	40
X71	R10	18	R12	20
X71	Z	31		
X72	R7	1	R14	20
X72	R15	9	R16	10
X72	Z	29		
X73	R7	1	R18	20
X73	R19	8	R20	10
X73	Z	29		
X81	R8	1	R11	16
X81	R12	22	R13	14
X81	Z	39		
X82	R8	1	R15	8
X82	R16	11	R17	7
X82	Z	37		
Y11	R9	-10	R23	1
Y11	R39	1	R40	1
Y11	Z	60		
Y21	R10	-10	R23	1
Y21	R39	1	R40	1
Y21	Z	50		
Y31	R11	-10	R23	1
Y31	R39	1	R40	1
Y31	Z	58		
Y41	R12	-10	R23	1
Y41	R39	1	R40	1
Y41	Z	80		
Y51	R13	-10	R23	1
Y51	R39	1	R40	1



Y51	Z	75		
Y62	R14	-10	R24	1
Y62	R41	1	R42	1
Y62	Z	105		
Y72	R15	-10	R24	1
Y72	R41	1	R42	1
Y72	Z	112		
Y82	R16	-10	R24	1
Y82	R41	1	R42	1
Y82	Z	122		
Y92	R17	-10	R24	1
Y92	R41	1	R42	1
Y92	Z	116		
Y63	R18	-16	R25	1
Y63	R43	1	R44	1
Y63	R45	1	Z	75
Y73	R19	-16	R25	1
Y73	R43	1	R44	1
Y73	R45	1	Z	80
Y83	R20	-16	R25	1
Y83	R43	1	R44	1
Y83	R45	1	Z	90
Y74	R21	-20	R26	1
Y74	R46	1	Z	80
Y84	R22	-20	R26	1
Y84	R46	1	Z	90
M11	R23	-200	R27	1
M11	R31	1	Z	95
M21	R23	-200	R27	1
M21	R32	1	Z	190
M12	R24	-200	R28	1
M12	R33	1	Z	95
M22	R24	-200	R28	1
M22	R34	1	Z	190
M33	R25	-200	R29	1
M33	R35	1	Z	210
M43	R25	-200	R29	1
M43	R36	1	Z	421
M53	R25	-200	R29	1
M53	R37	1	Z	585
M64	R26	-200	R30	1
M64	R38	1	Z	205
Q11	R31	-1	R39	200
Q21	R32	-1	R40	200
Q12	R33	-1	R41	200
Q22	R34	-1	R42	200
Q33	R35	-1	R43	200
Q43	R36	-1	R44	200
Q53	R37	-1	R45	200
Q64	R38	-1	R46	200

```

Q64 Z -200
      FINE 'MARKER' 'INTEND'
RHS
RH R1 1 R2 1
RH R3 1 R4 1
RH R5 1 R6 1
RH R7 1 R8 1
RH R27 1 R28 1
RH R29 1 R30 1
RH R39 240 R40 260
RH R41 240 R42 260
RH R43 206 R44 212
RH R45 224 R46 209
BOUNDS
UP BOUD Y11 100
UP BOUD Y21 100
UP BOUD Y31 100
UP BOUD Y41 100
UP BOUD Y51 100
UP BOUD Y62 100
UP BOUD Y72 100
UP BOUD Y82 100
UP BOUD Y92 100
UP BOUD Y63 100
UP BOUD Y73 100
UP BOUD Y83 100
UP BOUD Y74 100
UP BOUD Y84 100
ENDATA
/*
//

```

APPENDIX D. COMPUTER CODE FOR THE SHOP LOADING MODEL

```
//BO23CHEN JOB 40495, INUD87, MSGLEVEL=(2,1), REGION=600K, TIME=2
/*LONGKEY CSCHEN
/*PRIORITY IDLE
/*JOBPARM CARDS=10000, LINES=10
//*ROUTE PRINT MVSI.LOCAL
//MPSCL PROC ACT='A43CBO.', VOL=USER07
//*MOD2
//*****
//*
//* MPSX/370
//*
//* CATALOG PROCEDURE FOR RUNNING MPSCL.
//*
//* APS SPD 12/07/84 PTL
//*
//*****
//MPSCOMP EXEC PGM=DPLCOMP
//STEPLIB DD UNIT=SYSDA, VOL=SER=&VOL, DISP=SHR,
// DSN=&ACT.DPL.MPSX370
//SCRATCH1 DD UNIT=SYSDA, SPACE=(TRK, (2, 2))
//SCRATCH2 DD UNIT=SYSDA, SPACE=(TRK, (2, 2))
//SCRATCH3 DD UNIT=SYSDA, SPACE=(TRK, (2, 2))
//SCRATCH4 DD UNIT=SYSDA, SPACE=(TRK, (2, 2))
//SYSMLCP DD UNIT=SYSDA, DISP=(NEW, PASS), SPACE=(TRK, (2, 2))
//SYSPRINT DD SYSOUT=A, DCB=(RECFM=FBA, LRECL=133, BLKSIZE=133)
//MPSEXEC EXEC PGM=DPLEXEC, COND=(0, NE, MPSCOMP), PARM='TASK'
//STEPLIB DD UNIT=SYSDA, VOL=SER=&VOL, DISP=SHR,
// DSN=&ACT.DPL.MPSX370
//ETA1 DD UNIT=SYSDA, SPACE=(CYL, (6))
//ETA2 DD UNIT=SYSDA, SPACE=(CYL, (6))
//MATRIX1 DD UNIT=SYSDA, SPACE=(CYL, (6))
//SCRATCH1 DD UNIT=SYSDA, SPACE=(CYL, (6))
//SCRATCH2 DD UNIT=SYSDA, SPACE=(CYL, (6)), SEP=(SCRATCH1)
//PROBFILE DD UNIT=SYSDA, SPACE=(CYL, (6))
//MIXWORK DD UNIT=SYSDA, SPACE=(CYL, (2))
//*REPWORK DD UNIT=SYSDA, SPACE=(CYL, (6))
//*REPFILE DD UNIT=SYSDA, SPACE=(CYL, (6))
//*FORTFILE DD UNIT=SYSDA, VOL=SER=&VOL, DISP=(NEW, KEEP),
//* DSN=&ACT.FORTFILE, SPACE=(CYL, (2, 1)),
//* DCB=(RECFM=VBS, LRECL=204, BLKSIZE=1024)
//SYSMLCP DD DSN=*.MPSCOMP.SYSMLCP, DISP=(OLD, DELETE)
//SYSPRINT DD SYSOUT=A, DCB=(RECFM=FBA, LRECL=133, BLKSIZE=133)
//SYSPUNCH DD SYSOUT=B
//END PEND
// EXEC MPSCL
//MPSCOMP.SYSIN DD *
PROGRAM
INITIALZ
```

```

MOVE(XDATA, 'TEST1')
MOVE(XPBNAME, 'PBFILE')
CONVERT('SUMMARY')
SETUP('BOUND', 'BOUD')
MOVE(XOBJ, 'Z')
MOVE(XRHS, 'RH')
OPTIMIZE
XMXFNLOG=0
OPTIMIX
EXIT
PEND

```

```

/*
//MPSEXEC.SYSIN DD *
NAME TEST1 FREE
ROWS

```

```

N Z
E R1
E R2
E R3
E R4
E R5
E R6
E R7
E R8
E R9
E R10
E R11
E R12
E R13
E R14
E R15
L R16
L R17
L R18
L R19
L R20
L R21
L R22
L R23
L R24
L R25
L R26
L R27
L R28
L R29
L R30
L R31
L R32
L R33
G R34

```

```

COLUMNS

```

	DEBE	'MARKER'	'INTORG'
X11	Z	30	R1 1
X11	R16	14	R17 3
X11	R18	13	
X12	Z	35	
X12	R1	1	R20 14
X12	R21	3	R22 13
X13	Z	25	R1 1
X13	R24	5	R25 4
X13	R26	5	R27 6
X14	Z	20	R28 2
X14	R29	7	R30 6
X14	R1	1	
X14	R33	15	R34 15
X15	R1	1	R32 1
X15	Z	55	
X21	Z	54	
X21	R2	1	R16 20
X21	R17	14	R18 14
X21	R19	6	
X22	Z	59	R2 1
X22	R20	20	R21 14
X22	R22	14	R23 6
X25	R2	1	R32 1
X25	Z	79	
X31	Z	37	R3 1
X31	R16	17	R17 10
X31	R19	10	
X32	Z	42	R3 1
X32	R20	17	R21 10
X32	R23	10	
X33	Z	32	R3 1
X33	R24	7	R25 3
X33	R26	7	R27 7
X34	Z	27	R3 1
X34	R28	4	R29 7
X34	R30	5	R31 4
X34	R33	20	R34 20
X35	Z	62	R3 1
X35	R32	1	
X41	Z	18	R4 1
X41	R16	2	R17 4
X41	R18	2	R19 10
X42	Z	23	R4 1
X42	R20	2	R21 4
X42	R22	2	R23 10
X43	Z	25	R4 1
X43	R24	1	R25 3
X43	R26	2	R27 6
X44	Z	22	R4 1
X44	R29	5	R30 2

X44	R31	3		
X44	R33	10	R34	10
X45	R4	1	R32	1
X45	Z	43		
X51	Z	61	R5	1
X51	R16	11	R17	15
X51	R18	25	R19	10
X52	Z	56	R5	1
X52	R20	11	R21	15
X52	R22	25	R23	10
X53	Z	56	R5	1
X53	R24	10	R25	5
X53	R27	5		
X54	R5	1	R28	7
X54	R29	6	R31	3
X54	Z	51		
X54	R33	16	R34	16
X55	R5	1	R32	1
X55	Z	76		
X61	Z	41	R6	1
X61	R16	21	R18	10
X61	R19	10		
X62	Z	46	R6	1
X62	R20	21	R22	10
X62	R23	10		
X65	Z	66	R6	1
X65	R32	1		
X71	Z	25	R7	1
X71	R16	3	R17	11
X71	R18	6	R19	5
X72	Z	30	R7	1
X72	R20	3	R21	11
X72	R22	6	R23	5
X73	Z	20	R7	1
X73	R24	4	R25	4
X73	R26	4	R27	4
X75	R7	1	R32	1
X75	Z	50		
X81	Z	19	R8	1
X81	R16	7	R17	4
X81	R18	2	R19	6
X82	Z	24	R8	1
X82	R20	7	R21	4
X82	R22	2	R23	6
X83	Z	24	R8	1
X83	R24	6	R25	1
X83	R26	5		
X84	Z	21	R8	1
X84	R28	2	R29	4
X84	R30	3		
X84	R33	9	R34	9

X85 Z	44	R8	1
X85 R32	1		
X91 Z	13	R9	1
X91 R16	3	R17	6
X91 R18	3		
X92 Z	18	R9	1
X92 R20	3	R21	6
X92 R22	3		
X93 Z	19	R9	1
X93 R24	2	R25	4
X93 R27	4		
X94 Z	24	R9	1
X94 R28	2	R29	4
X94 R33	6	R34	6
X95 Z	38	R9	1
X95 R32	1		
X101 Z	22	R10	1
X101 R16	5	R18	5
X101 R19	12		
X102 Z	27	R10	1
X102 R20	5	R22	5
X102 R23	12		
X103 Z	29	R10	1
X103 R24	10	R26	4
X104 Z	26	R10	1
X104 R29	4	R30	2
X104 R31	5		
X104 R33	11	R34	11
X105 Z	47	R10	1
X105 R32	1		
X111 Z	14	R11	1
X111 R17	10	R18	4
X112 Z	19	R11	1
X112 R21	10	R22	4
X113 Z	17	R11	1
X113 R25	6	R26	4
X115 Z	39	R11	1
X115 R32	1		
X121 Z	34	R12	1
X121 R16	3	R17	4
X121 R18	12	R19	15
X122 Z	39	R20	3
X122 R21	4	R22	12
X122 R23	15	R12	1
X123 Z	30	R12	1
X123 R25	5	R26	7
X123 R27	12		
X124 Z	26	R12	1
X124 R28	6	R29	4
X124 R30	4	R31	6
X124 R33	20	R34	20

X125	Z	59	R12	1
X125	R32	1		
X131	Z	28	R13	1
X131	R17	12	R18	4
X131	R19	12		
X132	Z	33	R13	1
X132	R21	12	R22	4
X132	R23	12		
X133	Z	32	R13	1
X133	R24	3	R25	6
X133	R26	2	R27	7
X135	Z	53	R13	1
X135	R32	1		
X141	Z	46	R14	1
X141	R16	10	R17	10
X141	R18	10	R19	16
X142	Z	51	R20	10
X142	R21	10	R22	10
X142	R23	16	R14	1
X143	Z	43	R14	1
X143	R24	10	R25	5
X143	R27	15		
X144	Z	36	R14	1
X144	R28	10	R29	2
X144	R30	4	R31	8
X144	R33	24	R34	24
X145	Z	72	R14	1
X145	R32	1		
X151	Z	26	R16	3
X151	R17	3	R18	12
X151	R19	8	R15	1
X152	Z	31	R15	1
X152	R20	3	R21	3
X152	R22	12	R23	8
X155	Z	51	R15	1
X155	R32	1		
Y1	Z	10	R16	-40
Y1	R17	-40	R18	-40
Y1	R19	-40		
Y2	Z	20	R20	-40
Y2	R21	-40	R22	-40
Y2	R23	-40		
Y3	Z	15	R24	-24
Y3	R25	-24	R26	-24
Y3	R27	-24		
Y4	Z	30	R28	-24
Y4	R29	-32	R30	-16
Y4	R31	-24		
Y4	R33	-96	R34	-72
Y5	Z	2	R32	-15
	FINE	'MARKER'	'INTEND'	



```
RHS
RH R1 1 R2 1
RH R3 1 R4 1
RH R5 1 R6 1
RH R7 1 R8 1
RH R9 1 R10 1
RH R11 1 R12 1
RH R13 1 R14 1
RH R15 1
BOUNDS
UP BOUD Y1 1
UP BOUD Y2 1
UP BOUD Y3 1
ENDATA
/*
//
```

APPENDIX E. COMPUTER CODE FOR MACHINE AND TOOL LOADING MODEL

```

//B023CHEN JOB 40495,INUD87,MSGLEVEL=(2,1),REGION=600K,TIME=2
/*LONGKEY CSCHEN
/*PRIORITY IDLE
/*JOBPARM CARDS=10000,LINES=10
//*ROUTE PRINT MVS1.LOCAL
//MPSCL PROC ACT='A43CB0.',VOL=USER07
//*MOD3 DEFAULT CASE
//*****
//*
//* MPSX/370
//*
//* CATALOG PROCEDURE FOR RUNNING MPSCL.
//*
//* APS SPD 12/07/84 PTL
//*
//*****
//MPSCOMP EXEC PGM=DPLCOMP
//STEPLIB DD UNIT=SYSDA,VOL=SER=&VOL,DISP=SHR,
// DSN=&ACT.DPL.MPSX370
//SCRATCH1 DD UNIT=SYSDA,SPACE=(TRK,(2,2))
//SCRATCH2 DD UNIT=SYSDA,SPACE=(TRK,(2,2))
//SCRATCH3 DD UNIT=SYSDA,SPACE=(TRK,(2,2))
//SCRATCH4 DD UNIT=SYSDA,SPACE=(TRK,(2,2))
//SYSMLCP DD UNIT=SYSDA,DISP=(NEW,PASS),SPACE=(TRK,(2,2))
//SYSPRINT DD SYSOUT=A,DCB=(RECFM=FBA,LRECL=133,BLKSIZE=133)
//MPSEXEC EXEC PGM=DPLEXEC,COND=(0,NE,MPSCOMP),PARAM='TASK'
//STEPLIB DD UNIT=SYSDA,VOL=SER=&VOL,DISP=SHR,
// DSN=&ACT.DPL.MPSX370
//ETA1 DD UNIT=SYSDA,SPACE=(CYL,(6))
//ETA2 DD UNIT=SYSDA,SPACE=(CYL,(6))
//MATRIX1 DD UNIT=SYSDA,SPACE=(CYL,(6))
//SCRATCH1 DD UNIT=SYSDA,SPACE=(CYL,(6))
//SCRATCH2 DD UNIT=SYSDA,SPACE=(CYL,(6)),SEP=(SCRATCH1)
//PROBFILE DD UNIT=SYSDA,SPACE=(CYL,(6))
//MIXWORK DD UNIT=SYSDA,SPACE=(CYL,(2))
//*REPWORK DD UNIT=SYSDA,SPACE=(CYL,(6))
//*REPROFILE DD UNIT=SYSDA,SPACE=(CYL,(6))
//*FORTFILE DD UNIT=SYSDA,VOL=SER=&VOL,DISP=(NEW,KEEP),
//* DSN=&ACT.FORTFILE,SPACE=(CYL,(2,1)),
//* DCB=(RECFM=VBS,LRECL=204,BLKSIZE=1024)
//SYSMLCP DD DSN=*.MPSCOMP.SYSMLCP,DISP=(OLD,DELETE)
//SYSPRINT DD SYSOUT=A,DCB=(RECFM=FBA,LRECL=133,BLKSIZE=133)
//SYSPUNCH DD SYSOUT=B
//END PEND
// EXEC MPSCL
//MPSCOMP.SYSIN DD *
PROGRAM

```

```

INITIALZ
MOVE(XDATA, 'TEST1')
MOVE(XPBNAME, 'PBFILE')
CONVERT('SUMMARY')
SETUP('BOUND', 'BOUD')
MOVE(XOBJ, 'Z')
MOVE(XRHS, 'RH')
OPTIMIZE
XMXFNLOG=0
OPTIMIX
EXIT
PEND

```

```

/*
//MPSEXEC.SYSIN DD *
NAME TEST1 FREE
ROWS
N Z
E R1
E R2
E R3
E R4
E R5
E R6
E R7
E R8
E R9
E R10
E R11
E R12
E R13
E R14
E R15
E R16
L R17
L R18
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```

L R34  
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E R81  
E R82  
E R83

E R84  
 E R85  
 E R86  
 E R87  
 E R88  
 E R89  
 E R90  
 E R91  
 E R92  
 E R93  
 E R94  
 L R95  
 G R96  
 G R97  
 G R98  
 G R99

COLUMNS

	DEBE	'MARKER'	'INTORG'
X1111	Z	22	R1 1
X1111	R51	104	R55 104
X1111	R21	1	R95 104
X1111	R96	104	
X1112	Z	23	R1 1
X1112	R22	1	R52 110
X1112	R55	110	R95 110
X1112	R97	110	
X1123	Z	14	R1 1
X1123	R23	1	R53 101
X1123	R56	101	R95 101
X1123	R98	101	
X1242	Z	35	R2 1
X1242	R26	1	R52 120
X1242	R58	120	R95 120
X1242	R97	120	
X1243	Z	30	R2 1
X1243	R27	1	R53 106
X1243	R58	106	R95 106
X1243	R98	106	
X1271	Z	14	R2 1
X1271	R32	1	R51 68
X1271	R61	68	R95 68
X1271	R96	68	
X1272	Z	29	R2 1
X1272	R33	1	R52 130
X1272	R61	130	R95 130
X1272	R97	130	
X1362	Z	27	R3 1
X1362	R30	1	R52 110
X1362	R60	110	R95 110
X1362	R97	110	

X1363	Z	21	R3	1
X1363	R31	1	R53	118
X1363	R60	118	R95	118
X1363	R98	118		
X14A1	Z	16	R4	1
X14A1	R37	1	R51	84
X14A1	R64	84	R95	84
X14A1	R96	84		
X14A2	Z	7	R4	1
X14A2	R38	1	R52	76
X14A2	R64	76	R95	76
X14A2	R97	76		
X14D4	Z	19	R4	1
X14D4	R43	1	R54	100
X14D4	R67	100	R95	100
X14D4	R99	100		
X2111	Z	21	R5	1
X2111	R21	1	R51	114
X2111	R55	114	R95	114
X2111	R96	114		
X2112	Z	35	R5	1
X2112	R22	1	R52	126
X2112	R55	126	R95	126
X2112	R97	126		
X2131	Z	28	R5	1
X2131	R24	1	R51	114
X2131	R57	114	R95	114
X2131	R96	114		
X2132	Z	21	R5	1
X2132	R25	1	R52	98
X2132	R57	98	R95	98
X2132	R97	98		
X2283	Z	33	R6	1
X2283	R34	1	R53	119
X2283	R62	119	R95	119
X2283	R98	119		
X22G1	Z	54	R6	1
X22G1	R46	1	R51	25
X22G1	R70	25	R95	25
X22G1	R96	25		
X23A1	R7	1	R37	1
X23A1	R51	106	R64	106
X23A1	Z	27	R95	106
X23A1	R96	106		
X23A2	R7	1	R38	1
X23A2	R52	66	R64	66
X23A2	Z	19	R95	66
X23A2	R97	66		
X23H3	Z	42	R7	1
X23H3	R47	1	R53	29

X23H3	R71	29	R95	29
X23H3	R98	29		
X2442	R8	1	R26	1
X2442	R52	116	R58	116
X2442	Z	14	R95	116
X2442	R97	116		
X2443	R8	1	R27	1
X2443	R53	112	R58	112
X2443	Z	25	R95	112
X2443	R98	112		
X24C1	R8	1	R41	1
X24C1	R51	96	R66	96
X24C1	Z	17	R95	96
X24C1	R96	96		
X24C3	R8	1	R42	1
X24C3	R53	84	R66	84
X24C3	Z	34	R95	84
X24C3	R98	84		
X31C1	R9	1	R41	1
X31C1	R51	67	R66	67
X31C1	Z	10	R95	67
X31C1	R96	67		
X31C3	R9	1	R42	1
X31C3	R53	102	R66	102
X31C3	Z	26	R95	102
X31C3	R98	102		
X31F4	R9	1	R45	1
X31F4	R54	134	R69	134
X31F4	Z	14	R95	134
X31F4	R99	134		
X3293	R10	1	R35	1
X3293	R53	110	R63	110
X3293	Z	32	R95	110
X3293	R98	110		
X3294	R10	1	R36	1
X3294	R54	120	R63	120
X3294	Z	25	R95	120
X3294	R99	120		
X32I4	Z	40	R10	1
X32I4	R48	1	R54	40
X32I4	R72	40	R95	40
X32I4	R99	40		
X33B2	R11	1	R39	1
X33B2	R52	117	R65	117
X33B2	Z	17	R95	117
X33B2	R97	117		
X33B4	R11	1	R40	1
X33B4	R54	132	R65	132
X33B4	Z	22	R95	132
X33B4	R99	132		

X33J2	R11	1	R49	1
X33J2	R52	47	R73	47
X33J2	Z	27	R95	47
X33J2	R97	47		
X3431	R12	1	R24	1
X3431	R51	82	R57	82
X3431	Z	8	R95	82
X3431	R96	82		
X3432	R12	1	R25	1
X3432	R52	85	R57	85
X3432	Z	17	R95	85
X3432	R97	85		
X34E2	R12	1	R44	1
X34E2	R52	110	R68	110
X34E2	Z	19	R95	110
X34E2	R97	110		
X4123	R13	1	R23	1
X4123	R53	49	R56	49
X4123	Z	22	R95	49
X4123	R98	49		
X4142	R13	1	R26	1
X4142	R52	114	R58	114
X4142	Z	31	R95	114
X4142	R97	114		
X4143	R13	1	R27	1
X4143	R53	140	R58	140
X4143	Z	37	R95	140
X4143	R98	140		
X4251	R14	1	R28	1
X4251	R51	137	R59	137
X4251	Z	36	R95	137
X4251	R96	137		
X4254	R14	1	R29	1
X4254	R54	118	R59	118
X4254	Z	29	R95	118
X4254	R99	118		
X42K2	R14	1	R50	1
X42K2	R52	38	R74	38
X42K2	Z	39	R95	38
X42K2	R97	38		
X43D4	R15	1	R43	1
X43D4	R54	120	R67	120
X43D4	Z	35	R95	120
X43D4	R99	120		
X43E2	R15	1	R44	1
X43E2	R52	115	R68	115
X43E2	Z	41	R95	115
X43E2	R97	115		
X4471	R16	1	R32	1
X4471	R51	68	R61	68



X4471	Z	13	R95	68
X4471	R96	68		
X4472	R16	1	R33	1
X4472	R52	53	R61	53
X4472	Z	8	R95	53
X4472	R97	53		
X4483	R16	1	R34	1
X4483	R53	87	R62	87
X4483	Z	24	R95	87
X4483	R98	87		
Y11	R17	10	R21	-20
Y11	R75	1		
Y12	R18	10	R22	-20
Y12	R75	1		
Y23	R19	14	R23	-20
Y23	R76	1		
Y31	R17	8	R24	-20
Y31	R77	1		
Y32	R18	8	R25	-20
Y32	R77	1		
Y42	R18	12	R26	-20
Y42	R78	1		
Y43	R19	12	R27	-20
Y43	R78	1		
Y51	R17	13	R28	-20
Y51	R79	1		
Y54	R20	13	R29	-20
Y54	R79	1		
Y62	R18	6	R30	-20
Y62	R80	1		
Y63	R19	6	R31	-20
Y63	R80	1		
Y71	R17	5	R32	-20
Y71	R81	1		
Y72	R18	5	R33	-20
Y72	R81	1		
Y83	R19	18	R34	-20
Y83	R82	1		
Y93	R19	12	R35	-20
Y93	R83	1		
Y94	R20	12	R36	-20
Y94	R83	1		
YA1	R17	11	R37	-20
YA1	R84	1		
YA2	R18	11	R38	-20
YA2	R84	1		
YB2	R18	4	R39	-20
YB2	R85	1		
YB4	R20	4	R40	-20
YB4	R85	1		

YC1	R17	13	R41	-20
YC1	R86	1		
YC3	R19	13	R42	-20
YC3	R86	1		
YD4	R20	12	R43	-20
YD4	R87	1		
YE2	R18	15	R44	-20
YE2	R88	1		
YF4	R20	12	R45	-20
YF4	R89	1		
YG1	R17	4	R46	-20
YG1	R90	1		
YH3	R19	4	R47	-20
YH3	R91	1		
YI4	R20	5	R48	-20
YI4	R92	1		
YJ2	R18	5	R49	-20
YJ2	R93	1		
YK2	R18	4	R50	-20
YK2	R94	1		

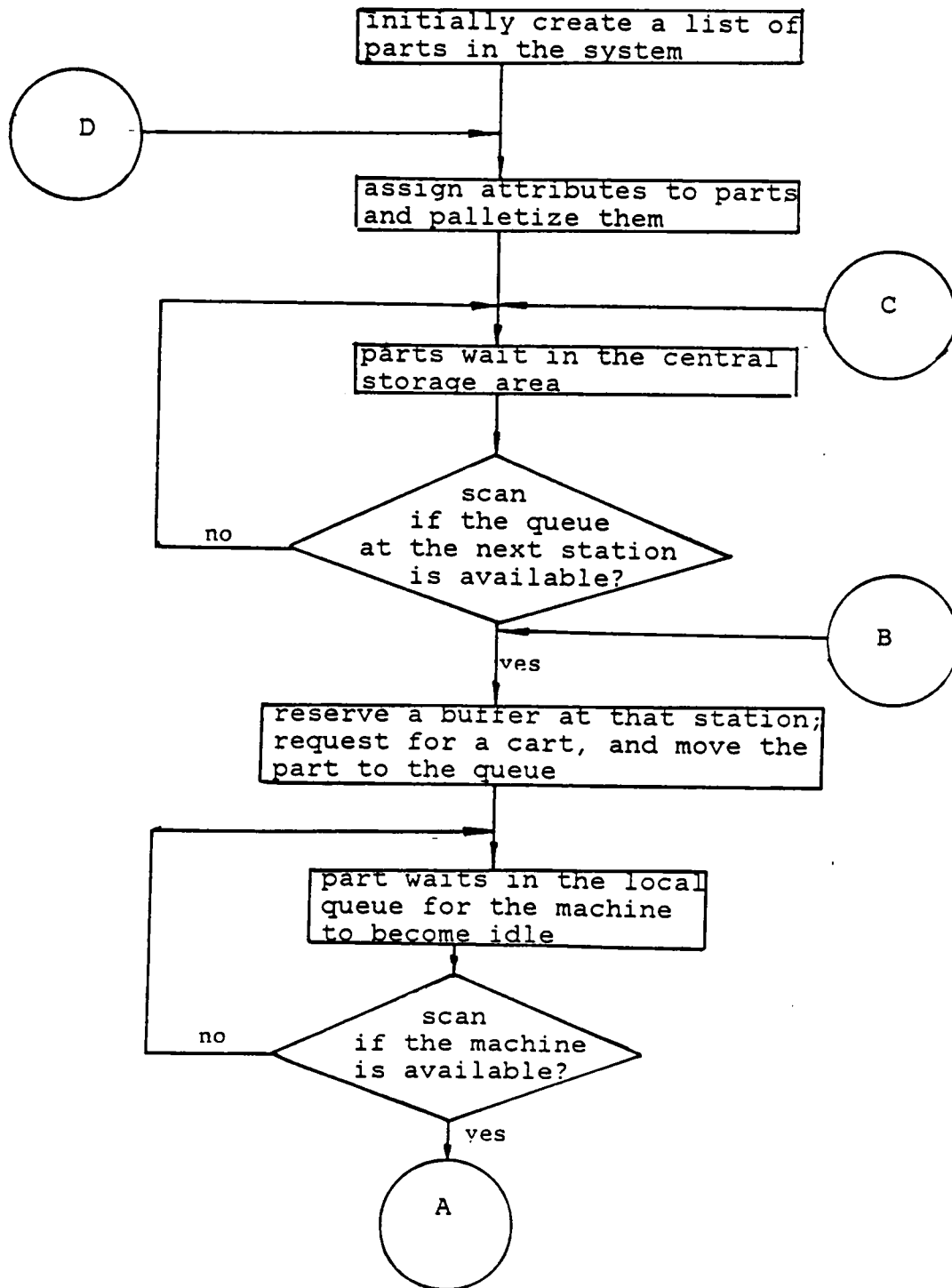
FINE 'MARKER' 'INTEND'

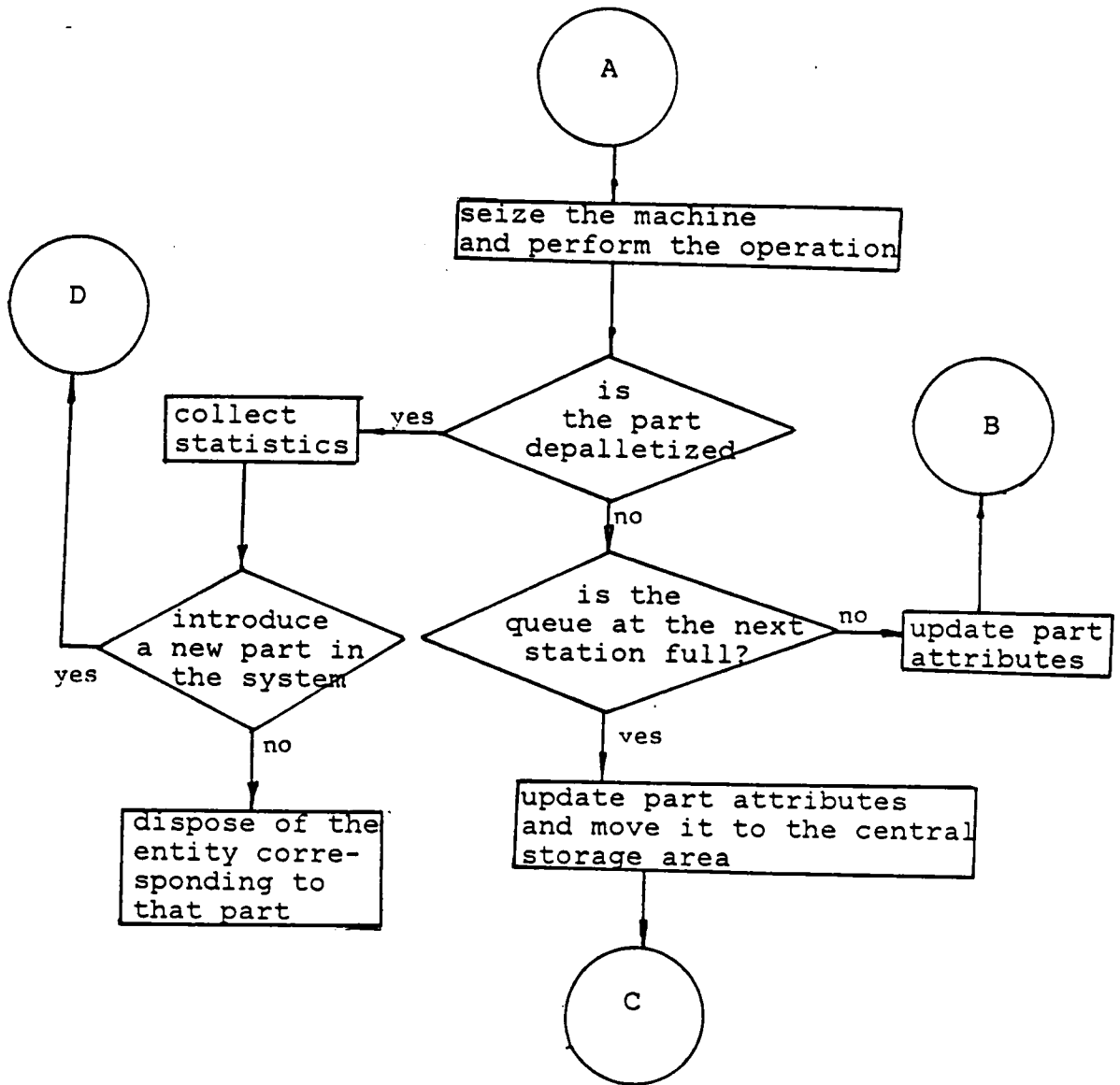
RHS

RH	R1	1	R2	1
RH	R3	1	R4	1
RH	R5	1	R6	1
RH	R7	1	R8	1
RH	R9	1	R10	1
RH	R11	1	R12	1
RH	R13	1	R14	1
RH	R15	1	R16	1
RH	R17	60	R18	60
RH	R19	60	R20	60
RH	R51	480	R52	480
RH	R53	480	R54	480
RH	R55	150	R56	150
RH	R57	150	R58	150
RH	R59	150	R60	150
RH	R61	150	R62	150
RH	R63	150	R64	150
RH	R65	150	R66	150
RH	R67	150	R68	150
RH	R69	150	R70	150
RH	R71	150	R72	150
RH	R73	150	R74	150
RH	R75	1	R76	1
RH	R77	1	R78	1
RH	R79	1	R80	1
RH	R81	1	R82	1
RH	R83	1	R84	1
RH	R85	1	R86	1

```
RH R87 1 R88 1
RH R89 1 R90 1
RH R91 1 R92 1
RH R93 1 R94 1
RH R95 1536
RH R96 246 R97 246
RH R98 246 R99 246
BOUNDS
UP BOUD Y11 2
UP BOUD Y12 2
ENDATA
/*
//
```

APPENDIX F. BASIC PART FLOW DIAGRAM OF THE SIMULATION MODEL





Appendix F. BASIC PART FLOW DIAGRAM OF THE SIMULATION MODEL

APPENDIX G. ENTITY ATTRIBUTES FOR THE SIMAN MODEL

A(1) = job type

A(2) = operation sequence number for the current operation

A(3) = station number for current operation

A(4) = position of processing time in parameter list

A(5) = processing time for current operation

A(6) = sequence number for next operation

A(7) = station number for next operation

A(8) = queue number, the in-coming queue for the station for next operation

A(9) = for storage of the index of the selected transporter unit

A(10) = arrival time of an entity

M = attribute of an entity denoting its current station number

## APPENDIX H. SIMAN VARIABLES

- X(1) = number of part type 1 created to the system  
X(2) = number of part type 2 created to the system  
X(3) = number of part type 3 created to the system  
X(4) = number of part type 4 created to the system  
X(5) = nominal queue length of the in-coming queue  
at station 1  
X(6) = nominal queue length of the in-coming queue  
at station 2  
X(7) = nominal queue length of the in-coming queue  
at station 3  
X(8) = nominal queue length of the in-coming queue  
at station 4  
X(9) = nominal queue length of the in-coming queue  
at station 5  
X(10)= total number of part type 1 to be completed  
X(11)= total number of part type 2 to be completed  
X(12)= total number of part type 3 to be completed  
X(13)= total number of part type 4 to be completed  
X(14)= used to calculate times between two entities  
leaving the system  
X(15)= capacity of in-coming queue at station 1  
X(16)= capacity of in-coming queue at station 2  
X(17)= capacity of in-coming queue at station 3  
X(18)= capacity of in-coming queue at station 4  
X(19)= capacity of in-coming queue at station 5  
J = system index variable, an integer  
NR(I)= the number of busy units of resource I

$NQ(I)$ = the number of entities residing in queue I

$NT(I)$ = the number of busy units of transporter I



## APPENDIX I. QUEUES FOR THE SIMAN MODEL

file(1) = for entities waiting to be palletized at station 5  
file(2) = for palletized entities waiting at station 5 to be transported to station 6  
file(3) = queue at station 6 (central storage) for jobs going to station 1  
file(4) = queue at station 6 (central storage) for jobs going to station 2  
file(5) = queue at station 6 (central storage) for jobs going to station 3  
file(6) = queue at station 6 (central storage) for jobs going to station 4  
file(7) = queue at station 6 (central storage) for jobs going to station 5  
file(8) = queue at station 1  
file(9) = queue at station 2  
file(10)= queue at station 3  
file(11)= queue at station 4  
file(12)= queue at station 5  
file(13)= (dummy) queue at station 1 for entities out-going to station 6  
file(14)= (dummy) queue at station 2 for entities out-going to station 6  
file(15)= (dummy) queue at station 3 for entities out-going to station 6  
file(16)= (dummy) queue at station 4 for entities out-going to station 6  
file(18)= (dummy) queue at station 6 for jobs out-going to station 1

file(19)= (dummy) queue at station 6 for jobs out-going to station 2

file(20)= (dummy) queue at station 6 for jobs out-going to station 3

file(21)= (dummy) queue at station 6 for jobs out-going to station 4

file(22)= (dummy) queue at station 6 for jobs out-going to station 5

file(23)= (dummy) queue for in-coming jobs at station 1

file(24)= (dummy) queue for in-coming jobs at station 2

file(25)= (dummy) queue for in-coming jobs at station 3

file(26)= (dummy) queue for in-coming jobs at station 4

file(27)= queue for entity which activates a queue discipline at file(8)

file(28)= queue for entity which activates a queue discipline at file(9)

file(29)= queue for entity which activates a queue discipline at file(10)

file(30)= queue for entity which activates a queue discipline at file(11)

file(31)= (dummy) queue at station 1 for entities out-going to station 1-4

file(32)= (dummy) queue at station 2 for entities out-going to station 1-4

file(33)= (dummy) queue at station 3 for entities out-going to station 1-4

file(34)= (dummy) queue at station 4 for entities out-going to station 1-4

file(35)= queue for the entity which activates a queue discipline at file(3)

file(36)= queue for the entity which activates a queue discipline at file(4)

file(37)= queue for the entity which activates a queue  
discipline at file(5)

file(38)= queue for the entity which activates a queue  
discipline at file(6)

file(39)= queue for the entity which activates a queue  
discipline at file(7)

APPENDIX J. SYSTEM PARAMETERS FOR THE SIMAN MODEL

- 1 = routing and processing times of part type 1
- 2 = routing and processing times of part type 2
- 3 = routing and processing times of part type 3
- 4 = routing and processing times of part type 4
- 5 = mean processing time at station 5
- 6 = part transfer time between cart and workstation
- 7 = mean machine and MHS breakdown time
- 8 = mean machine and MHS repair time
- 9 = breakdown probability of each machine type
- 10= number of parts of each type to be finished
- 11= maximum (local) queue capacity at station 1-5
- 12= dummy parameter for data transfer
- 13= a very small constant to interrupt scanning activity

APPENDIX K. THE SIMAN MODEL

```
BEGIN;
;
;create a fixed number of part of each type to the system
;
JOB1      CREATE,3,,:MARK(10);
          ASSIGN:X(1)=X(1)+1;
          ASSIGN:A(1)=1:NEXT(STAT5);
;
JOB2      CREATE,3,,:MARK(10);
          ASSIGN:X(2)=X(2)+1;
          ASSIGN:A(1)=2:NEXT(STAT5);
;
JOB3      CREATE,3,,:MARK(10);
          ASSIGN:X(3)=X(3)+1;
          ASSIGN:A(1)=3:NEXT(STAT5);
;
JOB4      CREATE,3,,:MARK(10);
          ASSIGN:X(4)=X(4)+1;
          ASSIGN:A(1)=4:NEXT(STAT5);
;
;part palletization at station 5 by a material handler
;
STAT5     ASSIGN:M=5;
          QUEUE,1;
          SEIZE:MACHINE(5);
          DELAY:EX(5,1);
          QUEUE,2;
          REQUEST,A(3):CART;
          DELAY:CO(6);
          RELEASE:MACHINE(5);
          TRANSPORT:CART,6;
;
;assign attributes of each part and send to the central queue
;
          STATION,6;
          DELAY:CO(6);
          FREE:CART;
          ASSIGN:A(2)=A(2)+1;
          ASSIGN:A(3)=P(A(1),A(2));
          ASSIGN:A(4)=A(2)+5;
          ASSIGN:P(12,1)=P(A(1),A(4));
          ASSIGN:A(5)=P(12,1);
          ASSIGN:A(6)=A(2)+1;
          ASSIGN:A(7)=P(A(1),A(6));
          ASSIGN:A(8)=A(7)+7;
          BRANCH,1:
            IF,A(3).EQ.1,S1:
            IF,A(3).EQ.2,S2:
```

```

                IF, A(3).EQ.3, S3:
                IF, A(3).EQ.4, S4:
                ELSE, S5;
;
;central queue for parts waiting for a cart to station 1
;
S1            QUEUE, 3:DETACH;
SS1           ASSIGN: X(5)=X(5)+1;
              QUEUE, 18;
              REQUEST, A(3):CART;
              DELAY: CO(6);
              TRANSPORT: CART, A(3);
;
;central queue for parts waiting for a cart to station 2
;
S2            QUEUE, 4:DETACH;
SS2           ASSIGN: X(6)=X(6)+1;
              QUEUE, 19;
              REQUEST, A(3):CART;
              DELAY: CO(6);
              TRANSPORT: CART, A(3);
;
;central queue for parts waiting for a cart to station 3
;
S3            QUEUE, 5:DETACH;
SS3           ASSIGN: X(7)=X(7)+1;
              QUEUE, 20;
              REQUEST, A(3):CART;
              DELAY: CO(6);
              TRANSPORT: CART, A(3);
;
;central queue for parts waiting for a cart to station 4
;
S4            QUEUE, 6:DETACH;
SS4           ASSIGN: X(8)=X(8)+1;
              QUEUE, 21;
              REQUEST, A(3):CART;
              DELAY: CO(6);
              TRANSPORT: CART, A(3);
;
;central queue for parts waiting for a cart to station 5
;
S5            QUEUE, 7:DETACH;
SS5           ASSIGN: X(9)=X(9)+1;
              QUEUE, 22;
              REQUEST, A(3):CART;
              DELAY: CO(6);
              TRANSPORT: CART, A(3);
;
;parts wait at local queue for a machine
;

```

```

        STATION, 1-4;
        DELAY: CO(6);
        FREE: CART;
QQ1    QUEUE, M+7: DETACH;
QQ     ASSIGN: X(M+4)=X(M+4)-1;
        QUEUE, M+22;
        SEIZE: MACHINE(M);
        DELAY: A(5);
        ASSIGN: J=A(7);
;
;decision: a part is sent either to the central queue or to
;a local queue at a workstation for its next operation
;
        BRANCH, 1:
            IF, A(3).EQ.A(7).AND.X(M+4).LT.X(M+14), C1:
            IF, X(J+4).LT.X(J+14), C2:
            ELSE, C3;
;
;send the part to the local queue at the same workstation
;for its next operation
;
C1     RELEASE: MACHINE(M);
        ASSIGN: X(M+4)=X(M+4)+1;
        ASSIGN: A(2)=A(2)+1;
        ASSIGN: A(3)=P(A(1), A(2));
        ASSIGN: A(4)=A(2)+5;
        ASSIGN: P(12, 1)=P(A(1), A(4));
        ASSIGN: A(5)=P(12, 1);
        ASSIGN: A(6)=A(2)+1;
        ASSIGN: A(7)=P(A(1), A(6));
        ASSIGN: A(8)=A(7)+7:NEXT(QQ1);
;
;send the part to the local queue at other workstation
;for its next operation
;
C2     QUEUE, M+30;
        REQUEST, A(3): CART;
        DELAY: CO(6);
        RELEASE: MACHINE(M);
        ASSIGN: A(2)=A(2)+1;
        ASSIGN: A(3)=P(A(1), A(2));
        ASSIGN: A(4)=A(2)+5;
        ASSIGN: P(12, 1)=P(A(1), A(4));
        ASSIGN: A(5)=P(12, 1);
        ASSIGN: A(6)=A(2)+1;
        ASSIGN: A(7)=P(A(1), A(6));
        ASSIGN: A(8)=A(7)+7;
        ASSIGN: J=A(3);
        ASSIGN: X(J+4)=X(J+4)+1;
        TRANSPORT: CART, A(3);
;

```

```

;send the part to the central queue waiting for a change in
;system status
;
C3      QUEUE,M+12;
        REQUEST,A(3):CART;
        DELAY:CO(6);
        RELEASE:MACHINE(M);
        TRANSPORT:CART,6;
;
;the part is to be depalletized at station 5
;
        STATION,5;
        DELAY:CO(6);
        FREE:CART;
        QUEUE,12;
        SEIZE:MACHINE(5);
        ASSIGN:X(9)=X(9)-1;
        DELAY:EX(5,1);
        RELEASE:MACHINE(5);
        BRANCH,2:
            ALWAYS,CHECKS;
            ALWAYS,TALLYS;
;
;the entity is routed to check if introduction of another
;of the same type to the system is necessary
;
CHECKS  ASSIGN:A(10)=TNOW;
        ASSIGN:A(2)=0;
        ASSIGN:A(3)=0;
        ASSIGN:A(4)=0;
        ASSIGN:A(5)=0;
        ASSIGN:A(6)=0;
        ASSIGN:A(7)=0;
        ASSIGN:A(8)=0;
        BRANCH,1:
            IF,(X(1).LT.X(10)).AND.(A(1).EQ.1),JOB1:
            IF,(X(2).LT.X(11)).AND.(A(1).EQ.2),JOB2:
            IF,(X(3).LT.X(12)).AND.(A(1).EQ.3),JOB3:
            IF,(X(4).LT.X(13)).AND.(A(1).EQ.4),JOB4:
            ELSE,DISP;
;
DISP    COUNT:2,1:DISPOSE;
;
;the entity is routed to collect statistics and then disposed
;
TALLYS  COUNT:1,1;
        TALLY:1,INT(10);
        TALLY:2,BET(14):DISPOSE;
;
;an entity is created to initialize system variables
;

```



```

CREATE;
ASSIGN:X(10)=P(10,1);
ASSIGN:X(11)=P(10,2);
ASSIGN:X(12)=P(10,3);
ASSIGN:X(13)=P(10,4);
ASSIGN:X(15)=P(11,1);
ASSIGN:X(16)=P(11,2);
ASSIGN:X(17)=P(11,3);
ASSIGN:X(18)=P(11,4);
ASSIGN:X(19)=P(11,5):DISPOSE;
;
;to create an entity to trigger cart breakdown
;
TRAN      CREATE,1;
          DELAY:EX(7,1);
          HALT:CART;
          DELAY:EX(8,1);
          ACTIVATE:CART:NEXT(TRAN);
;
;to create an entity to trigger machine breakdown
;
MACH      CREATE,1;
          DELAY:EX(7,1);
          ASSIGN:A(1)=DP(9,1);
          ALTER:MACHINE(A(1)), -1;
          DELAY:EX(8,1);
          ALTER:MACHINE(A(1)), +1:NEXT(MACH);
;
;to test if a part can be sent to the local queue at
;workstation 1 from central queue
;
T1        CREATE,1;
          QUEUE,35;
          SCAN:NQ(3).GT.0.AND.X(5).LT.X(15).AND.NQ(18).EQ.0;
          SEARCH,3,1,NQ:MIN(NQ(A(8)));
          REMOVE:J,3,SS1;
          DELAY:CO(13):NEXT(T1);
;
;to test if a part can be sent to the local queue at
;workstation 2 from central queue
;
T2        CREATE,1;
          QUEUE,36;
          SCAN:NQ(4).GT.0.AND.X(6).LT.X(16).AND.NQ(19).EQ.0;
          SEARCH,4,1,NQ:MIN(NQ(A(8)));
          REMOVE:J,4,SS2;
          DELAY:CO(13):NEXT(T2);
;
;to test if a part can be sent to the local queue at
;workstation 3 from central queue
;

```

```

        CREATE, 1;
T3      QUEUE, 37;
        SCAN:NQ(5).GT.0.AND.X(7).LT.X(17).AND.NQ(20).EQ.0;
        SEARCH, 5, 1, NQ:MIN(NQ(A(8)));
        REMOVE: J, 5, SS3;
        DELAY:CO(13):NEXT(T3);
;
;to test if a part can be sent to the local queue at
;workstation 4 from central queue
;
        CREATE, 1;
T4      QUEUE, 38;
        SCAN:NQ(6).GT.0.AND.X(8).LT.X(18).AND.NQ(21).EQ.0;
        SEARCH, 6, 1, NQ:MIN(NQ(A(8)));
        REMOVE: J, 6, SS4;
        DELAY:CO(13):NEXT(T4);
;
;to test if a part can be sent to the local queue at
;workstation 5 from central queue
;
        CREATE, 1;
T5      QUEUE, 39;
        SCAN:NQ(7).GT.0.AND.X(9).LT.X(19).AND.NQ(22).EQ.0;
        SEARCH, 7, 1, NQ:MIN(NQ(A(8)));
        REMOVE: J, 7, SS5;
        DELAY:CO(13):NEXT(T5);
;
;to select a part from the local queue for processing on
;machine 1
;
Q1      CREATE, 1;
        QUEUE, 27;
        SCAN:NR(1).EQ.0.AND.NQ(8).GT.0.AND.NQ(23).EQ.0;
        SEARCH, 8, 1, NQ:MIN(NQ(A(8)));
        REMOVE: J, 8, QQ;
        DELAY:CO(13):NEXT(Q1);
;
;to select a part from the local queue for processing on
;machine 2
;
Q2      CREATE, 1;
        QUEUE, 28;
        SCAN:NR(2).EQ.0.AND.NQ(9).GT.0.AND.NQ(24).EQ.0;
        SEARCH, 9, 1, NQ:MIN(NQ(A(8)));
        REMOVE: J, 9, QQ;
        DELAY:CO(13):NEXT(Q2);
;
;to select a part from the local queue for processing on
;machine 3
;
        CREATE, 1;

```

```

Q3      QUEUE,29;
        SCAN:NR(3).EQ.0.AND.NQ(10).GT.0.AND.NQ(25).EQ.0;
        SEARCH,10,1,NQ:MIN(NQ(A(8)));
        REMOVE:J,10,QQ;
        DELAY:CO(13):NEXT(Q3);
;
;to select a part from the local queue for processing on
;machine 4
;
        CREATE,1;
Q4      QUEUE,30;
        SCAN:NR(4).EQ.0.AND.NQ(11).GT.0.AND.NQ(26).EQ.0;
        SEARCH,11,1,NQ:MIN(NQ(A(8)));
        REMOVE:J,11,QQ;
        DELAY:CO(13):NEXT(Q4);
END;

```

APPENDIX L. THE SIMAN EXPERIMENTAL FRAME

```
BEGIN;
PROJECT,FMS,C S CHEN,5/08/85;
DISCRETE,100,10,39,6;
;RANKINGS:8-11,LVF(5);
COUNTERS:1,TOTAL NO. OF PART FINISHED,40:
          2,TOTAL NO. OF PART DISPOSED;
TALLIES:1,TIME IN SYSTEM:
          2,TIME BET LEAVE;
TRANSPORTERS:1,CART,1,1,64.0,5-A;
DISTANCES:1,1-6,0,32,32,16,16/32,32,16,16/0,16,16/16,16/0;
DSTAT:1,NR(1),M1 UTILI:2,NR(2),M2 UTILI:
        3,NR(3),M3 UTILI:4,NR(4),M4 UTILI:
        5,NR(5),M5 UTILI:6,NR(6),M6 UTILI:
        7,NT(1),TRANSPORTER:
        8,NQ(8),AVE. L OF Q8:9,NQ(9),AVE. L OF Q9:
        10,NQ(10),AVE. L OF Q10:11,NQ(11),AVE. L OF Q11:
        12,NQ(12),AVE. L OF Q12:13,NQ(13),AVE. L OF Q13:
        14,X(5),N. L OF Q8:15,X(6),N. L OF Q9:
        16,X(7),N. L OF Q10:17,X(8),N. L OF Q11;
PARAMETERS:
        1,3,1,3,2,5,10,7,12,8,0:
        2,1,3,2,2,5,11,12,7,12,0:
        3,1,4,2,1,5,7,12,12,8,0:
        4,3,4,4,1,5,5,12,12,7,0:
        5,3.0:
        6,0.1:
        7,240:
        8,5.0:
        9,.25,1,.50,2,.75,3,1.0,4:
        10,10,10,10,10:
        11,2,2,2,2,2:
        12,0.0:
        13,0.01;
RESOURCES:1-6,MACHINE,1,1,1,1,1,1;
REPLICATE,4,0,6000;
TRACE,200.,200.;
END;
```

## APPENDIX M. PROCEDURE TO DETERMINE SAMPLE SIZE

The equation used to determine the number of independent replications of simulation, required to attain a specified confidence interval for a random variable, is given by Miller and Freund(1978):

$$n = ((t_{\alpha/2, n-1} \cdot s)/E)^2$$

where

n = the sample size

$\alpha$  = type I error

t = a value from the table of critical values of the t statistic with n-1 degree of freedom

s = the sample standard deviation

E = the half width of the desired confidence interval  
(in this example,  $E = (480)(5\%) = 24$  minutes)

The steps, based on Pritsker and Pegden(1979) and Schmidt(1983), are as follows:

1. assume a sample size  $N_1$ ,
2. make  $N_1$  replications of simulation,
3. calculate the value of s and t based on the  $N_1$  replications,
4. determine the sufficient sample size by using the above equation and the calculated s and t values

5. if  $N_2 \leq N_1$ , then  $N_1$  is a sufficient sample size. if  $N_2 > N_1$ , make  $(N_2 - N_1)$  additional replications needed to obtain a sufficient sample size.

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