AN EVALUATION OF SCHEDULING POLICIES IN A DUAL RESOURCE CONSTRAINED ASSEMBLY SHOP

by

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(ABSTRACT)

Research in job shop scheduling has concentrated on sequencing simple, single component jobs that require no coordination of multiple parts for assembly. However, since most jobs in reality involve some assembly work, scheduling multiple component jobs through an assembly shop, where both serial and parallel operations take place, represents a more realistic and practical problem. The scheduling environment for multiple component jobs in terms of routing, sequencing, and the pacing of common components may be quite complex, and, as such, requires special scheduling considerations.

The purpose of this research is to evaluate scheduling policies for the production of assembled products in a job shop environment, termed "assembly shop". The specific scheduling policies examined include duedate assignment procedures, labor assignment procedures, and item sequencing rules. The sensitivity of these policies to product structure is also addressed.

The data for analysis is generated by a SLAM II simulation model of a hypothetical dual constrained assembly shop operation. The 2*3*3*3 complete factorial experiment is analyzed by an ANOVA procedure to statistically determine whether job structure, duedate assignment rule, labor assignment rule and item sequencing rule or their interaction significantly affect the mean flowtime, mean tardiness, and root mean square of tardiness of jobs completed by the assembly shop. Further analysis to identify where significant differences in performance occurs is conducted via Tukey multiple comparison tests, general linear contrasts, and confidence intervals.

The results of the multifactor analysis of variance indicate that: (1) The structure of jobs processed, as well as labor assignment and item sequencing policies, affect the flowtime and tardiness of jobs completed by the assembly shop. (2) Job structure influences duedate assignment, labor assignment, and item sequencing decisions. (3) The labor assignment rule chosen further affects the selection of item sequencing rule. (4) The method by which job duedates are assigned does not affect the selection of labor assignment rule or item sequencing rule.

Detailed interpretations of these results, along with suggested practical guidelines, are provided in the study.

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CHAPTER 1

ASSEMBLY SHOP SCHEDULING

PURPOSE AND OBJECTIVES

Decisions regarding the order in which items are processed at specific machine centers (i.e., sequencing decisions) have received scant attention in the context of manufacturing multi-component products. Research in job shop scheduling has concentrated on sequencing simple, single component jobs that require no coordination of multiple parts for assembly.[1] Practitioners have understandably declined to use the limited rules that have resulted from this research [43], but neither have they clamored for more suitable sequencing guidelines. In practice, expediters are employed to manually prioritize queued items by walking "hot" jobs through the shop. Furthermore, sequencing rules have no significant effect on completing an item by its duedate (the most important performance measure by industry standards) when duedates are loosely set [5], as they often are in industry. Such padding of duedates or leadtime is a serious problem in

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[1]For excellent reviews of this literature see [13,16,30,41,69,78,87].

industry that is compounded by products with complex, multi-level product structures [95].

The current pressure for improved productivity has caused a resurgence of interest in methods for reducing leadtimes, including the design of more efficient scheduling systems. Since the seventies material requirements planning (MRP) has become a prevalent production scheduling-inventory planning technique used primarily in job shop oriented operating systems [25,94]. Its superiority over traditional inventory techniques (for example, the reorder point system) for multiple component products has been frequently demonstrated [70; 85, p.162-167]. However, an MRP system only provides the means, through data manipulation, to make broad scheduling decisions; it does not encompass the short term scheduling decisions, such as machine loading and job sequencing, that keep the shop running. Most job shop scheduling research preceded the MRP era, and has yet to be updated. As such, operations management scholars, having mastered the mechanics of MRP systems, propose that attention be redirected toward coordinating the support decisions for an efficient production-inventory system [14,58].

Three such support decision areas that form the basic short term scheduling policies for an assembly shop include: (1) sequencing decisions for jobs requiring assembly operations (termed assembly shop scheduling); (2) procedures for assigning job duedates; and (3) allocation rules for a second constraining resource, in addition to the shop machines, labor. The primary focus of this research is on the impact and interaction of these three support decision areas in determining scheduling policies for an assembly shop. In addition, scheduling policies are also tested for consistency under varying conditions such as different product structures.

To gain a basic understanding of shop scheduling in an assembly environment requires the removal of its operation from the confines of a super scheduling system such as MRP. Therefore, this research evaluates alternative scheduling policies for the assembly shop without considering the MRP type decisions of master schedules and prescribed order release dates.

The purpose of this dissertation is to evaluate scheduling policies in a dual resource constrained assembly shop. The objectives are to determine:

(1) the appropriate sequencing rules to use with jobs that contain assembly operations;

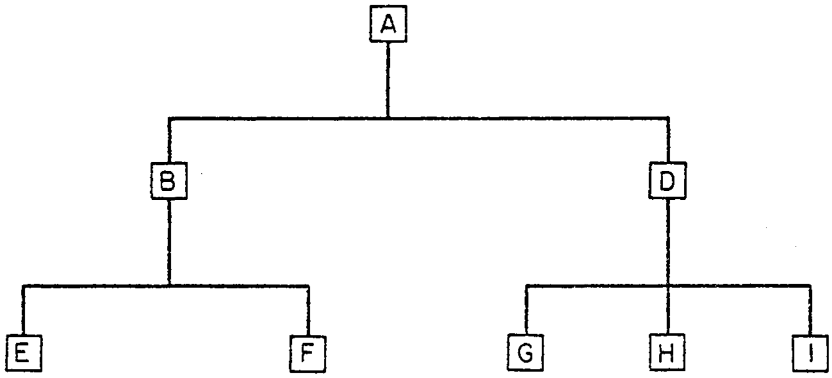
(2) the interaction of sequencing rule with other short term scheduling policies, specifically, labor assignment rule and duedate assignment rule; and

(3) the sensitivity of scheduling policy to the complexity of a product's structure.

BACKGROUND AND SIGNIFICANCE

Background

A job shop that processes jobs involving assembly operations is called an assembly shop. Each job can be thought of as the completion of a product which contains multiple components. The job or product structure resembles a tree, as shown in figure 1.1, that encompasses a series of parent-component relationships. The manufacture of each item (component) in the product involves a series of operations performed at specified machine centers. The assembly of items may take place at several points or levels within the product structure as well as at the final product assembly. Therefore, in an assembly shop each job is composed of several items which require the completion of a number of operations, including assembly operations.



PARENT ITEMS: A, B, D
COMPONENT ITEM: B, D, E, F, G, H, I

FIGURE 1.1
PRODUCT STRUCTURE DIAGRAM

The operations of a job in a simple job shop are performed in series as defined by precedence requirements. Alternatively, operations of a job in an assembly job shop include both serial and parallel operations; the parallel operations being components of the same assembly. As a result, in addition to the waiting time for a resource (machine and/or worker), scheduling in an assembly shop requires consideration of the time an item may have to wait for its parallel components before the required assembly operation can take place. This assembly waiting time is termed <u>staging time</u> or <u>stage delay</u>. Thus, the flow time for a component is the sum of the processing times of its operations, plus the waiting time at each machine center in its routing sequence, plus the staging time in the assembly area. Another descriptive term for assembly waiting time is <u>assembly delay</u>, defined as the difference between the completion of an item's earliest and latest components. Whereas staging time refers to the assembly waiting time for each individual component, assembly delay measures the total delay before the start of an assembly operation. An efficient scheduling system should consider reducing assembly delay, as well as normal queue delay for machine or labor resources.

One way to minimize assembly delay is to pace or coordinate the timely completion of all component items of the same assembly. As a job's structure becomes more complex,[2] pacing becomes more difficult to guage and duedate allowances more difficult to specify. These extra scheduling considerations and information requirements emphasize the complexity of assembly shop scheduling as compared to scheduling in a simple job shop.

Limitations of Previous Research

Job Shop Sequencing Rules

There presently exists a profusion of research on sequencing rules in simple job shops. Reviews of this research may be found in Conway, Maxwell, and Miller [20], Day and Hottenstein [28], Elmaghraby [31], Moore and Wilson [62], Buffa and Miller [15], Panwalker and Iskander [72], and Blackstone, Phillips, and Hogg [13]. The most recent review, by Blackstone, et al., summarized the current state of scheduling research as follows: shortest processing time (SPT) is the best sequencing rule when the shop does not set the duedates or sets very tight duedates or sets loose duedates during highly congested periods. Otherwise,

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[2]As measured by the number of operations, number of assembly operations, and number of parallel operations

one of the following rules may be used, truncated SPT, earliest duedate, least slack, least slack per operation, critical ratio, first in system, first served, or COVERT [13, p.40].

The studies on which these results were based did not consider labor as a constraining resource or the processing of jobs which contained assembly operations. There is no evidence that these results are transferable to the scheduling of non-serially routed jobs or more complex scheduling environments.

Sequencing Rules for an Assembly Shop

The research to date on assembly shop scheduling is considerably less extensive than traditional job shop research, although most jobs realistically involve some assembly work. Reports of sequencing rules used in multi-component manufacture may be found in Bulkin, et al. [16], Reiter [76], Putnam, et al. [75], Berger [8], and Wasseweiler [89]. The companies discussed either sequenced jobs by the minimum slack per remaining operation rule[3] (S/OPN) [16,75,76], or by the smallest critical ratio[4] (CR) [8,75,76,89].

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[3] S/OPN = (duedate-current time-remaining processing time)/number of operations
[4] CR = (duedate-current time)/remaining processing time

Given the popularity of the S/OPN and CR rules, Berry, et al. [9,10,11] adapted the information requirements of the rules and concluded that incorporating average queue time per machine in the remaining processing time calculation actually decreased their performance. Adam and Surkis [1] experimented with different update intervals for the S/OPN rule. Biggs [12] tested the interaction of traditional lot sizing and sequencing rules in an MRP run production system. Goodwin and Goodwin [38] examined the interaction of sequencing rules, release date assignment rules and regeneration rules in an MRP system. Each of these studies showed how to better utilize traditional sequencing rules in a multi-component production system, but did not suggest or test rules especially designed for such an environment.

Studies of scheduling policies specifically for multiple component jobs with assembly constraints have been conducted by Carroll [19], Maxwell [56], Maxwell and Mehra [57], Siegel [80], Pai and McRoberts [71], Miller, Ginsberg, and Maxwell [60], and Rochette and Sadowski [77]. Each has shown that sequencing rules that excel in a simple job shop are inferior to certain assembly oriented sequencing rules. The form and complexity of the assembly oriented sequencing rules that were tested differs widely among the studies noted, as do the job structures to which the sequencing rules are applied. Unlike simple job shop scheduling, no predominant sequencing rule has been determined for assembly shop scheduling.

To summarize the research findings to date, it has been recommended that sequencing rules for an assembly shop:

(1) Incorporate SPT in some form [19,56,57,60,77,80]; SPT does not attempt to phase the completion of components but despite this limitation, SPT reduces shop congestion and component flow time and should be included at some point in the sequencing decision.

(2) Consider job structure [56,57,60,80]; The coordination of priorities assigned to parallel components is important in reducing staging time and job flow time. The complexity of a job's structure affects the variable (i.e., queue) portion of its flow time.

(3) Update job status [56,57,60,80]. Any sequencing rule should be dynamically calculated to keep track of and pace component progress as the job moves through the shop. In addition, the priority of a job should be increased as it nears its completion to accelerate its progress.

Research has shown that a difference does exist between simple job shop and assembly shop scheduling. While the shortest processing time (SPT) sequencing rule excels in simple job shop scheduling, no superior rule has been found in the research on assembly shop scheduling. In practice, dynamic duedate or slack oriented dispatching rules, which may be antithetical to SPT, are predominantly used in assembly environments. [15, p. 525]. Assembly shop research has shown the value of including SPT in composite sequencing rules, but at the same time has discounted its use as the sole basis for sequencing in an assembly environment. The dynamic slack rules partition an assembly job into a series of single component jobs and coordinate them through a system of common duedates. This approach has been termed suboptimal at best [20, p. 243]. Clearly, additional research needs to be done to reconcile these difficulties in job shop versus assembly shop scheduling and in the theory and practice of assembly shop scheduling.

Setting Duedates

Duedates are an important aspect of scheduling policy because they are part of the calculations for various sequencing rules (e.g., duedate and slack rules) and are yardsticks for important measures of performance (e.g., tardiness and lateness). With the exception of Goodwin and Goodwin [38], the literature which specifically addresses alternative methods for setting duedates either considers final product assembly only or operations of a job without assembly requirements. Therefore, when sequencing rules are tested in conjunction with duedate assignment rules, they are the simple rules of the traditional job shop. Studies of duedate assignment procedures have been conducted by Conway [20], Eilon and Hodgson [30], Elvers [32], Eilon and Chowdhury [29], Heard [41], Weeks and Fryer [91], Weeks [90], and Baker and Betrand [4,5]. From this research it can be concluded that processing time [5,32,90,91], shop load [5,29,90], and job structure [20,29] should be considered in setting internal duedates. In addition, the interaction of the job sequencing rule and the duedate assignment rule is important [5,32,90,91].

Duedates have been assigned in previous assembly shop research by a constant [60,38], a multiple of critical path length [57], a multiple of critical path length plus a multiple of the number of operations [56], and a multiple of total work content [80,38], but these studies did not test the merits of different duedate assignment procedures.

The exception is a study by Goodwin and Goodwin [38] where loose total work content, tight total work content, and constant allowance release date rules were tested. Confirming previous job shop studies, this study showed that the impact of item duedate assignment on sequencing rule performance depends on the tightness of the duedates. Several sequencing rules common to job shop research were also included in the experiment.

In view of the limited research on duedates and sequencing in assembly environments, it seems appropriate at this point to test the interaction of a wider variety of item sequencing rules and job duedate assignment rules in the assembly shop. This type of analysis has been performed with simple sequencing rules in a job shop environment [5,32,90,91], but never in an assembly shop with assembly oriented rules.

Labor As a Second Constraining Resource

Past research has concentrated on scheduling in a single constraint job shop; that is, machine capacity was assumed to be the only limiting resource. Prompted by observations from Rowe [78], Allen [2], Legrande [54], and Harris [40], more recent research efforts have included labor as a second constraining resource and labor assignment rules as part of the scheduling decision (see for example, Fryer [33,34,35,36], Hogg, et al. [44,45], Maggard [55], Nelson

[65,66,67], Rochette and Sadowski [77], Weeks and Fryer [92], Holstein and Berry [46], and Huang et al. [48]). Labor related decisions such as the nature and size of the work force, the degree of flexibility desired and the cost of insuring it, the extent of centralized control over labor assignment, and specific labor assignment procedures were studied. Decisions on labor flexibility defined the capacity of the resource, while labor assignment rules were varied in order to utilize the existing labor resource more efficiently. In some cases, the labor assignment rule had a greater impact on shop performance than did the sequencing rule [35].

The major research efforts in assembly shop scheduling have not considered labor, along with machines, as a constraining resource. In fact, an assembly shop was the setting for only one dual resource study [77] and the labor decisions in that case were simplistic. Any current study of scheduling policies in an assembly shop should not ignore the labor resource and its accompanying allocation decisions.

Significance

Whereas scheduling single component jobs through a simple job shop has been a subject of concentrated academic research, scheduling multiple component jobs in an assembly shop represents a more realistic and practical problem. The ability to use a computerized production planning technique such as MRP for scheduling and control of multiple component items relieves the burden of broad scheduling decisions so that more attention may be directed toward short term decisions such as sequencing items at machines, assigning labor, and determining duedate allowances.

This research will represent an extension of the existing research on scheduling by:

(1) testing, and recommending sequencing rules especially designed for jobs with assembly constraints;

(2) considering the allocation of labor and assignment of duedates within the context of a multi-component production setting;

(3) determining the interrelationship of item sequencing, labor assignment and duedate assignment rules in the scheduling of an assembly shop; and

(4) examining the impact of product structure on scheduling policies for assembled products.

SCOPE AND LIMITATIONS

This dissertation will examine the performance and interaction of several job structures, item sequencing rules, labor assignment rules, and duedate assignment rules through a simulation of a dynamic assembly shop. Eleven sequencing rules are examined in a preliminary study, from which three sequencing rules are selected for further testing, along with three labor assignment rules and three duedate assignment rules, in a complete factorial experiment. The choice of the specific rules to be tested is based on a logical progression from past research, insight into the unique requirements of an assembly environment, and recognition of the capabilities and limitations of the production planning and control system under which the scheduling policies operate. All combinations of these scheduling rules are tested on two sets of job structures, a "flat" and a "tall" set, consisting of five jobs each. The "flat" jobs have two or three levels and four to five components per assembly, while the "tall" jobs have three or four levels and two to three components per assembly. The scheduling rules and job structures are described in detail in Chapter 4 on Experimental Design.

Simulation

Simulation is considered the only viable approach for analyzing scheduling alternatives in a dynamic assembly shop. Siegel attempted to determine an optimal sequencing procedure through an analytic assessment of static and dynamic assembly shops with one and two machines. He concluded that for practical purposes even the static assembly case defies optimality and should be scheduled by priority dispatching rules. Furthermore, he termed the dynamic case "completely unamenable to formal analysis" [80, p. 202]. Therefore, the methodology selected for this dissertation is simulation.

The simulation language chosen to model the assembly shop operation is SLAM II. SLAM II, developed and maintained by Pritsker and Associates, was selected because of its capacity for both discrete event and network modeling [74]. This flexibility allows the operation of the shop to be modeled in network form, while precedence, assembly, and sequencing requirements are maintained in discrete event subroutines. Details of the simulation model are provided in Chapter 3.

The Experimental Assembly Shop

The assembly shop modeled for the experiment, shown in figure 1.2, will contain five machine centers, with the fifth machine center designated as an assembly area. Both intermediate and final product assembly is allowed. Each machine center contains two identical machines. Processing requirements are not interchangeable among machine centers (i.e., no alternate routing). Assembly operations at machine center 5 are assumed to be simple operations with negligible time requirements compared to operation processing times; therefore, they are treated as dummy operations requiring no resources and zero time units.

The workforce is heterogeneous in that three workers are trained to operate machine centers 1 and 2, while three additional workers may be assigned only to machine centers 3 and 4. Labor is homogeneous in that workers within each machine center group perform their tasks with equal efficiency.

Jobs arrive continuously during the simulation with time between arrivals generated from an exponential distribution. Upon arrival to the shop each job or product is randomly assigned a structure, for which routing and processing times have been pre-determined. Items at the

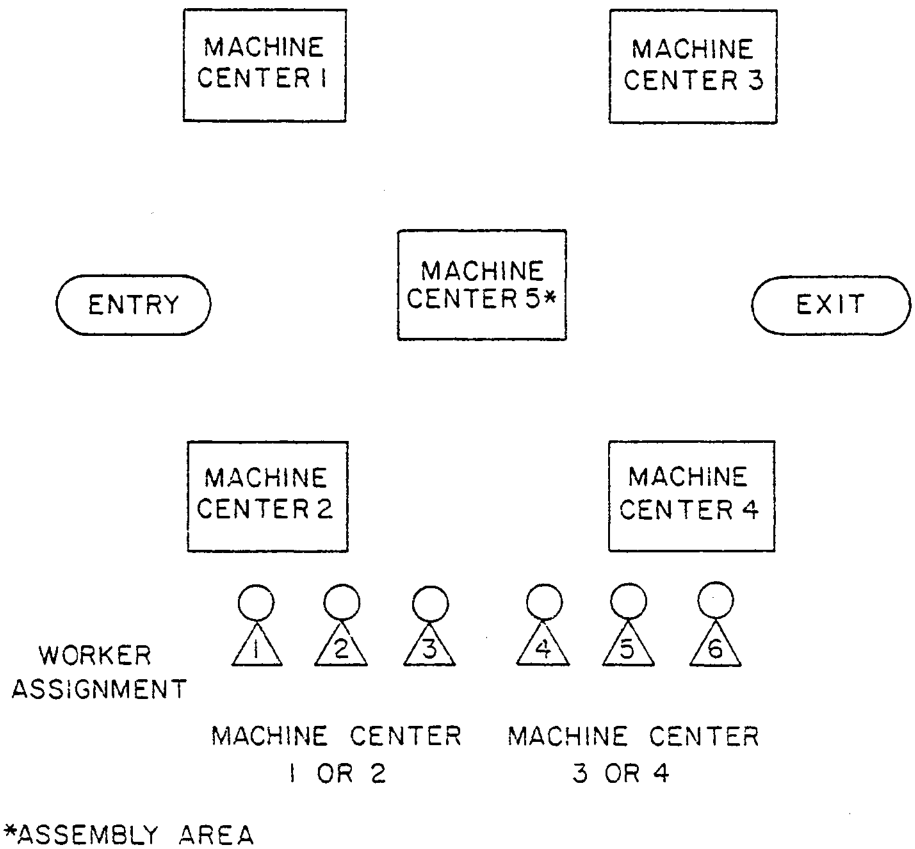


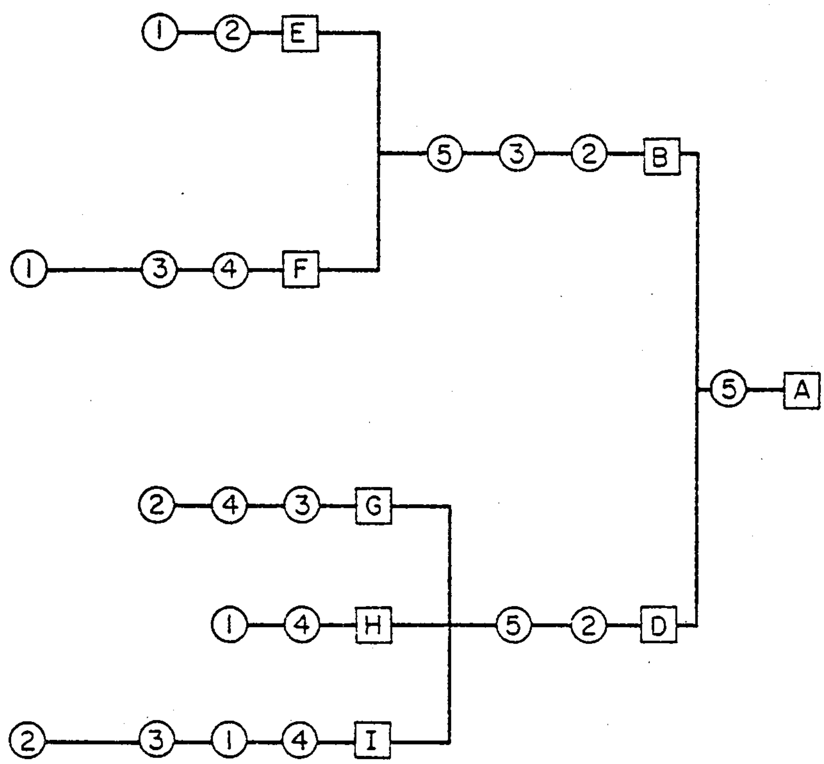
FIGURE 1.2
ASSEMBLY SHOP CONFIGURATION

lowest level of the job's structure then enter the shop at the machine centers specified for their first operation. There is an equal probability of an operation being performed at machine centers 1 through 4. Assignment to machine center 5 is determined by the assembly structure of the job. Figure 1.3 depicts a sample job structure with routing requirements. The assembly shop operation is described in more detail in Chapter 3.

Testing Procedures

The two sets of job structure, three duedate assignment rules, three labor assignment rules, and three item sequencing rules form a 2*3*3*3 complete factorial experiment. An analysis of variance (ANOVA) is performed to assess significant differences in the levels of these four factors and their interactions. Post-ANOVA analyses in the form of multiple comparison tests of significance and selected linear contrasts are conducted to determine where significant differences in performance occur.

The ANOVA procedure uses mean flowtime, mean tardiness, and root mean square of tardiness as measures of performance; whereas, the post-ANOVA analysis concentrates on differences in root mean square of tardiness. Experimental design and statistical procedures are discussed further in Chapter 4.



(i) OPERATION AT MACHINE CENTER i:
ALL ASSEMBLY OPERATIONS OCCUR AT MACHINE CENTER 5.

[j] COMPLETION OF ITEM j:
COMPLETION OF ITEM A REPRESENTS JOB FLOW TIME.

FIGURE 1.3
JOB STRUCTURE WITH ROUTING REQUIREMENTS

Model Validation and Experimental Limitations

This experiment on alternative scheduling policies is conducted on a hypothetical assembly shop through simulation. The simulation methodology used to test the alternative scheduling policies does not produce optimal results, and thus, must be applied with caution. Problems such as steady state, sample size, and autocorrelation need to be addressed before the results of the experiment are considered valid.

The generalizability of experimental results will be enhanced by the sensitivity analysis performed on job structure. However, the validity of the results is assured only for the specific model on which testing is performed.

The following factors are considered in the scheduling environment:

- dynamic arrivals
- multiple resources (machine and labor)
- flat and tall job structures
- assembly operations
- item sequencing rules
- labor assignment rules
- duedate assignment rules.

The following factors are <u>not</u> considered in the scheduling environment:

- lot sizes
- safety stock
- master scheduling
- order release dates
- uncertain processing times
- alternate routings
- machine breakdowns or labor absences
- transport time or allocation of the material handling resource
- pre-emption
- scrap or rejects
- machine or labor efficiencies
- variable setup times
- restrictions on queue size.

It is believed that the omission of these factors will not significantly alter the validity of experimental results from this study.

PLAN OF PRESENTATION

Chapter 2, entitled <u>Review of Related Literature</u>, summarizes the research to date in the areas of assembly shop scheduling, duedate assignment procedures, and allocation of the labor resource.

Chapter 3, entitled Simulation Methodology, describes the assembly shop, the simulation model, and the conditions under which the simulation experiment is conducted.

Chapter 4, entitled Experimental Design, explains the factors and factor levels, presents the results from the preliminary testing of sequencing rules, constructs the ANOVA model, and discusses the post-ANOVA analysis to be performed.

Chapter 5, entitled Results and Interpretations, presents and interprets the results of the experiment in the form of performance rankings, graphs, multiple comparison tests of significance, confidence intervals, and specific linear contrasts.

Finally, Chapter 6, entitled Summary and Conclusions, concludes the dissertation with a summary of the work performed, a discussion of its limitations, and recommendations for further research in the area of assembly shop scheduling.

CHAPTER 2

REVIEW OF RELATED LITERATURE

Job shop scheduling has been an area of extensive and intense research in the past three decades. Excellent reviews of this research literature may be found in Sisson [81], Gere [37], Conway, Maxwell, and Miller [20], Elmaghraby [33], Day and Hottenstein [28], Panwalker and Iskander [72], Moore and Wilson [62], Buffa and Miller [15], and Blackstone, Phillips, and Hogg [13]. The general problem in job shop scheduling is one of determining the sequence of a dynamic set of jobs as they form queues and are routed through various machine centers for processing. For complex models, involving a continuous arrival of jobs, it is generally conceded that simulation is the only viable analysis technique. Numerous job sequencing or dispatching rules have been tested through simulation; one study by Conway [20], for example, tested 92 different priority rules.

Early job shop simulators developed in the sixties [19,20,54,64] operated under the following assumptions [37]: (1) each machine is continuously available for assignment (no breakdowns, or divisions for shifts, days, or breaks), (2) jobs are a simple sequence of operations (no assembly operations), (3) each operation, once started, must be performed to completion (no preemptive priorities), (4) each machine can handle at most one operation at a time, (5) a job can be processed on at most one machine at a time (no lot splitting or lap phasing), (6) job routing is given and no alternate routings are permitted, (7) setup time is included in an operation's processing time, (8) transit time for all jobs between machines is negligible, (9) duedates, if given, are fixed, (10) no overtime or subcontracting is allowed (fixed capacity), and (11) the shop is constrained by a single resource type (machine limited system).

Later studies relaxed one or more of these limiting assumptions. This dissertation explores the relaxation of assumption number 2 by sequencing jobs with assembly operations, number 9 by considering the basis for assigning duedates, and number 11 by including labor as a second constraining resource. A review of the current state of research in these three areas follows.

SEQUENCING RULES FOR AN ASSEMBLY SHOP

A limited number of studies on sequencing rules have considered jobs with assembly operations. These studies are discussed below in order of their appearance in the literature.

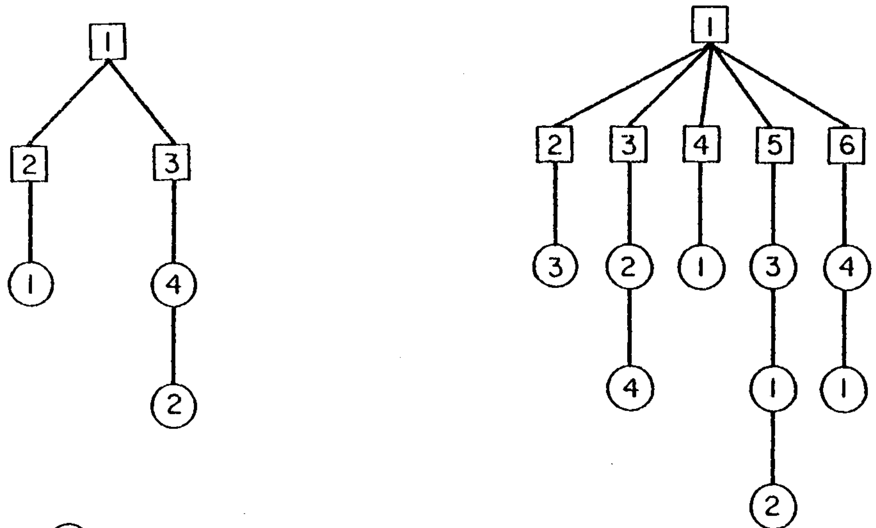
Carroll [18] was the first to consider the scheduling of multiple component jobs. In his unpublished dissertation, Carroll included a section on scheduling assembly jobs of three or six components per job with a maximum of two components per assembly. The shortest processing time rule (SPT), the slack per remaining operation rule (S/OPN), the COVERT rule (delay cost/processing time), and the COVERT rule modified by heuristics involving dynamic critical path analysis were tested on shops with one or two machines per machine center.

For the one machine-three component and two machine-three component cases, S/OPN outperformed SPT. Staging time was high with SPT causing parallel components to be "out of phase" with each other and job tardiness to rise. COVERT performed better than its two heuristic versions that used critical path information.

For the one machine-six component case, SPT again performed poorly and S/OPN performed well, but COVERT produced the lowest mean tardiness. COVERT was not significantly improved by the addition of critical path heuristics. These results remained valid under both loose and tight duedates.

Carroll's study pointed out the special considerations of multiple component jobs, such as staging time and the phasing of component completions. He challenged the use of SPT as a reasonable rule for assembled products and attempted to design assembly oriented rules with critical path characteristics. But the major thrust of his dissertation was to promote the use of COVERT as a sequencing rule for various conditions, including assembly operations. Carroll's recommendations concerning sequencing rules for assembly jobs are not widely accepted because of the restrictive product structures on which they were based [20].

A more extensive study was undertaken by Maxwell [56] and is included in preliminary form in Conway, Maxwell, and Miller [20]. The simulation experiment tested eleven job shop oriented sequencing rules and seven assembly oriented sequencing rules on two level jobs wherein the final operation was an assembly. Every job had the same number



(i) OPERATION AT MACHINE CENTER i

[j] COMPLETION OF ITEM j

FIGURE 2.1
TYPICAL FAN STRUCTURED JOBS
USED BY MAXWELL (56)

of branches (i.e., components), but not necessarily the same number of operations. As an example, figure 2.1 shows a two and five branch product structure. Jobs of this type are referred to as fan structured. Maxwell tested the sequencing rules on three job sets with branches of size two, five, and ten.

The job shop oriented sequencing rules tested included the traditional first come, first served (FCFS), first in system, first served (FISFS), shortest processing time (SPT), earliest duedate (DDATE), smallest slack (SLACK), and slack per remaining operation (S/OPN). Hybrid rules were also tested including SPT with ties broken by SLACK (SPT-SLACK), a two class SLACK rule with SPT as tiebreaker within each class separated at slack time μ (SLACK-SPT μ), S/OPN except those with zero or negative slack ordered in proportion to the remaining number of operations (S/OPN-PN), a two class S/OPN rule with ties broken by SPT within each class (S/OPN-SPT μ), and S/OPN except those with zero or negative slack ordered by smallest remaining processing time (S/OPN-RD).

The assembly oriented rules tested were: the smallest number of uncompleted items in a job (NUJOB), NUJOB with ties broken by SPT (NUJOB-SPT), the smallest remaining work for the item with the maximum remaining work, not re-evaluated as operations of parallel items are completed (MAXRWP-NR), the smallest difference between the maximum remaining work for parallel items and the remaining work on the specific item in queue, not re-evaluated (MAXRWD-NR), the smallest number of remaining operations for the item with the maximum number of remaining operations in a job, not re-evaluated (MAXNRP-NR), the smallest difference between the maximum number of remaining operations of parallel items and the number of remaining operations in the specific item in queue, tie broken by SPT (MAXNRD-SPT), and MAXNRD not re-evaluated (MAXNRD-NR).

The rules that did not re-evaluate an item's priority once it entered a queue performed poorly because pacing of parallel components did not occur. SPT and SPT-SLACK performed well in processing items through the job shop portion of the shop, while S/OPN and NUJOB performed well in the assembly portion. The performance of combination rules based on these preliminary results was encouraging. NUJOB-SPT and MAXRD-SPT resulted in a significantly lower mean flowtime than SPT, but did not lower mean tardiness. On the other hand, S/OPN-SPT µ produced a dramatic reduction in tardiness. In experiments on differing number of components per job, MAXRND-SPT had the smallest mean flowtime for two or five components, but was outperformed by NUJOB-SPT for jobs with ten components. The SPT rule worsened significantly as the number of components increased.

This study suggested that sequencing rules in an assembly shop should consider job structure and job status to reduce the staging time of parallel components and use SPT as a tie breaker to reduce each item's flowtime. It also demonstrated that the complexity of a product's structure affects sequencing rule performance. A major limitiation of Maxwell's early work is a lack of generalizability due to the simplicity of the fan structured jobs examined.

Maxwell and Mehra's [57] study of an assembly shop used a more complex product structure and a more sophisticated approach to designing assembly oriented sequencing rules. The number of levels in each product's structure ranged from two to five, and the number of components between two and four. The maximum number of operations per job was held to forty. In addition, all items at the same level had the same number of components and any path from the same level to final product assembly contained the same number of operations.

Four factors were considered in various combinations in the design of sequencing rules. An operation slack factor (OSF) kept track of the progress of individual operations. A processing time factor (PTF) generalized the SPT rule by summing the processing time of all remaining operations in a job. The operation urgency factor (OUF) gave higher priority to complex jobs, as measured by the number of levels and number of operations, with tighter duedates. The precedence constraint factor (PCF) tried to coordinate the completion of operations of the same assembly. For example, when comparing operations of the same assembly, PCF gave higher priority to the operation requiring the longest processing time; and when comparing operations from different jobs, the operation with the higher processing time compared to the remaining operations for the same assembly received highest priority.

General results indicated that composite rules which combined local operation status and job status performed better than any single factor sequencing rule. Also, a higher allowance was necessary in setting duedates for assembled items. Specific results revealed a weighted combination of SPT, OSF and OUF as the best performer given the information required for its implementation. The SPT component reduced shop congestion, the OSF component reduced the lateness variance, and the OUF component reduced staging delay.

The major contribution of Maxwell and Mehra's work is the observation that job structure and job status, as well as operation characteristics, are important considerations in sequencing operations through an assembly shop. Deficiencies of the study include the difficulty in practically applying many of the sequencing rules as their complexity and information requirements grow.

Siegel [80] in an unpublished dissertation undertook a thorough study of scheduling jobs with assembly constraints. He began by exploring optimal solutions for static and dynamic assembly shops with one or two machines. A branch and bound algorithm and queuing model were developed, but determined intractable for all but the simplest of models. A simulation experiment was then performed to test sequencing rules suggested by previous assembly shop studies on more extensive product structures.

Three job structure sets were tested in the experiment. Jobs from the standard set on which primary testing was performed had a maximum of three levels and between two and four components per assembly. Two additional jobs sets, used for sensitivity analysis, had between two and four or five levels of assembly and a maximum of three components per assembly. The probabilities of the number of components per assembly varied among job sets. Experimentation across job structure sets produced similar results. Thus, the sequencing recommendations from this study were deemed relevant over a range of structurally distinct job populations.

For the standard sequencing rules, FISFS and SPT, SPT resulted in both a lower mean flowtime and a lower mean tardiness. This is a reversal of Maxwell's [56] findings, although Maxwell did show the performance of SPT worsening as the number of components per assembly broadened.

Two assembly oriented rules, assembly delay indicator (ADI) and remaining degree of assembly (RDA)[1], were also outperformed by SPT. Combined with SPT as a tiebreaker, these rules resembled MAXRND,SPT and NUJOB,SPT tested by Maxwell [56]. However, the importance of assembly status reported in Maxwell's study did not extend to the more complex job structures tested by Siegel, as SPT also outperformed these combined rules. Rules that combined ADI, RDA, and SPT fared no better.

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[1]That is, the remaining number of uncompleted components for a particular assembly

Even the duedate dependent rules of job duedate, operation duedate, and slack were outperformed by SPT. Combining path length to terminal operation with the DDATE sequencing rule significantly improved its performance, but not enough to better SPT. The performance of other combination duedate rules was equally disappointing.

Three global dynamic rules, smallest remaining number of operations, smallest longest remaining path, and smallest remaining total work, showed a 10% to 33% improvement in mean tardiness over SPT. These simple rules contained the following attributes: (1) pacing - the same priority was assigned to all items in a job; (2) structural dependence - the rules recognized the entire structure of a job, but ignored structural details such as the number of levels, number of assemblies, and assembly status; and (3) acceleration - as jobs neared completion, their progress was accelerated. The good performance of these rules confirmed the results of earlier assembly shop studies.

In order to take advantage of SPT under crowded queue conditions, Siegel added a processing time factor to several sequencing rules that was proportional to queue congestion. Its performance in combination with duedate oriented rules was especially promising. In fact, the best sequencing rule that emerged from the extensive testing was a weighted duedate-shop congestion combination. Siegel also considered the addition of an anticipated congestion factor, but the resulting small improvement in performance was not enough to justify the difficulties of its implementation.

Siegel's work is significant because it consolidated previous assembly shop research by performing tests on a variety of product structures. His findings may be summarized as follows: (1) The attributes of pacing, structural dependence, and acceleration are fundamental in the performance of the superior sequencing rules. (2) SPT alone is not an effective sequencing rule for assembly shops, but when included as a shop congestion factor it yields significant improvements in other sequencing rules. (3) Locally structural dependent and operation duedate rules are ineffective for sequencing assembly jobs. (4) The dynamic evaluation of priorities and job status, as well as shop conditions, are important considerations in assembly shop scheduling.

Pai and McRoberts [71] studied an assembly shop where common components were fabricated to be assembled into a variety of products. Priority rules were tested separately for machine center queues and assembly area queues against the FCFS queue discipline. The rules considered order quantity and importance (price) in the assembly area and queue length (average, current, or updated current) in the fabrication area. The results were inconclusive; facility utilization and flowtime measures did not differ appreciably among sequencing rules, and no priority rules were equally effective in minimizing average queue time for all component items.

Miller, Ginsberg, and Maxwell [60] applied the assembly shop concept to scheduling aircraft maintenance. The product structure was very simple with one level of assembly and one operation per component item of a job. The eighteen sequencing rules tested were divided into the following categories: (1) those based on length of operations, (2) those based on operation counts, (3) those based on total work content, (4) those based on shop congestion, and (5) those independent of processing time.

Specific results of the simulation showed that sequencing by smallest total work content for unstarted jobs produced the smallest mean flowtime. In addition, data on started but not completed operations was relevant for count and work content rules. Processing time should be used in calculating work content rules, whereas expected completion time was more appropriate for length rules. The study concluded that the best sequencing rules considered job attributes more significant than operation attributes, gave operations with SPT priority, and were dynamic.

Rochette and Sadowski [77] considered assembly operations in their simulation study of scheduling in the needle trade industry. Nine different routings, eight of which involved some assembly, were included. Eight sequencing rules were tested, but only one was created for the assembly environment. That rule, a product of SPT times total remaining work was the best performer, but did not significantly outperform SPT.

The most recent research involving sequencing assembly operations (1982) was conducted by Goodwin and Goodwin [38]. Their simulation study examined three release date rules, six sequencing rules, and three regeneration rules in an MRP operated production system. The sequencing rules were those popular in job shop research, SPT, DDATE, operation DDATE, SLACK, operation SLACK, and look ahead (LA). The release date rules included a loose and tight total work content and a constant allowance. The regeneration rules included no regeneration, periodic, and continuous regeneration of seqeuencing rule priorities.

The products assembled had a maximum of four levels with one operation per item.

Sequencing rule was found to be the most important factor across all performance measures. Contrary to the results reported in job shop research, DDATE and SLACK were not outperformed by their operation counterparts. In addition, SPT and LA performed poorly in terms of mean tardiness, while DDATE combined with other policy variables to produce the best overall performance.

Conclusions from this study include: (1) Duedate sequencing rules and total work release date rules are recommended for assembly systems. (2) The regeneration of priorities in combination with traditional sequencing rules is not recommended. (3) The impact of sequencing rule is dependent on the tightness of the leadtime allowance. (4) The interactions of scheduling policies in an assembly shop are strong.

Table 2.1 summarizes the discussion of assembly shop scheduling research by describing the product structures used and listing the best sequencing rules that emerged. From table 2.1, it is apparent that no one sequencing rule dominated the scheduling of assembly shops in the studies conducted. However, although the varied product structures

TABLE 2.1

SUMMARY OF MAJOR ASSEMBLY SHOP RESEARCH

STUDY	PRODUCT STRUCTURE	BEST SEQUENCING RULE[1]
Carroll (1965)	Max 2 comp/ass'y; 3 or 6 comp/job;	COVERT (6); S/OPN (3)
Maxwell (1969)	Fan structure; 2,5,or 10 comp/job	MAXNRD-SPT (2,5) NOPT-SPT (10)
Maxwell & Mehra (1968)	Symmetrical; 2 to 5 levels; max 40 oper/job	SPT+OSF+OUF (weighted)
Siegel (1971)	Asymmetical; 3 job sets; max 3 comp/ass'y	DDATE+SC (weighted)
Miller, Ginsberg, & Maxwell (1975)	1 ass'y/job; 1 oper/item	TWK-US
Rochette & Sadowski (1976)	8 ass'y jobs; max 4 ass'y/job; max 3 comp/ass'y	SPT*TWK (weighted) or SPT
Goodwin & Goodwin (1982)	Max 4 levels/job; 1 oper/item	DDATE

where comp = components, ass'y = assembly, and oper = operations

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[1] These sequencing rules are explained in the text of Chapter 2.

used in the studies make their results difficult to compare, there are some commonalities among the top sequencing rules in each study. Shortest processing time appeared in some form as part of the best sequencing rules in Carroll [18], Maxwell [56], Maxwell and Mehra [57], Siegel [80], and Rochette and Sadowski [77]. Also, some form of duedate appeared in the best rules of Carroll [18], Maxwell and Mehra [57], Siegel [80], and Goodwin and Goodwin [38]. Finally, with the exception of COVERT [18], MAXNRD-SPT [57], and SPT [77], the best sequencing rules considered the entire job structure.

Applications and Related Studies

Several applications of sequencing rules in assembly environments have been reported in the literature. Bulkin, Colley, and Steinhoff [16] studied the sequencing of jobs that fed assembly lines at the El Segundo Division of Hughes Aircraft. Using slack per remaining operation (S/OPN), there was a 10% increase in the number of orders completed by their duedate, a 60% reduction in expediting, and a reduction in cycle time, work-in-process, and resource utilization.

Wassweiler [89] described the use of critical ratio (CR) for sequencing items at the Racine Works of Twin Disc and extolled the virtues of using an MRP system in conjunction with CR to increase the accuracy of the remaining work and duedate components of the rule.

Putnam, et al. [75] from Rath and Strong reported the problems and progress of a number of practical installations (e.g., Black and Decker, Hughes Aircraft, Stromberg and Carlson, Jones and Lamson, and Moog) using either slack time or critical ratio sequencing rules. In comparing the practical performance of S/OPN and CR, CR was recommended because it clearly indicates the progress of a job as on schedule, ahead of schedule, or behind schedule. Critical ratio also provides a more accurate estimate of completion time when operation and queue times vary.

Berger [8] also discussed the application of critical ratio as a sequencing rule for the AC Electronics Division of General Motors.

Because of the reported widespread use of S/OPN and CR in industry, several simulation studies have been conducted to compare the operation of these rules and to test proposed variations in their application. Berry [9] examined sequencing rules for a hypothetical fabrication shop that produced component parts for an assembly shop. SPT, FISFS, S/OPN, CR, and a two class SPT sequencing rule were examined. For periods of low demand, there was little difference in sequencing rule performance. However, during periods of high demand, S/OPN, which included inventory status information, performed the best. The static FISFS also performed well. The performance of CR was not improved by the timeliness of inventory information.

Berry and Rao [11] tested critical ratio against slack time sequencing rules with varying information content on queue time and stock status in a shop that manufactured items for stock replenishment under an order point inventory control system. The results of the study were counterintuitive. Including average queue time per machine in the duedate calculations of the rules had little effect on their performance. In addition, rules with dynamic duedates actually performed worse than those whose duedates were not updated.

Another study by Berry and Finlay [10] further explored the addition of waiting time information to the CR and S/OPN sequencing rules. The results confirmed those of the earlier study that queue time data does not improve tardiness performance, but does significantly increase shop and inventory costs. Berry surmised that an item's actual queue time was too dependent on its priority for average queue time figures to be valid.

Adam and Surkis [1] studied update intervals for the S/OPN sequencing rule. From a practical viewpoint, it was recommended that the priority of an item be updated upon its entry to a queue and periodically.

The critical ratio rule was compared to SPT in a study by Biggs [12] on the interaction of lot sizing and sequencing rules in an MRP system. Four volume/cost sequencing rules were tested, along with CR and SPT. EOQ, lot for lot, periodic order quantity, part period balancing, and Wagner-Whitin lot sizing rules were examined. No universal conclusions were reached for either lot sizing or sequencing, but the following results were presented: EOQ with CR minimizes lateness and stockouts, EOQ with SPT minimizes setups, and lot for lot with SPT minimizes average inventory.

Green and Appel [39] surveyed sequencing rules used in industry by foremen and industrial engineers. They found "program in greatest trouble" to be the most popular rule, followed by DDATE and operation DDATE. S/OPN was ranked fifth out of the nine rules presented. SPT was not among the sequencing rules actually used for on schedule conditions and was used sparingly for behind schedule conditions.

In summary, reported applications of sequencing rules for assembled products have emphasized the use of the slack per operation or critical ratio sequencing rules [16, 89, 75, 8]. Academic studies concerning the operation of S/OPN and CR found that inventory status information [9], waiting time information [10] and the dynamic calculation of duedates [11] generally did not improve the performance of the two sequencing rules. Also, periodic update intervals were found sufficient for good performance [1].

A comparison of CR and SPT produced varied results depending on the lot sizing rule and performance measure employed [12]. Finally, in a recent survey (1981) of sequencing rules used in industry, neither S/OPN or SPT received high rankings [39].

Resource Constrained Project Scheduling

The resemblance of a product structure diagram to a PERT network is so strong that a discussion of assembly shop literature cannot exclude similar studies in project scheduling. This section briefly reviews job shop scheduling research studied in the context of resource constrained project networks.

The job shop scheduling problem can be expressed as a resource constrained project network by considering each job a project with the network precedence requirements represented by a specified sequence of operations on designated machines. The constrained resource is machine availability. Assembly operations may be included, although typically jobs are assumed to be unique orders with a simple serial structure. Usually, a job requires only one resource (machine) per operation and only one unit of a resource is available [26].

Procedures for obtaining optimal solutions to the resource constrained problem have not proved computationally feasible for the large, complex projects found in practice [26,27]. This holds true for job shop applications especially, as the flexibility of operations enlarges solution options [23]. Recommendations for heuristic procedures tested through simulation models are conflicting, seemingly dependent on the characteristics of the particular project considered. In light of these results, Patterson [73] suggests that the user try several heuristic approaches in a simulation format to develop a schedule and select the one which best meets his or her desired objectives.

Davis' [26] review of project scheduling under resource constraints includes a category of heuristic procedures tested in job shop environments. Bannerjee [7] and Calica [17] viewed the multi-product shop loading problem as a project network and developed a priority function based on activity duration, activity slack, and project slack. Mize [61] compared the performance of nine multi-attribute and three single attribute heuristics as sequencing rules in a multi-project job shop and found that the top three performers were complex rules containing some form of minimum job slack. Slack refers to the difference between an activity's non-constrained late start and constrained early start time and is calculated dynamically.

Mueller-Mehrbach [63], in a study of sixteen heuristics applied to single project job shop scheduling and compared to optimal results, found that smallest early finish time generally produced the best results. No significant difference in project duration was detected from the use of smallest late start or smallest late finish time. Patterson [73] found minimum job slack most effective in a multi-project job shop.

Several applications of resource constrained network heuristics to manufacturing have been reported [83,21,87,88,43]. The most interesting, by Smith [83], includes the representation in modified network form of a product's bill of material, as well as its sequence of operations. Other articles suggest the relationship between assembly shop and network scheduling. Trilling [86] provided examples of network scheduling of assembled and disassembled products under early start, minimum slack, and COVERT scheduling rules. Smith and Aquilano [82] presented an MRP approach to project scheduling which points out the relationship of networks, product structures, and scheduling.

In summary, heuristic procedures for resource constrained networks tested through simulation are conflicting and seem to depend on the characteristics of the particular project considered. Reported applications of scheduling assembled products by networks are specialized and limited.

Representing the operation of a job shop as a constrained network and utilizing the critical path concept is an appealing idea, but its direct application is limited for the following reasons: (1) it does not allow for the continuous arrival of jobs, (2) multiple jobs with assembly requirements become bulky to model, and (3) the flexibility of the job shop cannot be adequately portrayed. Optimal solutions have been obtained for up to 50 serial jobs in a one resource network [26]. Unless a job shop scheduling problem with assembly constraints can be solved optimally through network analysis, there is no need to undergo the awkwardness of formulating the model in this manner.

This observation is not to imply that concepts in resource constrained project scheduling are inapplicable to assembly shop scheduling. To the contrary, the following issues relate quite clearly: (1) the calculation of slack as an item's capacitated (constrained) versus uncapacitated (unconstrained) schedule; and (2) the effect of project (product) characteristics on sequencing rule performance. Newly designed sequencing rules for multi-component scheduling should take these factors into account.

PROCEDURES FOR ASSIGNING DUEDATES

The assigning of duedates internally involves an estimation of the flowtime or completion time of a job. Flowtime is influenced by processing time, queue time, and assembly wait time, the most certain of which is processing time. Queue time is highly sensitive to shop load and the priority of an item in queue (i.e., the sequencing procedures used). Assembly wait time is further affected by the flowtimes of each component required for assembly. For this factor, minimizing the variance of component flowtime is more important than minimizing flowtime itself.

The methods used to assign duedates affect the calculation of duedate oriented sequencing rules and certain measures of performance, such as tardiness. The research to date that compares duedate assignment procedures was, with one exception, performed in job shops, rather than assembly shops. Nevertheless, this section reviews that research in hopes that some of the lessons learned in assigning duedates to serial jobs may be useful for serial-parallel jobs as well.

Conway, Maxwell, and Miller [20] considered duedate assignment as part of the RAND job shop study. Four duedate assignment rules, six simple dispatching rules and three shop utilization levels were tested. The duedate assignment rules included TWK (nine times the total processing time), NOP (proportional to the number of operations), CON (a constant allowance for each job), and RAN (a random allowance). The study found that duedate assignment methods that considered job characteristics, such as TWK or NOP, were more efffective than those that did not.

Eilon and Hodgson [30] in a simple two parallel machine shop tested five sequencing rules with various weighted processing times as a basis for duedate assignment. They determined that the optimal weight can be determined as a function of shop load and dispatching rule.

Elvers [32] examined tight versus loose duedates against ten sequencing rules. He concluded that SPT produces the smallest mean tardiness for tight duedates and that the SLACK or DDATE dispatching rule performs best under loose duedates. This study indicated a significant interaction between duedate tightness and dispatching rule.

Eilon and Chowdhury [29] considered a job's arrival time, its number of operations, shop congestion, and congestion at each machine in assigning duedates. They found that the duedate assignment rule that measured machine congestion as queue length performed best, accompanied by a modified SPT rule, SI*, which divided jobs into groups of negative and positive slack and sequenced by SPT within each group. The implication of this study is that duedate assignment procedures that include shop congestion perform better than those based on job content.

Heard [41] used dynamic programming to assign optimal duedates in a one machine shop, but his procedure is generally considered too unrealistic to apply in practice.

Weeks and Fryer [91] designed a simulation experiment involving two labor assignment rules, three job sequencing rules and three duedate weights; then used a regression model to determine the optimal duedate weight to minimize a cost function composed of flowtime, lateness, earliness, duedate, and labor transfer costs. Regression was proposed as a more accurate means of determining the duedate assignment procedure for a particular firm than choosing from the general rules presented in academic studies.

Weeks [90] presented a simulation model to test three shop systems, two sequencing rules, and seven duedate assignment rules. He concluded that all three factors significantly affect shop performance. For duedate oriented dispatching rules, he recommended basing duedate on shop congestion rather than total work content. He also noted that duedate performance worsens as the shop gets more complex, although shop size is irrelevant.

Baker and Betrand [5] studied duedate assignment and sequencing rules in a one machine shop. They recommended that the SPT sequencing rule be used for tight duedates with any duedate assignment rule. For loose duedates, the sequencing rule had no impact and a workload dependent duedate assignment rule performed best. For medium duedates, both duedate assignment and dispatching rule were important. The selection of a duedate sequencing rule and total work content duedate assignment rule were recommended.

A later study by Baker and Betrand [4] suggested the use of a modified duedate sequencing rule that would sequence by duedate until a job was late, then use SPT, similar to Eilon and Chowdhury's SI* rule. This rule automatically adjusts with the tightness of duedates. A workload oriented duedate assignment rule was matched with the modified duedate rule.

Kanet [50] pointed out the importance of minimizing the variance of job flowtime as well as flowtime and suggested the use of total absolute difference in completion time as a measure of variation. The relevance of this performance measure to an assembly shop is timely because of the phasing of component completion times for assembly.

The sole study comparing duedate assignment procedures in an assembly environment was conducted by Goodwin and Goodwin [38]. Since the study was performed in an MRP production setting, methods for determining order release dates, rather than duedates, were actually tested. The total work content (TWK) release date was determined by multiplying the sum of the processing times of all items in a job by a constant and subtracting this from the job's duedate. Both a loose and tight TWK rule were examined. The constant allowance (CA) release date was determined by subtracting a constant from the job's duedate. Sequencing rules and regeneration rules were also examined.

Results showed a strong interaction between release date rules and sequencing rules. For earliness and tardiness measures of performance, the SPT and look ahead sequencing rules interacted best with loose allowances, while duedate sequencing rules performed better with tight allowances. For mean flowtime, the TWK release date rules performed better than CA, with the loose TWK producing the lowest mean flowtime across sequencing rules.

The research on setting internal duedates for simple job shops has emphasized three areas of concern: (1) the basis for duedate assignment, (2) loose versus tight duedates, and (3) the interaction of duedate assignment procedures and sequencing rules. As a basis for duedate assignment, Conway, et al. [20], Baker and Betrand [5], and Goodwin and Goodwin [39] recommended job content; while Eilon and Chowdhury [29] and Weeks [90] preferred shop congestion. No study recommended constant or random duedate assignments.

The studies analyzing duedate weights found a strong interaction between duedate tightness and sequencing rule performance [4,5,30,32,91]. The SPT rule was recommended for tight duedates [5,32], while a DDATE rule [32] or any sequencing rule [5] were recommended for loose duedates.

Baker and Betrand [4] explored this interaction further by designing an SPT oriented sequencing rule that adjusted to the tightness of the duedates assigned. Weeks [90] also found an interaction between duedate assignment and sequencing rule, but according to the basis of duedate assignment. For DDATE sequencing rules, shop congestion was a better duedate base than job content.

No optimal procedures for determining duedates were determined in the studies examined, although Heard [41], Weeks and Fryer [91], and Kanet [50] offered suggestions for reasonable duedate calculations.

The only study of duedate assignment procedures for assembled products [39] supported some of the simple job shop results and refuted others. In support of previous job shop research, duedates based on job content performed best in the assembly environment and duedate tightness strongly affected sequencing rule performance. However, in direct contrast to job shop recommendations [32], SPT performed better under loose duedates and DDATE better under tight duedates.

LABOR AS A CONSTRAINING RESOURCE

Labor has been included as a constraining resource in a limited number of studies on job shop scheduling and in one study involving assembly jobs. This section summarizes the research to date on dual resource constrained scheduling systems.

Analytical solutions to scheduling dual resource constrained systems were attempted by Avi-Itzhak, Maxwell and Miller [3], Nelson [68], and Takacs [84], but were successful only for specific simple job shops. Early simulation studies that recognized the importance of the labor constraint in job shop scheduling include Rowe [78], Allen [2], Legrande [54], and Harris [40]. Actual shop data was used in all of these studies.

Allen [2] studied the utilization of labor in a simulation study of an actual job shop under declining shop load. He examined alternative sequencing rules that would maintain labor utilization at a high level until new orders were received and shop load increased. Machine and labor flexibility were also examined, machine flexibility in terms of alternate routings and labor flexibility in terms of heterogeneity. The 40 worker labor force was divided into 13 skill classes, 5 skill classes, and one skill class. Results indicated that SPT was generally the best sequencing rule and that labor flexibility had more impact on utilization than machine flexibility. In addition, the effects of machine and labor flexibility were relatively independent.

Rowe [78] performed the first large scale evaluation of sequencing rules in a simulation of a General Electric plant. Both labor and machines were included in the scheduling environment. Legrande [54] completed a similar study at Hughes Aircraft under Rowe's direction.

Harris [40] investigated a 160 machine job shop in an unpublished doctoral dissertation. Although labor was not included in the initial study, a new model was developed that incorporated man-machine work centers to provide a more realistic description of the operational job shop.

These early studies pointed out the value of considering labor as a constraining resource, but it was Nelson's general model for a dual constrained production system [67] and subsequent simulation experiments [65,66] that stimulated the majority of research on labor as a second resource.

In his first work, Nelson [67] introduced a general model of labor and machine limited production and tested a variety of labor allocation decisions with a job shop simulation. His purpose was to illustrate the importance and flexibility of decisions involving the labor resource. Three sequencing rules, FCFS, FISFS, and SPT, and five labor assignment rules, FCFS, FISFS, SPT, Random (RAN), and longest queue (LNQ), were tested. The labor force was considered at four levels and efficiency ratings were assigned to the workers. The degree of centralized control over labor assigment, labor flexibility, and job routings were also included in the experiments performed.

Results revealed that reducing the size of the labor force increases labor flexibility, and moving from centralized to decentralized control increases mean flowtime for all labor assignment rules. It was further determined that introducing flexibility into the labor force of a job shop reduces mean flowtime more than in a flow shop, and the LNQ labor assignment rule in conjunction with the SPT or FISFS sequencing rule produces the lowest job flowtime.

In his next study, Nelson [66] compared the labor and machine limited production system to its reduced machine limited counterpart, but found no equivalent relationship.

The most recent Nelson paper [65] on dual resource constrained systems considered, in more detail than his previous work, the issues of labor efficiency and degree of centralized control over labor assignment. Queue discipline and routings were also varied and a labor cost function was developed. Results included the observation that centralized control becomes more important as labor efficiency decrease. In addition, the proportion of operations performed by least efficient labor increases dramatically when control is completely decentralized. Also, under no central control, the SPT sequencing rule produces a higher degree of poor labor efficiency assignments. Job routings have little effect on the labor decisions.

Maggard [55] wrote his dissertation on dual resource constrained job shops under the direction of Nelson. His simulation experiment varied the number of machine centers, number of laborers, mean service rate, and labor efficiency. From the experiment it was determined that the performance of the homogeneous labor system is superior to comparable heterogeneous labor systems; for each system of fixed facilities, an optimum number of laborers can be determined; and the dual resource constrained shops yield lower waiting time values than their single constraint, machine limited counterparts.

Fryer [33,34,35,36] also conducted a series of simulation studies on labor decisions in the dual resource constrained job shop. Fryer [35] first examined two labor assignment rules (FISFS and LNQ) and two sequencing rules (FISFS and SPT) in a shop with a more complex organizational structure than in previous studies. Labor was homogeneous and could be transfered among divisions, work centers, and machines. This study concluded that sequencing rule performance is dependent on labor policy, when a worker should be transfered is more important than where, sequencing rule affects labor transfers, and labor assignment is often more important than item sequencing.

Using the same model, Fryer [34] next examined the effect of labor flexibility on job shop performance. The FISFS sequencing rule was used and both interdivision and intradivision transfers were allowed. Interdivision transfers took place after the worker had been idle a specified period of time. Transfers were made to the division with the largest total time in the system for all jobs in that division. Interdivision transfers were allowed when the queue of the current work center reached a certain value. Transfers were made on the basis of the machine center with the job which had been in the system the longest (FISFS). Results showed that a decrease in mean flowtime at high flexibility levels occurred at the expense of an increase in interdivisional transfers. Intradivisional transfers had little effect on mean flowtime.

Fryer [33] further studied the interaction of shop size with labor flexibility. Three shop sizes, along with FISFS and SPT sequencing rules, LNQ and no transfer interdivisional labor rules, and FISFS and LNQ intradivisional labor assignment rules, were examined. Results from the study included the observation that mean flowtime increases as the system loses flexibility and moves from the FISFS to LNQ labor assignment rule.

Finally, Fryer [36] studied organizational segmentation and labor transfer policies. Segmentation refers to dividing a fixed number of work centers equally into a varying number of divisions. The study showed that as segmentation increases, mean flowtime and interdivisional transfers increase, while intradivisional transfers decrease. The performance ranking of scheduling rules did not change.

Weeks and Fryer [92] studied four duedate assignment rules (constant and different weights on TWK), three labor assignment rules (FISFS, LNQ, and S/OPN), and three sequencing rules (FISFS, SPT, and S/OPN) in a job shop simulation. Labor could only be reassigned if its current queue was empty. SPT was determined the best sequencing rule and FISFS the best labor assignment rule.

Several studies of dual constrained job shops emphasized special concerns of the researcher. Holstein and Berry [46] were concerned about the cost of labor transfers. They compared LNQ with a newly designed work flow labor assignment rule under SPT, FISFS, and S/OPN sequencing rules in a job shop simulation. The number of labor transfers was reduced by the new rule, but mean flowtime increased. SPT produced the least difference in labor assignment performance.

Hogg et al. [44,45] presented a two part study of a labor and machine limited job shop. In the first part, sequencing was determined by FCFS, labor was heterogeneous, and labor assignment rules included longest waiting time (LWF) and most efficient job. Most efficient job was determined the best labor assignment rule. In part II, labor was homogeneous and assigned by LWF. Labor blocking, system size, and workforce size were also considered. The largest system was found to be the most efficient. In addition, a measure of system effectiveness was proposed.

Huang, Moore, and Russell [48] examined the impact of workload on scheduling policies in a dual resource constrained job shop. Four sequencing rules (SPT, FISFS, FCFS, and LCFS), three labor assignment rules (LNQ, LWF, and RAN), and three shop utilization levels (70%, 85%, and 99%) were examined in the simulation experiment. Results showed scheduling policies to be significantly different only at the high utilization levels. The LNQ labor assignment rule and SPT sequencing rule performed best.

The only assembly shop study involving the labor constraint was performed by Rochette and Sadowski [77]. Labor was assigned to the machine center containing the highest priority job. Jobs were assigned priorities by eight different sequencing methods (FISFS, FCFS, SPT, DDATE, SLACK, S/OPN, NOPT, and SPT*TWK). Labor flexibility was introduced as a variable with either no switching of machine centers allowed or switching with a 10% loss of labor efficiency. Workforce flexibility was found to improve performance across sequencing rules. Also, no significant improvement in performance was recorded when the number of machines was doubled keeping the same workforce.

In summary, studies of dual resource constrained scheduling systems have considered a variety of labor allocation decisions, such as, labor flexibility [2,33,34,48,55,65,67,77], degree of centralized control [34,35,36,46,67], size of the labor force [45,55,67,77], labor efficiency [44,55,67,77], and labor assignment rules [33,35,36,44,48,67,92]. In addition, the interaction of labor allocation with sequencing rules [33,35,46,48,65,67,77,92], shop size [33,55], shop load [48], job routings [65], and duedate assignment rules [92] have also been studied.

General conclusions from this research include the following: (1) Increased labor flexibility and centralized control over labor improves shop performance. (2) Increasing the size of the work force does not necessarily improve performance. (3) A significant interaction exists between the labor allocation decision and item sequencing rule. (4) In some cases, the labor assignment rule is more important than the item sequencing rule. Recommendations for best labor assignment rule were conflicting among the studies, but the best sequencing rules did not vary from the rules traditionally recommended.

SUMMARY

This chapter has summarized the research to date in three areas of interest to this present work, that of sequencing rules for an assembly shop, procedures for assigning duedates, and labor as a constraining resource. These topics represent three of the factors included in the simulation experiment to be performed on scheduling policies for an assembly shop. The background of research in this chapter is essential to understanding the particular selection of item sequencing, duedate assignment, and labor assignment rules to be tested.

The research on sequencing rules for assembly shops has not produced a dominant sequencing rule, but it has shown that scheduling in assembly shops is different from scheduling in simple job shops. For example, the dominant sequencing rule for simple job shops, SPT, was determined insufficient for sequencing items to be later assembled. Among the sequencing rules that did perform well in the assembly shop were those which included SPT in some form, considered the entire job structure, and were dynamically calculated. A valid comparison among studies is difficult because of the varying product structures on which the rules were tested. Thus, one of the objectives of this research is to test sequencing rules for assembly shops on two distinct sets of job structures, representing flat jobs with many components per assembly and tall jobs with fewer components per assembly but more levels of assembly.

Selecting the sequencing rules to be included in the experiment is difficult because of the multitude of rules available and the lack of agreement on their performance. Therefore, a preliminary simulation experiment will be undertaken to analyze the performance of traditional sequencing rules used in simple job shops, some of the best sequencing rules from previous assembly shop studies and some newly created rules especially designed for assembled products. The preliminary experiment is explained and its results presented in Chapter 4.

For the most part, the research on duedate assignment procedures has been performed in simple job shops. Results of the research indicated that duedates assigned by job content or shop congestion performed better than constant or random duedates. Also, the tightness of duedates significantly affected sequencing rule performance.

Assigning duedates for assembled products provides a wider variety of choices than for non-assembled products. For example, in a serial job, job content is simply the sum of operation processing times; whereas, in an assembly job, job content may be calculated by summing all of the operation processing times in a job or summing the operation processing times along a certain path in the job's structure, or in some fashion, weighting item processing time by the number of components per assembly. The only assembly shop study that compared duedate assignment procedures [39] did not consider these options, but rather compared the traditional job content and constant allowance duedate rules.

This study will test various job content duedate assignment procedures to determine if they affect job performance and if they interact with other scheduling policies or the structure of the jobs being processed. Although duedate tightness may vary among the duedate assignment procedures tested, tightness is not considered per se in the experiment.

The research on labor as a second constraining resource included labor allocation decisions that were varied and sometimes complex. It was generally concluded that increased labor flexibility and centralized control increased shop performance, while increasing the size of the labor force did not necessarily improve performance.

In addition, labor assignment decisions interacted strongly with sequencing criteria.

Recognizing the importance of the labor allocation decision, along with the merits of a simple experimental design, this research will concentrate on testing various labor assignment rules in an assembly environment. The labor force will be heterogeneous with centralized control, but no variations of these policies will be tested. The particular labor assignment rules to be tested are two which have appeared most often in the literature and one created expressly for the assembly environment. Only one previous study of assembly shops [77] has considered the labor resource and, in that study, different labor assignment rules were not tested.

The next chapter on Simulation Methodology describes the hypothetical assembly shop on which the various scheduling policies will be tested, presents the simulation model of the assembly shop, and discusses the experimental conditions for the simulation study.

CHAPTER 3

SIMULATION METHODOLOGY

For this dissertation, the operation of a hypothetical assembly shop is simulated under various combinations of scheduling policies. Chapters 1 and 2 discussed the special concerns of assembly shop scheduling. Chapter 4 presents the scheduling policies to be considered in the simulation experiment. This chapter describes the assembly shop, the simulation model, and the conditions under which the experiment is performed.

THE ASSEMBLY SHOP

Assembly shop is used to denote a production facility in which both serial and parallel operations take place; unlike a job shop where only serial operations are allowed. The jobs processed by this hypothetical assembly shop contain items which require the completion of a series of operations before they are available for combination with other items belonging to a common assembly. The assembled item, in turn, may undergo a series of operations before it too is assembled into a higher level item. Thus, the production process in terms of routing, sequencing, and pacing of common components may be quite complex.

The assembly shop modeled has five machine centers, with the fifth machine center designated as an assembly area. Machine centers one through four contain two identical machines, for a total of eight machines in the shop. Processing times are preassigned to the items enqueued at these machine centers from a poisson distribution with a mean of .01 days. Routing is also predetermined so that an operation has an equal probability of being performed at any of the four machine centers. The manufacture of each item requires from one to three processing operations. Machine centers may be revisited, but not consecutively. Machine center 5 is a dummy center for items awaiting assembly. Assembly requires zero processing time and no manpower or equipment. Routing to machine center 5 is determined by the assembly requirements of a job's structure.

The labor force for the assembly shop consists of six workers with two skill categories. Three workers are able to perform only the operations required at machine centers one and two. Three additional workers may be assigned only to machine centers three and four. There is no difference in worker efficiency within each skill category.

Jobs arrive to the shop continuously according to an exponential distribution with a mean interarrival time of .75 days. The minimum interarrival time is limited to .10 days. The arrival rate was set so that approximately an 84% utilization level is achieved by the most limited resource. The ten job types which may enter the assembly shop are classified as either flat or tall, according to their parent-component structure. These jobs or products are structurally diagrammed in Appendix I and II. Upon arrival, there is an equal probability of a job being assigned structure one through five from either the flat or tall job structure set, whichever is being tested during the particular simulation run. Job structure, routing, and processing times have been predetermined and are read into the simulation program before it is executed.

Structures for the flat jobs were generated from a set of uniform distributions such that the number of levels ranged from two to three, the number of components per assembly from four to five, the number of operations from one to three, and the machine center assignment from one to four. Processing times were also generated for each operation independent from machine center, level, or job. After the structures were generated, machine center assignments were adjusted so that a relatively balanced load in terms of number of operations and sum of processing times was distributed across machine centers.

Structures for the tall jobs were restricted to the number of items generated for each flat structured job. The number of levels for tall jobs was uniformly distributed between two and four, and the number of components per assembly between two and three. The number of operations, machine center assignments and processing times for each tall job was matched with its corresponding flat job. Single component assemblies were sometimes forced at the lower levels of tall job structures by the restriction on the number of items per job. Quantity per assembly for every item across structures was one. Also, completion of the end item for each job required no processing operations, only an assembly.

Unlike a job shop operation, a job does not enter the assembly shop as an entity. Rather, it is first exploded[1] to its lowest level and those items enter the shop at the machine center where their first operation is to be performed. Then, after an assembly has taken place, the newly assembled item re-enters the assembly shop at the machine center where its first operation is to be

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[1]Since the quantity per assembly is one for every item in all the job structures, a complicated explosion routine was not necessary.

performed. The process continues until the end item has been assembled and the completed job exits the shop.

Unlike an MRP system, all of the lowest level items in a job are released to the shop at the time of the job's arrival. The release of items to the shop is not predicated on their duedate, although the sequencing of those items at individual machine centers may be.

Figure 3.1 shows the assembly shop with machine and labor resources. Since the routing patterns are so varied and complex, they are not included in the diagram. However, the figure does portray the initial loading of the shop from an empty condition when job 2 from the flat structured job set has arrived and the sequencing rule is first come, first served.

THE SIMULATION MODEL

The operation of the assembly shop is modeled in the SLAM II simulation language. SLAM II is a versatile FORTRAN based simulation language which allows network, discrete event, and continuous modeling. For the assembly shop model, the machine centers and assembly process are modeled in network form, while precedence and assembly requirements and the calculation of sequencing and labor

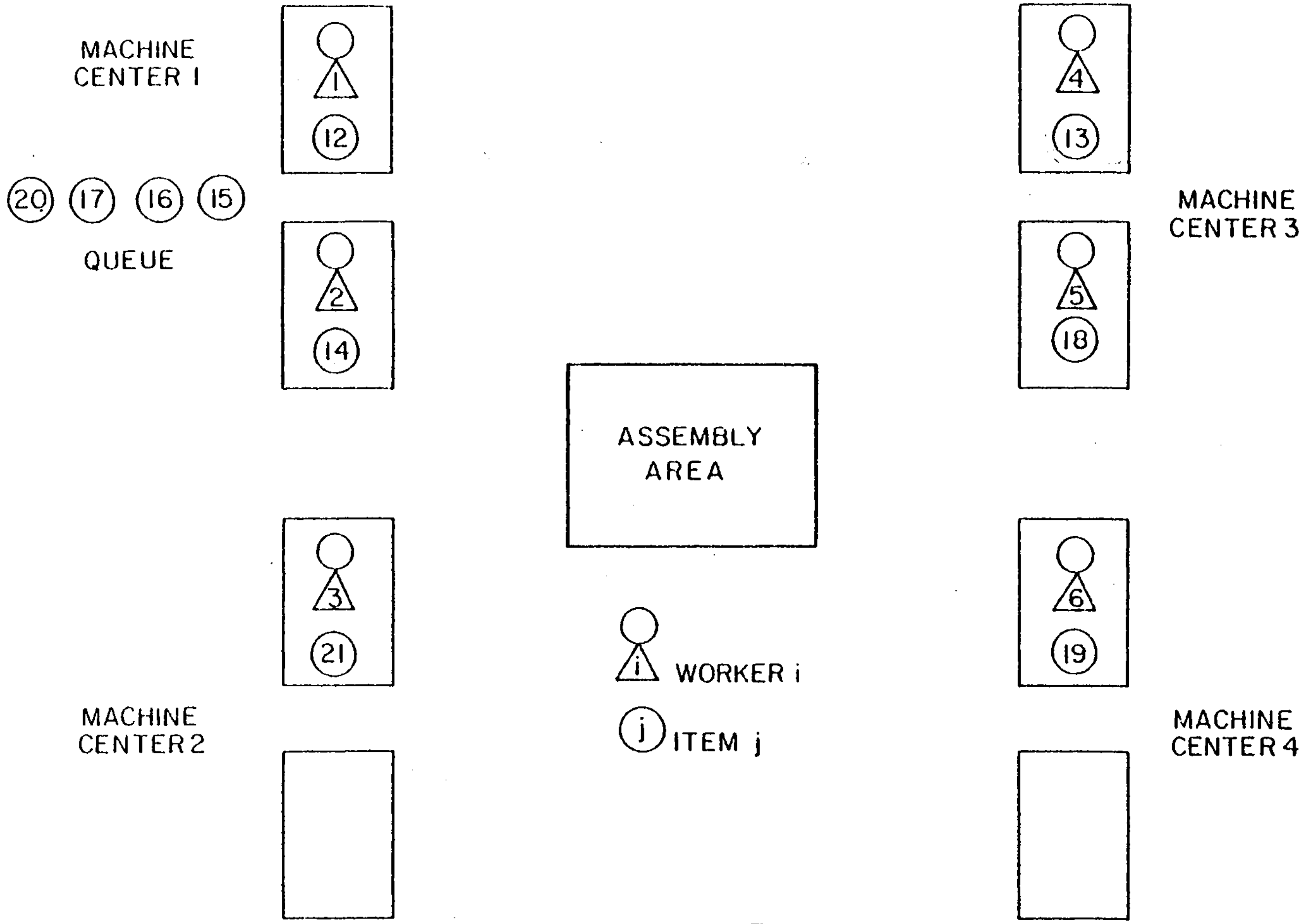


FIGURE 3.1

ASSEMBLY SHOP WITH FLAT JOB 2 LOADED

assignment rules are maintained in discrete event subroutines. The model is described in some detail in this section. Additional information on SLAM II and its capabilities may be found in Pritsker and Pegden [80].

Complete listings of the program used to generate job structures and the simulation program are provided in Appendix III and IV. Table 3.1 defines the variables that appear in the user defined common statement and are used in several of the subroutines. Table 3.2 lists the attributes that are carried by every item as it is routed through the assembly shop. Figure 3.2 also shows the relationships among the feeder program, the different subroutines, the main program, and the network portions. This information is useful in understanding the descriptions of the simulation model that follow.

Bill of Material Program

A short bill of material program was written in FORTRAN code within SLAM II to generate job structures that followed the parameters specified for flat and tall job sets. Output from this program was later read into the main program segment of the assembly shop simulation model. Thus, job structure, routing, and processing times were all predetermined by this feeder program before the simulation

TABLE 3.1

VARIABLE DEFINITIONS

VARIABLE	DEFINITION
XLEV(JTYPE)	no. of levels in the product structure of job type JTYPE
NITEM(JTYPE)	no. of items in JTYPE
PTOT(JTYPE)	total processing time for the completion of all items in JTYPE
NASM(JTYPE)	no. of assembly operations in JTYPE
NOPT(JTYPE)	no. of operations in JTYPE
CPATH(JTYPE)	critical path length for JTYPE
CPMOD(JTYPE)	modified critical path length for JTYPE
JPAR(JTYPE,ITEM)	parent to ITEM for JTYPE
XCOMP(JPAR,ITEM)	no. of components that make up ITEM for JTYPE
XOPER(JTYPE,ITEM)	no. of processing operations required for ITEM of JTYPE
PITEM(JTYPE,ITEM)	total processing time for all operations of ITEM for JTYPE
PATH(JTYPE,ITEM)	terminal path length from ITEM to the end item of JTYPE
BD(JTYPE,ITEM)	assembly branch duedate allowance for ITEM of JTYPE
NCOMP(JTYPE,ITEM,NUM)	no. assigned to the NUMth component of ITEM for JTYPE

TABLE 3.1, CONTINUED

VARIABLE	DEFINITION
XMACH(JTYPE,ITEM,NOPT)	machine center assigned for the NOPTth operation of ITEM for JTYPE
PT(JTYPE,ITEM,NOPT)	processing time assigned to the NOPTth operation of ITEM for JTYPE
RWK(JOB)	remaining processing time for JOB
RASM(JOB)	remaining no. of assemblies for JOB
ROPT(JOB)	remaining no. of operations for JOB
ZZ(15), A(15), B(15)	attribute arrays used for allocation of labor resource
QMC(MACH)	sum of processing times for items enqueued at MACH
COUNT	no. of completed jobs

Index variables:

JTYPE = 1,...,5 job types
ITEM = 1,...,50 items in a particular job type
JOB = 1,...,1000 jobs that have entered the shop
MACH = 1,...,4 machine centers
NUM = 1,...,5 components of an item

TABLE 3.2

ATTRIBUTE DESCRIPTIONS

ATTRIBUTE	DESCRIPTION
1	Job type
2	Arrival time of job to shop
3	Job duedate
4	Item number
5	Operation number
6	Component number
7	Processing time for current operation
8	Arrival time of component for assembly
9	Job number assigned by arrival
10	Current machine center
11	Sequencing rule criteria for items being processed; Matching criteria for items being assembled
12	Sequencing rule component for more complex rules
13	Last time sequencing rule was updated

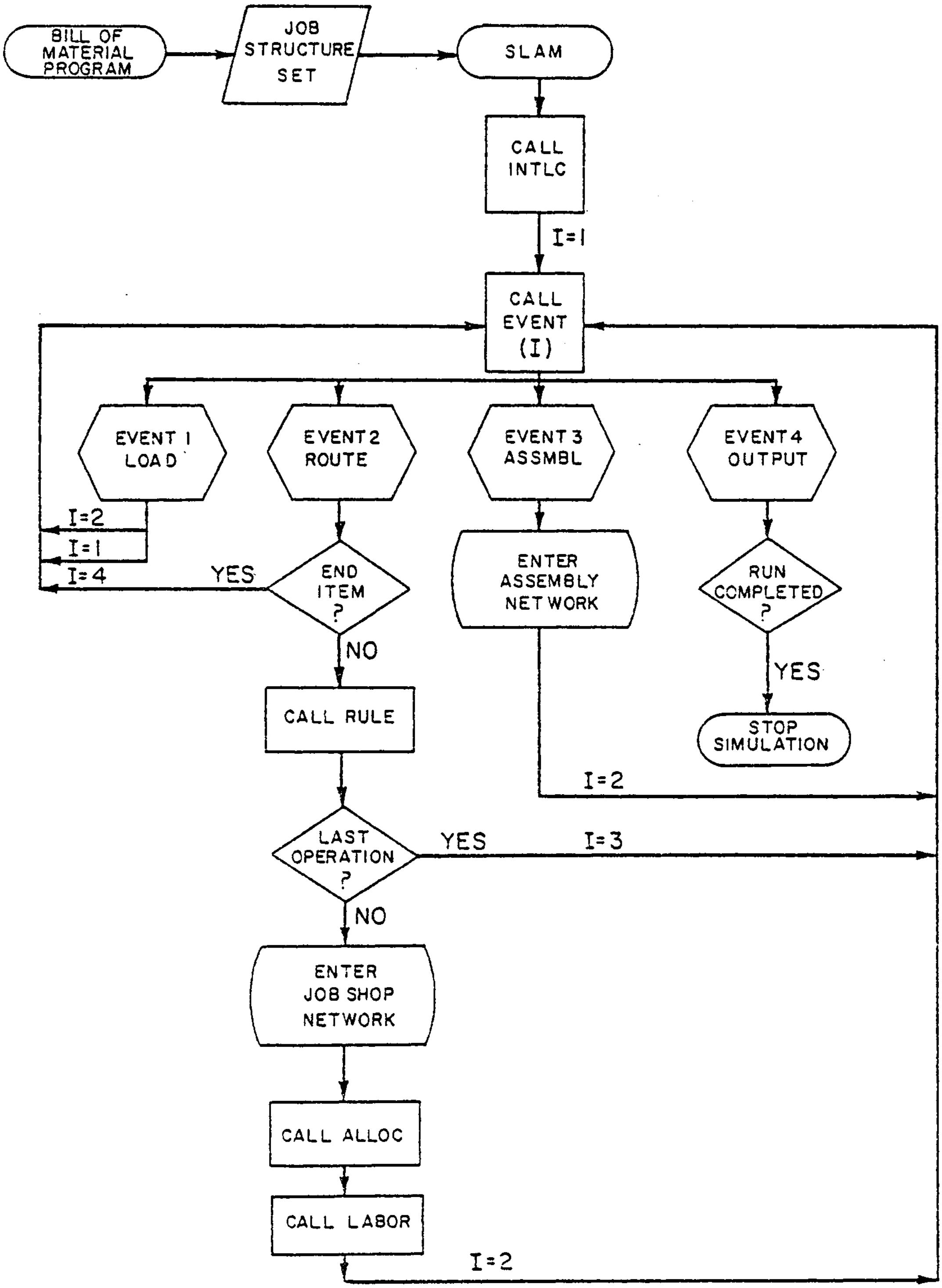


FIGURE 3.2 PROGRAMING LOGIC FOR SIMULATION MODEL

model was ever executed. A listing of the bill of material program for flat structured jobs is included in Appendix III.

Discrete Event Programming

The discrete event portion of the assembly shop simulation program consists of a main program and nine subroutines. Each program segment is briefly discussed below. Complete listings may be found in Appendix IV.

Main Program

The main program is encountered only once, at the beginning of each set of simulation runs. For that reason, the predetermined job structure and processing data is inputed into this segment of the simulation model. In addition, the critical path and modified critical path are calculated for each job type and the duedate allowance is calculated for each assembly. Mean interarrival time is also specified. Finally, the SLAM subroutine is called.

Subroutine INTLC

Subroutine INTLC is called before each simulation run to set initial conditions and schedule the first job arrival.

Subroutine EVENT

Subroutine EVENT schedules five events. Event 1 is job arrival. Event 2 routes component items through the shop. Event 3 assembles components into parent items. Event 4 calculates statistics when a job is finished. Event 5 removes dummy items introduced to labor queues in order to allocate the labor resource.

Subroutine LOAD

Subroutine LOAD assigns a job number, job type, and duedate to each arrival. It loads the lowest level items of a job into the shop by entering the item into the network at the machine center where its first operation is performed. It also assigns attributes to each item prior to the item's entrance into the network.

Subroutine ROUTE

Whenever an item completes processing at a machine center in the job shop network or is assembled in the assembly network, it is referred back to the ROUTE subroutine. From subroutine ROUTE, subroutine OUTPUT is called for end items of a job and subroutine ASSMBL is called upon completion of the last operation of an item. For other items, subroutine ROUTE updates their operation number, determines the next machine center in their routing sequence, and re-enters them into the job shop network at the proper machine center node. Finally, if a dynamic sequencing rule is being used, subroutine ROUTE updates the information required and calls subroutine RULE.

Subroutine ALLOC

Subroutine ALLOC allocates the labor resource if a worker is available, a machine is free, and the conditions of the labor assignment rule are met. Requirements of the LNQ and LWF labor assignment rules are tested in this subroutine. However, an additional subroutine, LABOR, must be summoned to enact the more complicated ADI,SPT labor assignment rule. The definitions and calculations of these rules are presented in Chapter 4.

Subroutine LABOR

Subroutine LABOR determines whether an item's parent is in assembly delay by searching the assembly network for components of the same assembly. It is used solely for the ADI,SPT labor assignment rule.

Subroutine ASSMBL

Subroutine ASSMBL updates the attributes of an item to those of its parent, then re-enters the item into the assembly network at the node corresponding to the number of components in the assembly.

Subroutine OUTPUT

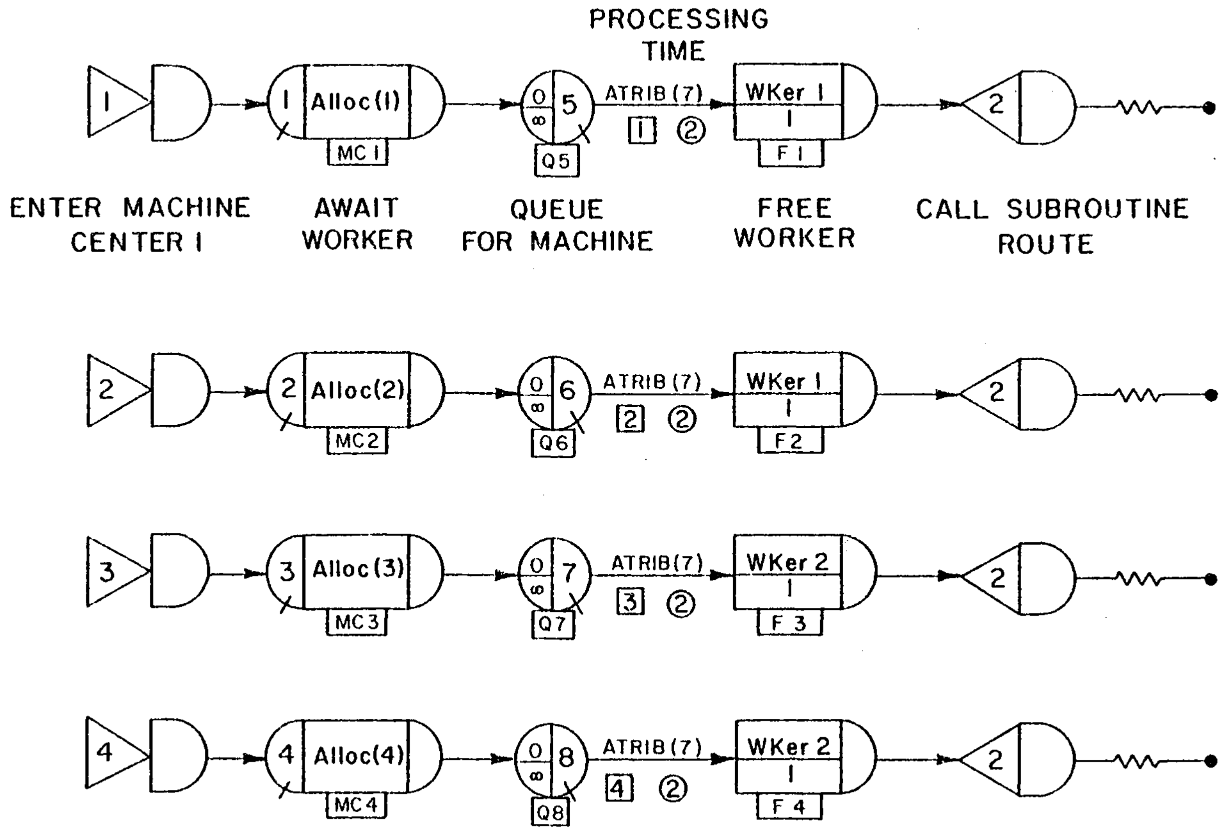
Upon completion of a job, subroutine OUTPUT accumulates statistics on job flowtime, job tardiness, and the square of job tardiness. It also counts the number of jobs that have left the shop and clears the statistics after 50 jobs have been completed. It stops the simulation after 500 additional jobs have exited.

Subroutine RULE

Subroutine RULE is called when dynamic sequencing rules are used. It searches the machine center queues and updates attribute 11 for all items of the same job.

Network Programming

Two separate networks, of a job shop and an assembly operation, complete the simulation program. The networks interact with the discrete event subroutines throughout the processing of jobs in the assembly shop. Network diagrams are presented in figures 3.3 and 3.4 and are briefly described below. A complete coding of the networks is included in Appendix IV in the final segment of the simulation program listing.



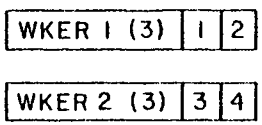


FIGURE 3.3
JOB SHOP PORTION OF NETWORK

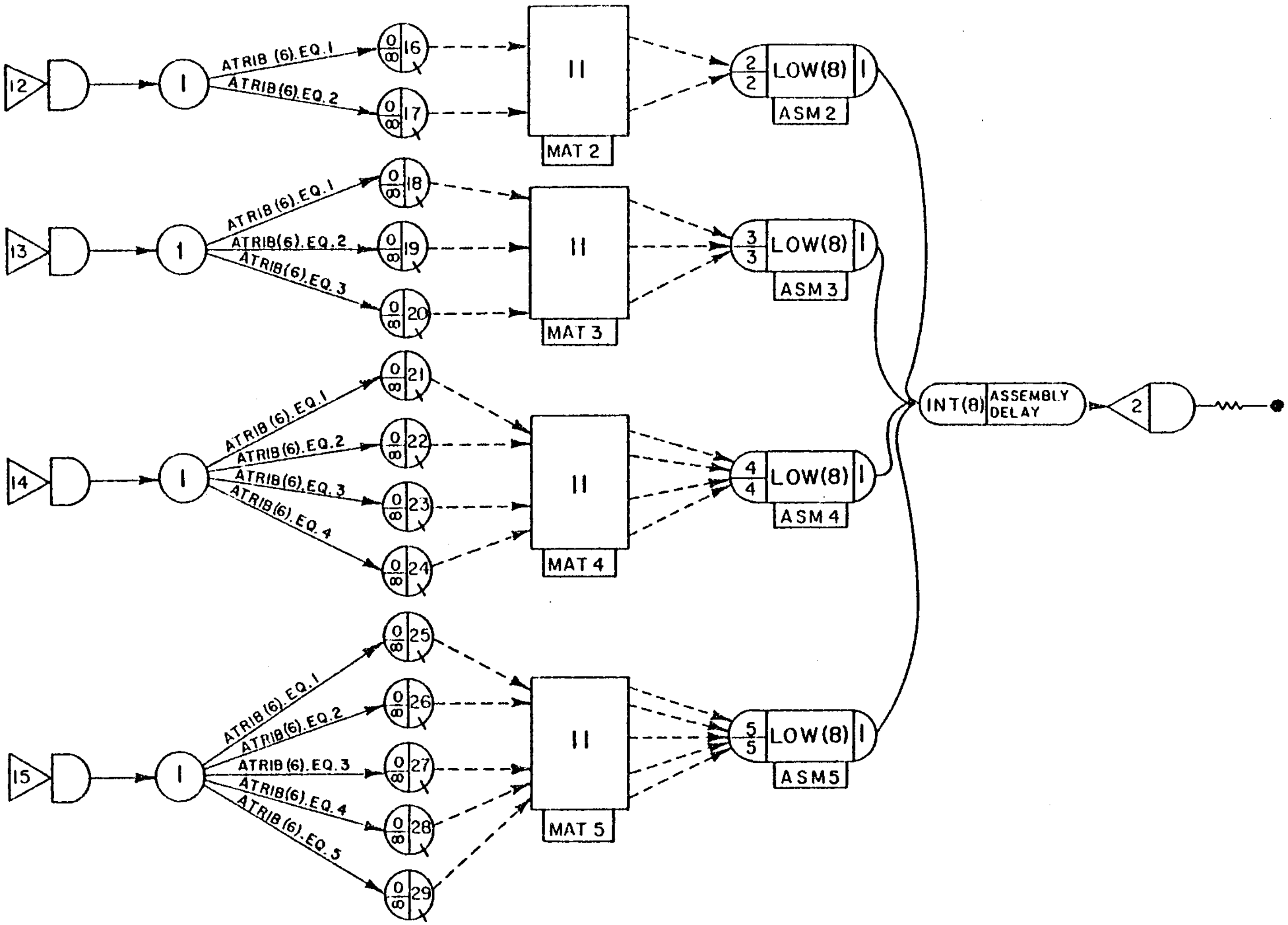


FIGURE 3.4 ASSEMBLY PORTION OF NETWORK

Job Shop Portion

The job shop portion of the network consists of four separate identical segments for each machine center. Referring to figure 3.3, the resource blocks in the lower left corner show three workers of type 1 available to machine centers 1 and 2, and three workers of type 2 available to machine centers 3 and 4. An item enters the network at ENTER nodes 1, 2, 3, or 4 according to the next machine center in its routing sequence. It then waits for a worker and a machine at AWAIT node 1, 2, 3, or 4 from which subroutine ALLOC is called. Items enqueued at the AWAIT node are re-sequenced when a new item joins the queue or when progress has been made on items of a job common to those in the queue. The sequencing rule is specified on the PRIORITY control card, but when necessary, priorities are updated by subroutines ROUTE and RULE.

If the scheduling rule and resource availability conditions have been met and a worker is allocated, the item proceeds to the machine center QUEUE node and is immediately processed for a length of time specified by attribute 7. When processing has been completed, the worker is released at a FREE node for reallocation and the item exits the network. EVENT 2, subroutine ROUTE, is called to determine the next processing requirements for the item.

Assembly Portion

The assembly portion of the network, shown in figure 3.4, is divided into four segments depending on the number of components per assembly. For example, if the parent of an item has two components, the item would enter the network at ENTER node 12. If the item is the first component, as recorded in attribute 6, it is routed to QUEUE node 16. The item waits at QUEUE node 16 until the second component reaches node 17. The items are matched at the MATCH node labeled MAT2 by identical values of attribute 11 and are assembled into one entity at ASSEMBLE node ASM2.

Recall that the item entered the network from subroutine ASSMBL where attribute 11 was specified unique to the assembly and attribute 8 recorded the current time. The newly assembled item, formerly the parent item, takes the lowest value of attribute 8 of its components as its attribute 8 and proceeds to the COLCT node where assembly delay statistics are collected on the difference between attribute 8 and the current time. Finally, the item exits the network and is referred to discrete EVENT 2, subroutine ROUTE, for further processing instructions.

Program Changes

The simulation program was written expressly for this research and was not designed for widespread usage. However, parameter changes in number of job types, arrival rate, processing time distributions, item sequencing rule, and duedate assignment procedure would not be difficult. Changing job structures would require the preparation of a new set of input data and possibly an expansion of the assembly network. The most time consuming change in the simulation model would occur if different labor assignment rules were enacted.

EXPERIMENTAL CONDITIONS

This section discusses the conditions under which the simulation experiment was performed and addresses some of the problems inherent with a simulation methodology, including model verification, steady state, length of each simulation run, and number of simulation runs.

Model Verification

Since the assembly shop modeled in this research is hypothetical, no empirical validation of its operation is possible. However, diagnostic tests can be performed to ensure that the simulation model is operating as intended.

A SLAM trace was generated for each sequencing and labor assignment rule tested. Duedate assignments were verified with manual calculations. Utilization levels were recorded for each run and averaged from 83% to 85% for the ten run samples. Maximum and average machine center queue lengths were also recorded to observe whether a balanced load was maintained throughout the shop. Statistical collections on assembly delay and root mean square of tardiness were checked by hand to guarantee their accuracy.

Based on these actions, it appears that the assembly shop simulation model is performing as designed and, in simple form, provides an accurate representation of a production facility manufacturing assembled products.

Steady State and Length of Simulation Run

Statistics from a system may be biased when start-up conditions that are atypical of its normal operation are included in the data collected. It is rare that a manufacturing facility begins its day empty and idle; some work is inevitably in progress. Thus, a method must be found to minimize the effects of a shop operating at reduced utilization levels during the initial periods of simulated time. Shannon [79] suggests either: (1) using a long enough computer run so that data from the initial periods become insignificant; (2) excluding some of the initial periods from consideration; or (3) choosing initial starting conditions that are more typical of steady state conditions.

The approach chosen for this research is that of number 2, estimating when steady state conditions are achieved and eliminating all prior data from statistical calculations. To approximate steady state, a test run of the simulation model was made under the FISFS sequencing rule, LNQ labor assignment rule, TWK duedate assignment rule, and FLAT job structure.[1] Average queue length, mean flowtime, and utilization level were recorded for each 10 jobs completed by the assembly shop until 100 jobs had exited the shop. These system statistics stabalized before 50 jobs had been completed. Thus, the system reached steady state by the completion of approximately 50 jobs.

The stopping criteria for the simulation model is based on the number of jobs completed, rather than the passage of a certain amount of time. Establishing a run length at least ten times that of the start-up period, the following experimental conditions result: after 50 jobs have been completed, all statistical arrays are cleared and

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[1]The scheduling rules in this model configuration are described in Chapter 4.

the simulation continues until 500 additional jobs have left the shop. Given that the time units represent days of operation, each run of the model simulates approximately one and a half years of production.

Sample Size

The number of simulation runs for each model configuration is a compromise decision between an assurance of statistical significance and the computer time and funds required by an experiment of this size and complexity. Law [53] recommends always making at least three replications of a simulation regardless of the cost per replication, although large samples are preferable. Also, longer simulation runs tend to require fewer replications. To determine a reasonable sample size for this experiment, twenty runs were made of the FISFS, LNQ, TWK, FLAT model configuration and the cumulative average of mean flowtime was calculated. No significant difference in average mean flowtime was found beyond ten simulation runs. Thus, ten was chosen as the number of simulation runs appropriate for this research.

SUMMARY

This chapter described the simulation model used to perform the current research on scheduling policies for an assembly shop. Details of the hypothetical assembly shop operation and experimental conditions were also explained.

The simulation model, programmed in SLAM II, included both discrete event and network programming in 555 lines of code. The assembly shop consisted of four machine centers with multiple machines per center, an assembly area, and a heterogeneous labor force. Jobs routed through the shop contained both serial and parallel operations. The section on experimental conditions discussed model verification, and the parameters of steady state, run length, and sample size.

CHAPTER 4

EXPERIMENTAL DESIGN

The objective of this study is to assess the impact of four factors, (1) job structure, (2) duedate assignment rule, (3) labor assignment rule, and (4) item sequencing rule, on job tardiness and job flowtime in an assembly shop. Job structure is tested at two levels, while item sequencing, labor assignment and duedate assignment are tested at three levels each. The result is a 2*3*3*3 complete factorial experiment.

With the exception of the item sequencing rule, the levels of each factor are predetermined before any testing is undertaken. The selection of the three item sequencing rules for testing in the full factorial model is made on the basis of a preliminary test of the appropriateness of eleven sequencing rules for use in assembly shop environments.

Results from the factorial experiment are analyzed via an analysis of variance (ANOVA) procedure. ANOVA is used to identify significant differences in mean job flowtime and tardiness performance. Post-ANOVA analysis in the form of linear contrasts is also conducted to determine which means are significantly different and the magnitude of their differences.

To begin the discussion of experimental design, the next section presents the performance measures by which the experiment is evaluated. The factor and factor levels are described in the sections to follow. Included in the discussion are results from the preliminary testing of sequencing rules. The multifactor ANOVA model is then presented. Finally, the statistical procedures of ANOVA and post-ANOVA analysis are discussed.

PERFORMANCE MEASURES

Mean job flowtime, mean assembly delay, mean tardiness, percent of jobs tardy, and root mean square of tardiness are reported in this study. Table 4.1 gives the mathematical formulation of each performance measure. These non-cost measures of performance were chosen because of the highly variable cost structures encountered in industry.

Mean flowtime is a traditional measure of performance in job shop research and is also useful for assembly shops. In this particular study, the comparison of systems with different methods for calculating duedates requires an

TABLE 4.1

MEASURES OF PERFORMANCE

Performance Measure	Description	Definition
Mean Flowtime	Mean flowtime of completed jobs	$\sum_{k \in \phi} (P_k - r_k)/N$
Mean Tardiness	Mean tardiness of jobs completed after their duedate	$\sum_{k \in \phi} \max(0, L_k)/NT$
Percent Tardy	Percent of jobs completed tardy	100NT/N
RMS Tardy	Root mean square of tardiness for jobs completed tardy	$\sqrt{\sum_{k \in \phi} \max\ (0, L_k^2)/NT}$
Assembly Delay	Mean waiting time of a parent item for completion of components for assembly	$\sum_{j \in \zeta} (\max_{\forall i \in S(j)} c_i - \min_{\forall i \in S(j)} c_i)/NA$

Notation:

N = number of jobs completed
ϕ = set of jobs completed
r_k = arrival time of kth job to shop
d_k = duedate of job k
P_k = time at which job k is completed
L_k = lateness of job k; $L_k = P_k - d_k$
$NT = \sum_{k \in \phi} A_k$ where $A_k = \begin{cases} 1 \text{ if } L_k > 0 \\ 0 \text{ if } L_k \leq 0 \end{cases}$; number of jobs tardy
c_i = completion time of item i
$S(j)$ = set of component items to parent j
ζ = set of items assembled
NA = number of items assembled

additional performance measure not directly affected by duedates, such as flowtime. In addition, the inventory costs of a particular scheduling policy are a function of job flowtime.

Mean assembly delay is a performance measure peculiar to assembly shops. It measures the time between completion of the earliest and latest components for an assembly. Because its focus is limited, assembly delay is useful in analyzing why a system performs in a certain way but is not a good overall measure of system performance. Therefore, it serves an informational role only in the evaluation of results.

The major cost factor in scheduling systems is delay cost [13]. Thus, the performance measure of primary interest in this study is job tardiness.[1] Tardiness, represented in the usual fashion as both mean tardiness and percent of jobs tardy, is reported. However, a dilemma arises when comparing systems with low mean tardiness and high percent of jobs tardy, to systems with higher mean tardiness but fewer jobs tardy. The root mean square of tardiness calculation is designed to solve this problem. Each job tardiness figure is squared, then summed over the

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[1] In this study, as in Maxwell's [56], the tardiness measures of performance consider only those jobs with strictly positive tardiness.

number of jobs tardy before taking the square root. The result is a root mean square (RMS) figure that tends to penalize systems with a few jobs that are very late more than those with many jobs that are a little late. Practitioners have expressed a preference for this logic in assessing the impact of late jobs [24]. Thus, root mean square is a more accurate and logical measure of tardiness than the mean alone. Nevertheless, both tardiness measures are reported in this study because of the widespread use of mean tardiness and the meaningfulness of its unit of measure.

Statistical analyses for the study are conducted on mean flowtime, mean tardiness and root mean square of tardiness performance measures. Additional analyses are performed on RMS of tardiness data. A detailed account of the statistics to be performed is provided in a later section in this chapter.

FACTORS AND FACTOR LEVELS

Job Structure

Two types of job structure sets are considered in the experiment. Each set consists of five jobs whose structure is randomly generated according to certain parameters on number of levels, number of assemblies, components per assembly, and operations per item. The flat structured jobs have two or three levels, one to seven assemblies, and four or five components per assembly. Tall structured jobs have three or four levels, three to eleven assemblies, and one to three components per assembly. For both types of jobs, all items, except the final product, are processed through one to three operations at four possible machine centers.

Jobs between sets are identical with respect to total number of items and processing requirements per item. As an example, Figure 4.1 compares job 2 from the flat structured job set with job 2 from the tall structured job set. Operations have not been included in the diagram because they tend to camouflage the structure of the job. A complete set of the ten job structures used in the experiment incorporating operations and machine center assignments is provided in Appendix I for flat jobs and Appendix II for tall jobs.

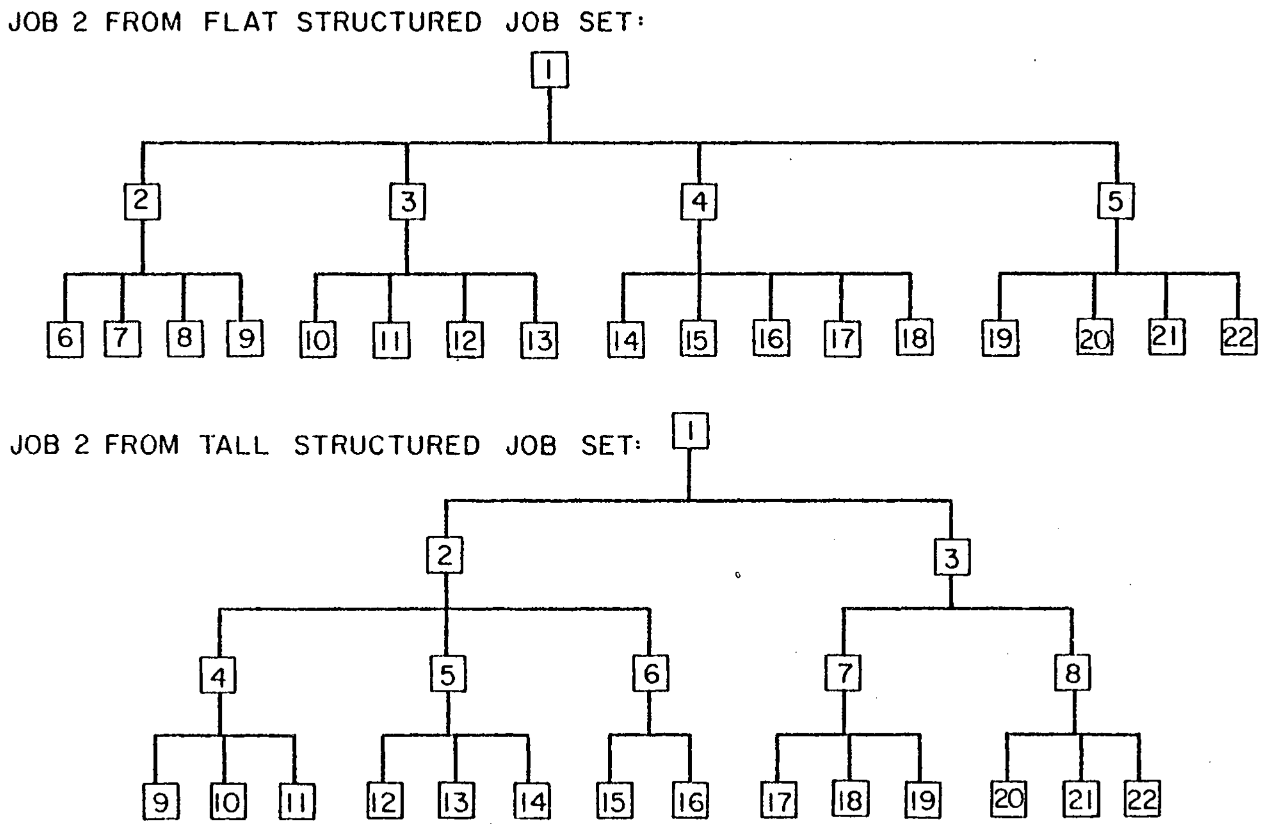


FIGURE 4.1

A COMPARISON OF FLAT VERSUS TALL JOB STRUCTURES

Duedate Assignment Rule

Job duedates are used to calculate certain sequencing rules and performance measures. Their assignment is based on best estimates of job completion that include processing time, queue time, and assembly waiting time. The three duedate assignment rules considered in this study are: (1) Total Work (TWK) - a multiple of the sum of processing times of all operations of a job; (2) Longest Path (LP) - a multiple of the sum of processing times along the LP of a job; and (3) Modified Longest Path (MLP) - a multiple of the sum of (item processing times * number of sister components) along the MLP of a job. Table 4.2 lists each duedate assignment rule and its calculation procedure.

TWK considers the entire job without regard for its structure. Flat and tall structured jobs receive identical duedates. LP considers the length of the job, while MLP also takes into account the breadth of the job. Each rule is weighted by a constant. Table 4.3 compares the tightness of the duedates assigned by these procedures.

The TWK duedate assignment rule is common in job shop literature; and was used by Siegel [80] and Goodwin and Goodwin [38] for assigning duedates in an assembly shop. The LP and MLP rules are appropriate only for assembly

TABLE 4.2

DUEDATE ASSIGNMENT RULES

Rule	Definition	Calculation
TWK	Total Work Content	$r_k + 2.*\sum_{\forall i \in C(k)} p_i$
LP	Longest Path	$r_k + 12.*\max_{\forall i \in C(k)} \sum_{\forall i \mid x_i=0} (p_i + p_{J_i} + p_{J_{J_i}} + \ldots + p_1)$
MLP	Modified Longest Path	$r_k + 3.*\max_{\forall i \in C(k)} \sum_{\forall i \mid x_i=0} [(p_i * x_{J_i}) + (p_{J_i} * x_{J_{J_i}}) + \ldots + p_1]$

Notation:

r_k = arrival time of job k

p_i = processing time for item i; i=1 is end item

C(k) = set of all items in job k

J_i = parent of item i

x_i = number of components of item i

TABLE 4.3

A COMPARISON OF DUEDATE ASSIGNMENT PROCEDURES

FLAT STRUCTURED JOBS

Job	TWK	LP	MLP
1	13.05	10.98	11.86
2	6.37	7.85	7.85
3	15.66	14.03	17.53
4	1.81	6.23	6.23
5	1.93	4.08	5.10
Total	38.82	43.17	48.58

TALL STRUCTURED JOBS

Job	TWK	LP	MLP
1	13.05	13.07	7.75
2	6.37	8.40	4.85
3	15.66	17.29	12.40
4	1.81	7.25	2.01
5	1.93	5.55	2.78
Total	38.82	51.57	29.85

shops. LP was previously used by Maxwell and Mehra [57] to assign duedates. assign duedates. MLP was designed for this particular study to test the effectiveness of a duedate rule that incorporates in some form the number of components per assembly.

Labor Assignment Rule

Items sequenced for processing at a machine center must be allocated a worker before they can be processed at an available machine. Allocation of the labor resource among machine centers is made according to one of the following labor assignment rules: (1) allocate worker to machine center with longest queue (LNQ); (2) allocate worker to machine center whose first item in line has waited the longest (LWF); (3) allocate worker to machine center whose first item in line has a parent in assembly delay; if none or both are delayed, allocate worker to machine center whose first item in line has the shortest operation processing time (ADI,SPT). Table 4.4 presents in mathematical form the labor assignment rules to be tested in the experiment.

The LNQ rule balances shop congestion and tries to prevent bottlenecks. The LWF rule is a natural rule that assumes items waiting the longest are needed the soonest.

TABLE 4.4

LABOR ASSIGNMENT RULES

Rule	Definition	Calculation
LNQ	Longest Queue	$\max_{\forall m \in R(1)} Q_m$
LWF	Longest Waiting Time	$\max_{\forall m \in R(1)} (A_{i,m} - TNOW)$
ADI,SPT	Assembly Delay Indicator, Shortest Processing Time	$\min_{\forall m \in R(1)} (ADI + P_{i,j,m})$

Notation:

$R(1)$ = set of machine centers at which worker resource 1 may be allocated

Q_m = queue length at machine center m; m=5 is assembly area

$A_{i,m}$ = arrival time of item i to machine center m, where item i is the first item in queue

TNOW = current time

$P_{i,j,m}$ = processing time of the jth operation of item i at machine center m

J_i = parent of item i

$$ADI = \begin{cases} 0 & A_{J_i,5} \neq 0 \\ 1 & \text{otherwise} \end{cases}$$

Both of these rules have appeared in job shop research. Nelson [65], Fryer [33,35,36], Weeks and Fryer [92], Holstein and Berry [46], and Huang et al. [48] used LNQ as a labor assignment rule, while Huang et al. [48] and Hogg et al. [44,45] allocated labor by LWF. Nelson [65], Fryer [34,35,36], and Weeks and Fryer [92] tested the following variations of LWF, the longest waiting time of any item in queue (FCFS) and the longest time in the system of any item in queue (FISFS). In the studies that compared labor rules, Nelson found LNQ to be superior to FCFS and FISFS, Huang judged LNQ superior to LWF, and Hogg found allocation by most efficient worker to be better than LWF. For both Fryer and Weeks, FISFS produced a lower mean flowtime than LNQ. LNQ and LWF were chosen as labor assignment rules for assembly shop scheduling because of their intuitive appeal and their prior application in job shop research.

The last labor assignment rule, ADI,SPT, is designed especially for assembly shops. The assembly delay indicator attaches an urgency to the processsing of items which have delayed the progress of additional components for assembly. As a tiebreaker, SPT processes items quickly and keeps both labor and machine resources utilized. This rule was used for sequencing items in assembly shops by Siegel [80] and Maxwell [56]. Maxwell found the rule to perform superbly for flat jobs with only one level of assembly. However, Siegel's testing of ADI,SPT on a variety of job structures produced disappointing results. ADI,SPT did not perform significantly better than SPT, due according to Siegel to its "narrow appreciation of job structure" [80,p.171].

ADI,SPT has never been tested as a labor assignment rule. It is included in this experiment so that an assembly oriented rule may be compared to more traditional labor allocation rules. As a refinement to the sequencing rule employed, the ADI,SPT labor assignment rule is expected to improve flowtime and reduce assembly delay without encountering the problems of myopia that occurred when used as a sequencing rule alone.

Item Sequencing Rule

The sequencing of items at each machine center is perceived as the most sensitive of the scheduling policies to the assembly environment. For that reason, a preliminary study of eleven sequencing rules is undertaken to identify candidates for further testing in the full factorial experiment. These rules may be categorized as simple static rules, simple dynamic rules and compound dynamic rules. Table 4.5 lists each rule by category and provides a brief description.

TABLE 4.5

ITEM SEQUENCING RULES

Simple Static Rules	Definition	Calculation
FISFS	First-in-system, first-served	r_k
SPT	Shortest processing time	$O_{i,j}$
DDATE	Job duedate	d_k
Simple Dynamic Rules		
RWK	Remaining total work	$\sum_{\forall i \in U(K)} p_i$
$ROPT^2$	Remaining no. of operations^2	$(n_k - c_k)^2$
SP	Shortest remaining path	$(q_i + p_{J_i} + p_{J_{J_i}} + \ldots + p_1)$
BS	Branch slack	$B_y - q_y$
Compound Dynamic Rules		
RWK+SC	Remaining total work + shop congestion factor	$\sum_{\forall i \in U(k)} p_i + SC$
$ROPT^2$+SC	Remaining no. of oper.^{2} + shop congestion factor	$.01*(n_k-c_k)^2+10.*SC$
BS+$ROPT^2$	Branch slack + remaining no. of oper.^{2}	$(BD-q_i)+.01*(n_k-c_k)^2$
LP+$ROPT^2$	Longest remaining path + remaining no. of oper.^{2}	$-PL+.01*(n_k-c_k)^2$

Note:All sequencing rules are processed low value first.

TABLE 4.5

CONTINUED

Notation:

r_k = arrival time of job k

p_i = processing time of item i; i=1 is end item

$O_{i,j}$ = processing time of the jth operation of item i

d_k = duedate of job k; TWK, LP or MLP (see Table 3.2)

U(k) = set of uncompleted items in job k

V(i) = set of uncompleted operations of item i

n_k = no. of operations in job k

c_k = no. of completed operations in job k

$q_i = \sum_{\forall i \in U(k), \forall j \in V(i)} O_{i,j}$, remaining processing time for item i

J_i = parent of item i

PL = path length = $q_i + p_{J_i} + p_{J_{J_i}} + \ldots + p_1$

X(i) = set of all components of item i

x_i = no. of components of item i

B_y = assembly branch duedate for item y

TWK: $\forall X(y)=0,\ B_y = r_k + 2.*\sum_{\forall y \in X(J_y)} p_y$

$\forall X(y)\neq 0,\ B_y = \sum_{\forall i \in X(y)} B_i + 2.*p_y$

MLP: $\forall X(y)=0,\ B_y = \max_{\forall y \in X(J_y)} (r_k + 3.*x_{J_y}*p_y)$

$\forall X(y)\neq 0,\ B_y = \max_{\forall i \in X(y)} (B_i + 3.*x_{J_y}*p_y)$

LP: $\forall X(y)=0,\ B_y = \max_{\forall y \in X(J_y)} (r_k + 12.*p_y)$

$\forall X(y)\neq 0,\ B_y = \max_{\forall i \in X(y)} (B_i + 12.*p_y)$

TABLE 4.5

CONTINUED

Notation:

$m_{i,j}$ = machine center where the jth operation of item i is performed

$Q(m_{i,j})$ = set of operations enqueued before machine center $m_{i,j}$

$SC = O_{i,j} * \sum_{\forall l,n \in Q(m_{i,j})} O_{l,n}$

Simple Static Rules

The simple static rules, first-in-system,first-served (FISFS), shortest processing time (SPT), and job duedate (DDATE), have been tested extensively in job shop research. All of these rules are easy to calculate and maintain, but emphasize different features. The FISFS rule ignores job structure and processing requirements. Instead, it paces the processing of items in a job by assigning common rankings, and accelerates jobs to completion that have been in the system the longest. The SPT rule ignores job structure, pacing, and acceleration, but concentrates on processing as many items through a machine center as possible. The DDATE rule considers acceleration by including job arrival time in its calculation, pacing to some extent by assigning all items of a job a common ranking, and job structure as part of the duedate calculation.

These rules have already been tested in assembly shop research. Maxwell [56] and Siegel [80] tested all three rules, Miller, Ginsberg, and Maxwell [60] tested SPT and FISFS, Goodwin and Goodwin [38] tested SPT and DDATE, and Rochette and Sadowski [77] examined SPT. For both Maxwell and Siegel, the SPT rule performed the best of the static rules tested, but for Goodwin and Goodwin, DDATE was the best performer.

These rules are included in this study because of their widespread use in past job shop and assembly shop research.

Simple Dynamic Rules

The simple dynamic rules, total work remaining (RWK), number of operations remaining ($ROPT^2$), shortest remaining path (SP), and assembly branch slack (BS), must be recalculated whenever an operation is completed. All of these rules, except the BS rule, take job structure into account, monitor job progress, and accelerate a job through the shop as it nears completion. Pacing by RWK and $ROPT^2$ is accomplished by assigning common priorities to all items of a job. The SP rule does not pace the processing of items in a job, rather it attempts to complete processing one path of an assembly before starting on another. The BS rule is the only rule that paces the completion of items in a common assembly. Coordination of all items of a job is achieved by setting branch duedates that accumulate to the job's duedate.

The RWK and ROPT rules were tested in some form by Maxwell and his associates [56,57,60] and Siegel [80] and performed well. Operation slack and job slack rules were also tested by Maxwell [57,60] Siegel [80], and Goodwin and Goodwin [38] with limited success. Depending on the type of product structure, these rules in some cases were equivalent to the BS rule. The SP rule was previously tested by Seigel [80] with mediocre results.

Compound Dynamic Rules

The compound dynamic rules are designed to enhance certain features of the simpler rules. By adding a shop congestion factor to the RWK and ROPT^2 rules, items with shorter processing times are pushed through the machine center if the queue is congested. The shop congestion factor, a multiple of the operation's processing time times the sum of processing times in the queue, is taken directly from Siegel [80] where it produced significant improvements in sequencing rule performance. Under these rules, items of the same job receive different rankings according to their operation processing times and machine center conditions.

The BS+ROPT^2 and LP+ROPT^2 rules are examples of specialized rules made useable by the addition of a stabalizing factor, ROPT^2. The branch slack combination rule retains the pacing effect of its simple rule while adding the acceleration and coordination advantages of the $ROPT^2$ factor. Squaring the number of operations remaining intensifies the acceleration effect. The longest path combination rule processes items first that have the longest sum of processing times to final product completion. Rankings within a job vary, but are coordinated to a degree by a common $ROPT^2$ factor. In addition, the $ROPT^2$ factor keeps lengthy arriving jobs from getting a higher priority than jobs already in the shop.

These composite rules have not been previously tested, nor has the squaring of ROPT as part of a composite sequencing rule.

Testing Procedures

A simulation model of the hypothetical dual constrained assembly shop described in Chapter 3 was used for the preliminary testing of these eleven rules. The simulation model, written in SLAM II, is the same model on which the full factorial experiment will be performed. The other factors to be tested in the full factorial experiment were set at the following levels and remained unchanged during the preliminary experiment: FLAT job structure, longest queue (LNQ) labor assignment rule, and total work content (TWK) duedate assignment rule. These factor levels were chosen for the preliminary testing because they are the rules most commonly found in the current body of research.

A single factor ANOVA was constructed to test the significance of sequencing rules on mean flowtime, mean tardiness, and RMS of tardiness of jobs completed in the assembly shop. Differences in mean performance values were further analyzed by Tukey multiple comparison test and the formation of 95% confidence intervals around mean differences. Selection of the three sequencing rules for further study was based on their performance, over ten simulation runs, at minimizing root mean square of tardiness and their emphasis on different job related characteristics.

Results of Preliminary Testing of Sequencing Rules

Ten simulation runs of 500 completed jobs were made for each of the eleven sequencing rules. The average mean flowtime, percent tardy, mean tardiness, root mean square of tardiness, and mean assembly delay for the multiple simulation runs of each sequencing rule are provided in table 4.6. An ANOVA F-test for significance of sequencing rule showed that mean flowtime, mean tardiness, and RMS of tardiness are significantly affected by the selection of sequencing rule at the .0001 level.

TABLE 4.6

SUMMARY OF PRELIMINARY RESULTS
ON SEQUENCING RULE PERFORMANCE

Sequencing Rule	Mean Flowtime	Mean Tardiness	Percent Tardy	RMS Tardy	Mean Assembly Delay
FISFS	3.49	2.58	.25	37.71	.82
SPT	6.05	7.62	.21	132.70	4.37
DDATE	2.50	.44	.009	1.71	.86
RWK	2.51	3.26	.017	14.34	.95
$ROPT^2$	2.50	4.58	.01	11.41	.87
SP	5.46	8.55	.13	102.19	4.15
BS	6.30	4.29	.32	67.68	1.05
RWK+SC	3.46	4.67	.06	42.77	2.05
$ROPT^2$+SC	2.53	8.54	.01	28.28	.97
BS+$ROPT^2$	2.81	1.21	.02	5.93	.76
LP+$ROPT^2$	2.37	2.58	.01	10.79	.64

Table 4.7 shows the ANOVA results by performance measure. A Tukey studentized range multiple comparison test was performed at the 5% level to reveal where significant differences in performance among sequencing rules occurred. Tables 4.8, 4.9, and 4.10 show the results of the Tukey test and establish confidence intervals around the mean differences for mean flowtime, mean tardiness, and RMS of tardiness respectively.

Analysis of Results

Referring to table 4.6, the DDATE sequencing rule performs as good or better than any other sequencing rule tested for all performance measures except assembly delay.

Mean assembly delay is low for most of the rules tested, but is the downfall for the SPT, SP, RWK+SC rules, triggering high mean flowtime and tardiness figures as well. These results were expected for the SPT rule since it considers only the current operation when sequencing an item and ignores its remaining operations, next level assembly, or remaining job structure. The shop congestion portion of RWK+SC causes the rule to switch to SPT when a queue is congested. This switch increased assembly delay and actually resulted in higher rather than lower flowtime

TABLE 4.7

ANOVA RESULTS FROM PRELIMINARY TESTING OF SEQUENCING RULES

Performance Measure	F-value	Significance Level	R^2	Coefficient of Variation
Mean Flowtime	18.15	.0001	.65	30.94
Mean Tardiness	4.88	.0001	.33	91.35
RMS of Tardiness	10.39	.0001	.51	100.62

TABLE 4.8

TUKEY 95% CONFIDENCE INTERVALS FOR SIGNIFICANT MEAN DIFFERENCES IN MEAN FLOWTIME BY SEQUENCING RULE

Sequencing Rule Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit
BS - FISFS	1.09	2.81	4.54
BS - BS+ROPT²	1.77	3.50	5.22
BS - ROPT²+SC	2.05	3.77	5.49
BS - RWK	2.07	3.79	5.52
BS - RWK+SC	1.12	2.84	4.56
BS - DDATE	2.08	3.80	5.52
BS - ROPT²	2.08	3.80	5.53
BS - LP+ROPT²	2.20	3.93	5.65
SPT - FISFS	.84	2.56	4.28
SPT - BS+ROPT²	1.52	3.24	4.97
SPT - ROPT²+SC	1.80	3.52	5.24
SPT - RWK	1.82	3.54	5.26
SPT - RWK+SC			
SPT - DDATE	1.83	3.55	5.27
SPT - ROPT²	1.83	3.55	5.27
SPT - LP+ROPT²	1.95	3.68	5.40
SP - FISFS	.24	1.97	3.69
SP - BS+ROPT²	.93	2.65	4.37
SP - ROPT²+SC	1.20	2.93	4.65
SP - RWK	1.22	2.95	4.67
SP - RWK+SC			
SP - DDATE	1.23	2.96	4.68
SP - ROPT²	1.23	2.96	4.68
SP - LP+ROPT²	1.36	3.08	4.81

TABLE 4.9

TUKEY 95% CONFIDENCE INTERVALS FOR SIGNIFICANT MEAN DIFFERENCES IN MEAN TARDINESS BY SEQUENCING RULE

Sequencing Rule Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit
SP - LP+$ROPT^2$	.05	5.97	11.88
SP - FISFS	.06	5.97	11.89
SP - BS+$ROPT^2$	1.42	7.33	13.25
SP - DDATE	2.19	8.10	14.02
$ROPT^2$+SC - LP+$ROPT^2$	.04	5.96	11.87
$ROPT^2$+SC - FISFS	.05	5.96	11.88
$ROPT^2$+SC - BS+$ROPT^2$	1.41	7.32	13.24
$ROPT^2$+SC - DDATE	2.18	8.09	14.01
SPT - BS+$ROPT^2$	.50	6.41	12.33
SPT - DDATE	1.27	7.18	13.10

TABLE 4.10

TUKEY 95% CONFIDENCE INTERVALS FOR SIGNIFICANT MEAN DIFFERENCES IN ROOT MEAN SQUARE OF TARDINESS BY SEQUENCING RULE

Sequencing Rule Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit
SPT - BS	1.26	62.29	123.33
SPT - RWK+SC	26.17	87.21	148.24
SPT - FISFS	31.23	92.27	153.30
SPT - $ROPT^2$+SC	40.66	101.70	162.73
SPT - RWK	54.59	115.63	176.66
SPT - $ROPT^2$	57.53	118.56	179.60
SPT - LP+$ROPT^2$	58.14	119.18	180.22
SPT - BS+$ROPT^2$	63.00	124.04	185.08
SPT - DDATE	67.24	128.28	189.31
SP - FISFS	3.45	64.48	125.52
SP - $ROPT^2$+SC	12.88	73.91	134.95
SP - RWK	26.81	87.84	148.88
SP - $ROPT^2$	29.75	90.78	151.82
SP - LP+$ROPT^2$	30.36	91.40	152.43
SP - BS+$ROPT^2$	35.22	96.26	157.29
SP - DDATE	39.46	100.50	161.23
BS - BS+$ROPT^2$	.71	61.75	122.78
BS - DDATE	4.95	65.99	127.02

and tardiness values. The SP rule advanced components of assemblies that could be completed quickly only to have them wait for the more lengthy components to be processed. This wasted time produced unusually high flowtime and tardiness figures.

Surprisingly, assembly delay for the BS rule, designed to accomodate that problem, is not among the lowest recorded. This can be explained by noting that while the branch slack rule may reduce assembly delay on one level of a job's structure, it increases the delay at the next level of assembly. When ROPT^2 is added to the BS rule, assembly delay, as well as the other performance values, are reduced.

Low mean flowtime figures are shared by six sequencing rules. Mean tardiness presents more of a variation in performance, with DDATE and BS+ROPT^2 reporting the lowest figures. A still greater variation in response is found for RMS of tardiness due to the wide differences in percent of jobs tardy from 32% to less than 1%. These observations on variability are supported by the coefficients of variation reported in table 4.7.

From the R^2 values in table 4.7, it can be seen that 65% of the variation in mean flowtime is explained by the selection of sequencing rule. Only 33% of the variation in mean tardiness and 51% of RMS of tardiness are explained by sequencing rules. These results show the preferability of root mean square over the mean as a measure of tardiness.

Multiple Comparison Tests

The results of Tukey multiple comparison tests found in tables 4.8, 4.9, and 4.10 provide the data for the following analysis of sequencing rule performance.

In terms of mean flowtime, the BS, SPT, and SP rules performed poorly. Every other sequencing rule tested had significantly lower mean flowtimes than these three rules. There was no significant difference in mean flowtime among the remainder of sequencing rules.

For mean tardiness, the DDATE and BS+ROPT^2 sequencing rules produced the lowest figures. They performed significantly better than the SPT, SP, and ROPT^2+SC rules. FISFS and LP+ROPT^2 also performed well, significantly better than SP or ROPT^2+SC. There were no significant differences in mean tardiness among the other sequencing rules tested.

For RMS of tardiness, DDATE and BS+ROPT^2 again produced the lowest figures, performing significantly better than SPT, SP, and BS. Also, LP+ROPT^2, FISFS, RWK, ROPT^2, and ROPT^2+SC produced significantly lower RMS of tardiness values than SPT or SP. Even the RWK+SC and BS rules yielded a significantly lower RMS of tardiness than SPT. The only sequencing rule which did not significantly outperform SPT was SP. The poor performance of SPT in assembly shops in light of its sterling performance in job shops is an area for further research.

Several sequencing rules are noteworthy because they did not differ significantly according to measures of tardiness. The DDATE rule, calculated as arrival plus 2*TWK, is a static version of RWK. In this experiment, the static rule actually outperformed the dynamic one, but the difference was not statistically significant. The addition of a shop congestion factor made no significant difference in the performances of RWK or $ROPT^2$, in fact producing worse results. While addition of an $ROPT^2$ factor to the BS rule did significantly improve its performance, neither $BS+ROPT^2$ nor $LP+ROPT^2$ performed significantly better than $ROPT^2$ alone.

Summary and Selection of Sequencing Rules

The following conclusions may be drawn from the results of this preliminary testing of sequencing rules: (1) the SPT rule, alone, does not appear to be an appropriate sequencing rule for the assembly shop; (2) the shortest remaining path (SP) rule is inadequate for sequencing in the assembly shop; (3) the addition of a shop congestion factor, as represented in this study, does not improve the performance of the sequencing rules so examined; and (4) the assembly branch slack (BS) rule does not perform well alone, but may be significantly improved with the addition of an acceleration factor such as $ROPT^2$.

Because of the similarity of results, considerable latitude is available in selecting the three sequencing rules to be included in the full factorial experiment. However, some elimination of alternatives is in order. Of the eleven sequencing rules tested, the SPT, SP, and BS rules may be discarded because of poor performance. The composite rules involving shop congestion did not show an improvement over their simpler counterparts, so they may be eliminated from consideration. Of the remaining six rules, DDATE, BS+$ROPT^2$, and LP+$ROPT^2$ were the best performers in terms of tardiness. Since they also have the capacity to change with other factors to be tested in the experiment, such as duedate assignment rule and job structure, they are chosen for further examination.

THE FACTORIAL EXPERIMENT

With the inclusion of the sequencing rules selected from preliminary testing, table 4.11 now summarizes the factors and factor levels to be examined in the full factorial experiment. The 2*3*3*3 complete factorial experiment tests 54 possible treatment combinations. Each combination is replicated ten times by simulating the model with different random number seeds for ten simulation runs. Determination of the length of each simulation run, length of the start-up period, and number of simulation runs was discussed in Chapter 3.

The ANOVA model, formally presented in the next section, was run on the SAS statistical package three separate times for each of the response variables of mean flowtime, mean tardiness, and RMS of tardiness.

The Multifactor ANOVA Model

The following fixed effects multifactor ANOVA model is constructed to test the main effects and all interaction effects of job structure, duedate assignment rule, labor assignment rule, and item sequencing rule on mean flowtime, mean tardiness, and RMS of tardiness in the assembly shop simulation.

TABLE 4.11

2 * 3 * 3 * 3 COMPLETE FACTORIAL EXPERIMENT

FACTOR A : Job Structure

1. FLAT
2. TALL

FACTOR B : Duedate Assignment Rule

1. TWK
2. LP
3. MLP

FACTOR C : Labor Assignment Rule

1. LNQ
2. LWF
3. ADI,SPT

FACTOR D : Item Sequencing Rule

1. DDATE
2. BS + $ROPT^2$
3. LP + $ROPT^2$

Model:

$$Y_{ijklm} = \mu.... + A_i + B_j + C_k + D_l + (AB)_{ij} + (AC)_{ik}\ (AC)_{ik} + (AD)_{il} + (BC)_{jk} + (BD)_{jl} + (CD)_{kl} + (ABC)_{ijk} + (ABD)_{ijl} + (ACD)_{ikl} + (BCD)_{jkl} + (ABCD)_{ijkl} + \varepsilon_{ijklm}$$

where:

i = indicator of job structure,

i = 1, 2

j = indicator of duedate assignment rule,

j = 1, 2, 3

k = indicator of labor assignment rule,

k = 1, 2, 3

l = indicator of item sequencing rule,

l = 1, 2, 3

m = indicator of number of simulation replications, m = 1, 2, ..., 10

Y_{ijklm} = response (mean flowtime, mean tardiness, or RMS of tardiness) to the ith job structure, jth duedate assignment rule, kth labor assignment rule, lth item sequencing rule, and mth replication

$\mu....$ = overall mean

A_i = main effect of the ith job structure

B_j = main effect of the jth duedate assignment rule

C_k = main effect of the kth labor assignment rule

D_l = main effect of the lth item sequencing rule

$(AB)_{ij}$ = interaction effect of ith job structure and jth duedate assignment rule

$(AC)_{ik}$ = interaction effect of ith job structure and kth labor assignment rule

$(AD)_{il}$ = interaction effect of ith job structure and lth item sequencing rule

$(BC)_{jk}$ = interaction effect of the jth duedate assignment rule and kth labor assignment rule

$(BD)_{jl}$ = interaction effect of the jth duedate assignment rule and lth item sequencing rule

$(CD)_{kl}$ = interaction effect of the kth labor assignment rule and lth item sequencing rule

$(ABC)_{ijk}$ = interaction effect of the ith job structure, jth duedate assignment rule, and kth labor assignment rule

$(ABD)_{ijl}$ = interaction effect of the ith job structure, jth duedate assignment rule, and lth item sequencing rule

$(ACD)_{ikl}$ = interaction effect of the ith job structure, kth labor assignment rule, and lth item sequencing rule

$(BCD)_{jkl}$ = interaction effect of the jth duedate assignment rule, kth labor assignment rule, and lth item sequencing rule

$(ABCD)_{ijkl}$ = interaction effect of the ith job structure, jth duedate assignment rule, kth labor assignment rule, and lth item sequencing rule

ε_{ijklm} = residual term; variation not accounted for by model components described above

Assumptions

For valid inferences under the ANOVA procedure, the error term must be statistically independent and normally distributed. In addition, within population variances must be equal for all treatments. The assumption of statistically independent error terms for the model is guaranteed by generating each simulation run with a new sequence of random numbers. While the assumptions of normality and equal variances cannot be assured, serious violations are unlikely in this experiment because of equal cell replications [51].

Post-ANOVA Analysis

If the ANOVA F-test indicates significant differences among factor level means, further analysis is in order to identify which means differ and the magnitude of their differences. Multiple comparison procedures make a series of pairwise comparisons of means with a modified t-test. The procedure chosen for this study is the Tukey studentized range test (also called HSD for "honestly significant difference") because it is the most conservative of the multiple comparison procedures available and produces the narrowest confidence intervals.

The Tukey method is appropriate when all factor level sample sizes are equal and all pairwise comparisons are considered. Although all pairwise comparisons may not be of interest in this experiment, the selection of pertinent comparisons is not made until an initial analysis of the data is conducted. It is therefore better to use a multiple comparison procedure such as Tukey where the family of statements includes all possible statements which may be later suggested by the data. The Tukey procedure and its derivation are described in detail in Neter and Wasserman [69].

For this experiment, the Tukey procedure is performed on all pairwise comparisons of main effects means for each of the three performance measures, mean flowtime, mean tardiness, and RMS of tardiness. Significance is indicated at the 5% level.

<u>Linear Contrasts</u>

Confidence intervals are useful with multiple comparison procedures because they portray the data in a manner which is easy to interpret and which leads to a practical as well as statistical assessment of the significance of a difference. Thus, in addition to the significance test, 95% Tukey confidence intervals are established for each pairwise comparison of factor level means. These confidence intervals are a form of linear contrasts.

If interaction effects prove significant, a specific comparison of means for treatments of interest may be conducted in the form of linear contrasts. Since these contrasts have not been designed prior to experimentation, Tukey confidence intervals are again appropriate. At this level of detail, contrasts are established only for the RMS of tardiness performance measure.

SUMMARY

A simulation experiment was designed to examine the impact of scheduling policies on the performance of a hypothetical assembly shop. The experiment considered four factors, (1) job structure, (2) duedate assignment rule, (3) labor assignment rule, and (4) item sequencing rule; and three performance measures, mean flowtime, mean tardiness, and root mean square of tardiness. Preliminary testing was performed to identify the levels of item sequencing rule to be included in the complete 2*3*3*3 factorial experiment.

The levels of the four factors may be assigned as follows: (1) FLAT or TALL job structures; (2) total work content (TWK), longest path (LP), or modified longest path (MLP) duedate assignment rule; (3) longest queue (LNQ), longest waiting time (LWF), or assembly delay indicator (ADI,SPT) labor assignment rule; and (4) job duedate (DDATE), composite branch slack ($BS+ROPT^2$), or composite longest path ($LP+ROPT^2$) item sequencing rule.

A total of 54 model configurations results from all possible combinations of the two job structures and three duedate assignment, labor assignment, and item sequencing rules. Operation of the hypothetical assembly shop is

simulated ten times with different random number seeds for each model configuration, for a total of 540 simulation runs.

The results of the simulation experiment in terms of mean flowtime, mean tardiness, and root mean square of tardiness for jobs completed by the assembly shop are statistically analyzed in a multifactor ANOVA model. The ANOVA procedure determines which of the four factors affects job performance and whether the interaction of the factors produces significant differences in job performance. Post-ANOVA analysis to identify where significant differences in performance occur is conducted via Tukey multiple comparison tests.

The next chapter presents and interprets the results of the simulation experiment.

CHAPTER 5

RESULTS AND INTERPRETATIONS

The assembly shop simulation was run 540 times, that is, 10 replications for each of the 54 factor combinations. Each of the 54 cells represented a unique combination of job structure, duedate assignment rule, labor assignment rule, and item sequencing rule. The data generated by the simulation experiment was analyzed by SAS' PROC ANOVA to assess the impact of job structure, duedate assignment rule, labor assignment rule, and item sequencing rule on mean flowtime, mean tardiness, and root mean square of tardiness for jobs completed by the hypothetical assembly shop operation.

Further analysis was performed on differences between factor level means in the form of Tukey multiple comparison tests of significance and simultaneous confidence intervals for all measures of performance. A similar analysis for significant interaction effects was conducted for the RMS of tardiness performance measure.

EXPERIMENTAL RESULTS

The mean flowtime, mean tardiness, percent tardy, RMS tardy, and mean assembly delay of each duedate, labor, and sequencing rule combination averaged over ten simulation runs are given for flat structured jobs in table 5.1 and for tall structured jobs in table 5.2. This data is analyzed via the ANOVA model presented in Chapter 4. First, however, some observations on the experimental results is in order.

Referring to table 5.1, mean flowtime for the flat structured jobs is remarkably similar under the different model configurations, with the exception of those involving the LWF labor assignment. Even within the LWF configurations, the ranking of sequencing rules is the same regardless of duedate assignment rule. On the basis of mean flowtime, LNQ dominates as the best labor assignment rule and LWF as the worst. There is no dominant item sequencing or duedate assignment rule.

The LNQ labor assignment rule produces a lower mean assembly delay than ADI,SPT, the rule designed to monitor assembly status. This surprising result may be caused by the assembly shop's inflexible labor force. Since LNQ balances the machine center queues, there is less chance of

TABLE 5.1
SUMMARY OF RESULTS FOR FLAT STRUCTURED JOBS

Job Struc.	Ddate Rule	Labor Rule	Seq. Rule	Mean Flowtime	Mean Tardiness	Percent Tardy	RMS Tardy	Ass'y Delay
FLAT	TWK	LNQ	DDATE	2.50	.44	.01	1.71	.86
			BS+ROPT[2]	2.81	1.21	.02	5.93	.76
			LP+ROPT[2]	2.37	2.58	.01	10.79	.64
		LWF	DDATE	4.61	1.57	.11	15.17	2.04
			BS+ROPT[2]	3.84	1.41	.06	10.54	1.31
			LP+ROPT[2]	3.97	2.22	.07	17.53	1.86
		ADI,SPT	DDATE	2.82	.80	.03	5.32	1.44
			BS+ROPT[2]	2.89	1.02	.03	7.41	1.15
			LP+ROPT[2]	2.69	3.77	.02	19.44	1.39
	LP	LNQ	DDATE	2.61	.48	.02	2.49	.86
			BS+ROPT[2]	2.47	1.27	.01	4.84	.69
			LP+ROPT[2]	2.37	3.24	.02	13.87	.64
		LWF	DDATE	4.72	1.16	.07	11.96	1.84
			BS+ROPT[2]	3.76	1.67	.03	9.16	1.40
			LP+ROPT[2]	3.97	3.02	.05	20.61	1.86
		ADI,SPT	DDATE	2.83	.63	.02	7.00	1.14
			BS+ROPT[2]	2.91	1.46	.04	10.44	1.34
			LP+ROPT[2]	2.69	4.20	.03	18.65	1.39
	MLP	LNQ	DDATE	2.54	.15	.005	.65	.87
			BS+ROPT[2]	2.47	1.01	.01	2.96	.72
			LP+ROPT[2]	2.37	1.73	.01	6.39	.64
		LWF	DDATE	4.67	.93	.03	5.08	2.06
			BS+ROPT[2]	3.68	1.53	.02	5.58	1.33
			LP+ROPT[2]	3.97	2.29	.03	12.77	1.86
		ADI,SPT	DDATE	2.85	.48	.01	2.62	1.33
			BS+ROPT[2]	2.70	1.14	.01	5.01	1.06
			LP+ROPT[2]	2.69	4.47	.02	21.39	1.39

TABLE 5.2
SUMMARY OF RESULTS FOR TALL STRUCTURED JOBS

Struc.	Ddate Rule	Labor Rule	Seq. Rule	Mean Flowtime	Mean Tardiness	Percent Tardy	RMS Tardy	Ass'y Delay
TALL	TWK	LNQ	DDATE	3.21	5.60	.03	17.90	.80
			BS+ROPT^2	3.42	4.10	.04	24.03	.73
			LP+ROPT^2	2.75	3.19	.01	14.84	.57
		LWF	DDATE	8.62	3.79	.53	80.48	2.02
			BS+ROPT^2	5.36	2.24	.19	33.70	1.16
			LP+ROPT^2	5.46	3.24	.17	45.16	1.41
		ADI,SPT	DDATE	3.55	2.14	.08	24.23	1.06
			BS+ROPT^2	3.61	2.26	.07	21.19	.93
			LP+ROPT^2	3.26	2.73	.06	25.78	.93
	LP	LNQ	DDATE	3.04	5.91	.01	11.20	.74
			BS+ROPT^2	2.92	1.42	.01	4.84	.67
			LP+ROPT^2	2.75	3.47	.01	8.41	.57
		LWF	DDATE	7.98	3.78	.23	54.64	1.78
			BS+ROPT^2	5.04	3.19	.05	22.88	1.15
			LP+ROPT^2	5.46	4.64	.08	42.35	1.41
		ADI,SPT	DDATE	3.69	3.58	.03	13.91	1.08
			BS+ROPT^2	3.44	3.02	.02	9.83	.89
			LP+ROPT^2	3.26	4.69	.02	24.08	.93
	MLP	LNQ	DDATE	3.17	4.94	.08	26.13	.75
			BS+ROPT^2	3.40	3.94	.08	41.13	.80
			LP+ROPT^2	2.75	5.04	.05	38.97	.57
		LWF	DDATE	7.96	4.30	.62	98.57	1.73
			BS+ROPT^2	4.90	2.68	.22	36.44	1.15
			LP+ROPT^2	5.46	3.98	.26	78.78	1.41
		ADI,SPT	DDATE	3.62	2.49	.15	28.26	1.02
			BS+ROPT^2	3.19	2.17	.11	23.23	.85
			LP+ROPT^2	3.26	3.76	.09	45.94	.93

a worker being idled by an empty queue at one machine center while queues lengthen at other machine centers. Similarly, LWF's poor performance may be attributed to its lack of consideration of shop congestion in any form.

In terms of tardiness, LNQ is the best labor assignment rule, LWF the worst labor assignment rule, and LP+ROPT² the worst sequencing rule across the other levels of scheduling policies. Percent of jobs tardy ranges from .5% for DDATE--LNQ--MLP to 11% for DDATE--LWF--TWK.

Results for the tall structured jobs shown in table 5.2 show a greater difference in scheduling policy performance in comparison to the results for flat structured jobs. Again, there is little variation in mean flowtime, except under the LWF labor assignment rule. No other scheduling rule, besides LWF, exerts either a positive or negative dominance on mean flowtime.

The LNQ labor assignment rule produces the smallest assembly delay and LWF the largest assembly delay across the levels of item sequencing and duedate assignment rules. Except for the LNQ--MLP configuration, the DDATE sequencing rule has the highest assembly delay under any duedate or labor assignment policy, a predictable result since the DDATE sequencing rule is not dynamically calculated or assembly oriented. The BS+ROPT² sequencing rule, which tries to pace component assembly, produces the lowest mean assembly delay.

In terms of tardiness, the LP duedate assignment rule exhibits the lowest values, followed by TWK and MLP. These results were expected since they follow the relative tightness of job duedates. Except for the negative dominance of LWF, there is no dominant labor assignment rule or item sequencing rule. Percent of jobs tardy range from 1% under the LNQ--LP combinations and LP+ROPT[2]--LNQ--TWK to 62% for DDATE--LWF--MLP.

These observations on the experimental results need clarification by a thorough statistical analysis. The results of the analysis of variance are presented in the next section, followed by an analysis of main effects and interaction analysis.

ANALYSIS OF VARIANCE

A summary of the results for the overall ANOVA model is given in table 5.3 by performance measure. The ANOVA model is significant at the .0001 level for all measures of performance. Mean flowtime produces the highest R^2 value and the least variability in response as measured by the

TABLE 5.3

SUMMARY OF ANOVA MODEL RESULTS FOR THREE MEASURES OF PERFORMANCE

Performance Measure	F-value	Significance Level	R^2	Coefficient of Variation
Mean Flowtime	35.98	.0001	.80	20.04
Mean Tardiness	3.74	.0001	.29	89.80
RMS of Tardiness	10.99	.0001	.54	91.08

coefficient of variation. The variation in response produced by mean tardiness is about equal to that of RMS of tardiness. However, the amount of variability explained by the ANOVA model under RMS of tardiness is almost double that explained by mean tardiness.

Tables 5.4, 5.5, and 5.6 show the ANOVA results for mean flowtime, mean tardiness, and RMS of tardiness respectively. The main effects of job structure and item sequencing rule are highly significant at the .0001 level for all measures of performance. In addition, for mean flowtime, the main effects of labor assignment rule and all first and second order interactions involving job structure, item sequencing, and labor assignment are significant at the .0001 level. Significant interactions for mean tardiness include job structure with labor assignment, job structure with item sequencing rule, and labor assignment with item sequencing rule.

For RMS of tardiness, all main effects are highly significant at the .0001 level. All first order interactions involving job structure, as well as the interaction of labor assignment with item sequencing rule and the interaction of job structure, labor assignment, and item sequencing, are highly significant.

TABLE 5.4

ANOVA TEST RESULTS FOR MEAN FLOWTIME

Source	D.F.	F-Value	Significance Level	
A	1	305.92	.0001	*
B	2	1.06	.3488	
C	2	557.36	.0001	*
D	2	55.32	.0001	*
A*B	2	.49	.6128	
A*C	2	61.02	.0001	*
A*D	2	16.77	.0001	*
B*C	4	.52	.7208	
B*D	4	.77	.5468	
C*D	4	38.62	.0001	*
A*B*C	4	.64	.6362	
A*B*D	4	.30	.8799	
A*C*D	4	12.38	.0001	*
B*C*D	8	.28	.9737	
A*B*C*D	8	.21	.9899	

Key: A = Job Structure
B = Duedate Assignment Rule
C = Labor Assignment Rule
D = Item Sequencing Rule
D.F. = Degrees of Freedom
* = Significant at the .05 level or less

TABLE 5.5

ANOVA TEST RESULTS FOR MEAN TARDINESS

Source	D.F.	F-Value	Significance Level
A	1	80.68	.0001 *
B	2	1.75	.1754
C	2	.31	.7317
D	2	18.82	.0001 *
A*B	2	1.22	.2949
A*C	2	5.72	.0030 *
A*D	2	11.94	.0001 *
B*C	4	.47	.7551
B*D	4	.69	.5971
C*D	4	2.52	.0407 *
A*B*C	4	1.22	.3008
A*B*D	4	.73	.5725
A*C*D	4	1.24	.2925
B*C*D	8	.72	.6712
A*B*C*D	8	.61	.7665

Key: A = Job Structure
B = Duedate Assignment Rule
C = Labor Assignment Rule
D = Item Sequencing Rule
D.F. = Degrees of Freedom
* = Significant at the .05 level or less

TABLE 5.6

ANOVA TEST RESULTS FOR ROOT MEAN SQUARE OF TARDINESS

Source	D.F.	F-Value	Significance Level
A	1	202.37	.0001 *
B	2	12.37	.0001 *
C	2	55.21	.0001 *
D	2	12.51	.0001 *
A*B	2	24.63	.0001 *
A*C	2	33.58	.0001 *
A*D	2	8.84	.0002 *
B*C	4	.56	.6883
B*D	4	1.01	.4037
C*D	4	9.88	.0001 *
A*B*C	4	1.36	.2474
A*B*D	4	.64	.6365
A*C*D	4	5.74	.0002 *
B*C*D	8	.55	.8204
A*B*C*D	8	.62	.7651

Key: A = Job Structure
B = Duedate Assignment Rule
C = Labor Assignment Rule
D = Item Sequencing Rule
D.F. = Degrees of Freedom
* = Significant at the .05 level or less

The most surprising result of the ANOVA test is the insignificant impact of duedate assignment rule on mean job flowtime and mean job tardiness, as well as the lack of a significant interaction between duedate assignment and sequencing rule for all measures of performance. Possible explanations include the fact that earlier reports [5,30,32,91] of significant duedate impact and interactions were based on varying levels of duedate tightness, rather than the basis of duedate assignment as in this research. Also, job duedates for this study may have been too loose to foster an interaction with item sequencing rule. In addition, most of the previous research on scheduling policies took place in simple job shops where the relationship between a job's duedate and the sequencing of one of its serial operations at a machine center is clearer than the disjointed relationship in an assembly shop between a job's duedate and the sequencing of the parallel operations of its component items at various machine centers. Finally, the insignificant impact of job duedate on mean flowtime can be explained in part by the observation that only two of the three sequencing rules tested (DDATE and $BS+ROPT^2$) had the capacity to change under different duedate assignment procedures.

Another disturbing result is the insignificance of labor assignment rule in terms of mean job tardiness, but the significant interaction of labor assignment rule with both job structure and item sequencing rule. From the data presented in tables 5.1 and 5.2, the LWF labor assignment rule seems to precipitate these interactions. Because of the low R^2 value for mean tardiness reported in table 5.3, no further analysis of interaction effects will be attempted. However, a detailed analysis of significant interactions according to root mean square of tardiness is contained in sections to follow later in this chapter.

Since the ANOVA F test showed statistically significant differences in factor level means, a Tukey multiple comparison test is performed on main effects means to analyze where those significant differences occurred. The results are presented in the following sections by factor.

ANALYSIS OF MAIN EFFECTS

Factor A Means

Tukey 95% confidence intervals for factor A comparisons of job structure are found in table 5.7 and are the basis for the following comments.

TABLE 5.7

TUKEY 95% CONFIDENCE INTERVALS FOR FACTOR A COMPARISONS

Performance Measure	Lower Confidence Limit	Factor Level Comparison	Upper Confidence Limit	
Mean Flowtime	.99	A2 - A1	1.24	*
Mean Tardiness	1.41	A2 - A1	2.20	*
RMS of Tardiness	20.54	A2 - A1	27.13	*

Key: Factor A = Job Structure
Level 1 = FLAT
2 = TALL
* = Significant at the .05 level or less

Tall structured jobs are significantly more difficult to process in the assembly shop than are flat structured jobs by every measure of performance. On an average, tall structured jobs take significantly longer to complete, are more often completed after their duedate, and are completed further past their duedate than are the flat structured jobs. This result is not surprising since, in a tall structured job, more items must wait for their components to be completed before processing can begin.

The significant differences in performance by job structure highlight the need to verify the results of experiments conducted in assembly shops by considering different types of job structures.

Factor B Means

Tukey 95% confidence intervals for factor B comparisons of duedate assignment rules are given in table 5.8.

The total work content (TWK) duedate assignment rule produces a slightly lower mean flowtime than the longest path (LP) or modified longest path (MLP) rules, but the difference for both comparisons is far from significant. There is no difference in mean flowtime between the LP and MLP rules.

TABLE 5.8

TUKEY 95% CONFIDENCE INTERVALS FOR FACTOR B COMPARISONS

Performance Measure	Lower Confidence Limit	Factor Level Comparison	Upper Confidence Limit	
Mean Flowtime	-.09	B1 - B2	.28	
	-.08	B1 - B3	.28	
	-.18	B2 - B3	.18	
Mean Tardiness	-.37	B2 - B3	.79	
	-.12	B2 - B1	1.04	
	-.33	B3 - B1	.83	
RMS of Tardiness	.58	B3 - B1	10.22	*
	5.38	B3 - B2	15.03	*
	-.02	B1 - B2	9.63	

Key: Factor B = Duedate Assignment Rule
Level 1 = TWK
2 = LP
3 = MLP
* = Significant at the .05 level or less

There is also no difference in mean tardiness by duedate assignment procedure. The TWK rule results in the smallest mean tardiness figure, followed by MLP and LP, but the differences are not significant.

As suggested earlier, the insignificant impact of duedate assignment procedures may be due to the common job content base of the duedate assignment rules tested, as well as the overall looseness of their resulting duedates.

For RMS of tardiness, the MLP duedate assignment rule performs significantly worse than either the TWK or LP rules. The LP rule produces the lowest RMS of tardiness, but it is not significantly lower than the TWK rule's performance.

One possible explanation of the MLP rule's poor performance is its emphasis on the number of components per assembly, which may be inappropriate for a variety of product structures.

Factor C Means

Table 5.9 contains the Tukey 95% confidence intervals for factor C comparisons of labor assignment rule.

In terms of mean flowtime and RMS of tardiness, the longest waiting time (LWF) labor assignment rule performs significantly worse than both the longest queue (LNQ) and

TABLE 5.9

TUKEY 95% CONFIDENCE INTERVALS FOR FACTOR C COMPARISONS

Performance Measure	Lower Confidence Limit	Factor Level Comparison	Upper Confidence Limit	
Mean Flowtime	1.90	C2 - C3	2.27	*
	2.21	C2 - C1	2.58	*
	.13	C3 - C1	.50	*
Mean Tardiness	-.56	C1 - C2	.59	
	-.40	C1 - C3	.75	
	-.42	C2 - C3	.74	
RMS of Tardiness	15.44	C2 - C1	25.09	*
	11.69	C2 - C3	21.34	*
	-1.07	C3 - C1	8.57	

Key: Factor C = Labor Assignment Rule
Level 1 = LNQ
2 = LWF
3 = ADI,SPT
* = Significant at the .05 level or less

assembly delay (ADI,SPT) rules. The LNQ rule performs better than ADI,SPT, but not significantly so.

In terms of mean tardiness, ADI,SPT yields the lowest figure, followed by LWF, but there is no significant difference in performance for any of the labor assignment rules.

Both the LNQ and ADI,SPT rules perform well because they consider shop congestion when assigning workers to machine centers; LNQ by balancing the machine center queues and ADI,SPT by breaking assembly delay ties with SPT ordering. The poor performance of LWF may be attributed to its failure to consider shop congestion in its allocation decision. The importance of queue congestion is magnified for assembly shops in general, because of the complex relationship of items composing a job and the oscillation of machine center loads due to exploding product structures, and in this particular assembly shop setting, because of the somewhat inflexible labor force.

Factor D Means

Item sequencing rule is a significant factor for all three measures of performance, but the rankings vary by performance measure. Table 5.10 shows the Tukey 95% confidence intervals for factor D comparisons of item sequencing rule.

TABLE 5.10

TUKEY 95% CONFIDENCE INTERVALS FOR FACTOR D COMPARISONS

Performance Measure	Lower Confidence Limit	Factor Level Comparison	Upper Confidence Limit	
Mean Flowtime	.49	D1 - D2	.86	*
	.56	D1 - D3	.92	*
	-.12	D2 - D3	.24	
Mean Tardiness	.58	D3 - D1	1.74	*
	.84	D3 - D2	2.00	*
	-.32	D1 - D2	.84	
RMS of Tardiness	5.21	D3 - D2	14.86	*
	2.07	D1 - D2	11.72	*
	-1.69	D3 - D1	7.96	

Key: Factor D = Item Sequencing Rule
Level 1 = DDATE
2 = BS+ROPT^2
3 = LP+ROPT^2
* = Significant at the .05 level or less

For mean flowtime, the duedate (DDATE) sequencing rule performs significantly worse than either the branch slack (BS+ROPT^2) or longest path (LP+ROPT^2) rules. The LP+ROPT^2 rule performs better than BS+ROPT^2, but the difference is not significant.

For mean tardiness, the DDATE and BS+ROPT^2 rules perform significantly better than LP+ROPT^2, with BS+ROPT^2 performing slightly better than DDATE.

For RMS of tardiness, BS+ROPT^2 produces significantly lower values than DDATE or LP+ROPT^2. DDATE is better than LP+ROPT^2, but not by a significant margin.

The good performance of BS+ROPT^2 reinforces the reported advantages of using slack time sequencing rules for assembled products [9,16,75]. Furthermore, the addition of an ROPT^2 factor causes short jobs to be processed quickly, pushes jobs out of the shop that are nearing completion, and coordinates items of the same job.

Summary of Factor Level Comparisons

The significant factor level comparisons from the assembly shop experiment may be summarized as follows: (1) Tall structured jobs take significantly longer to complete and have significantly higher tardiness values than flat structured jobs; (2) The modified longest path (MLP) duedate assignment rule produces a significantly higher tardiness figure than the other duedate procedures tested; (3) The longest waiting time (LWF) labor assignment rule results in significantly higher flowtime and tardiness values than the other labor assignment rules tested; and (4) The branch slack (BS+ROPT^2) item sequencing rule performs better than the other sequencing rules tested, yielding a significantly lower measure of tardiness than all other rules and a significantly lower flowtime than the DDATE sequencing rule.

INTERACTION ANALYSIS

The ANOVA F test showed several interaction effects to be significant for all three measures of performance. Only those found significant under RMS of tardiness will be analyzed further. Root mean square of tardiness was chosen because tardiness is the performance measure of primary interest in this study and RMS of tardiness is a more complete measure than mean tardiness, as indicated by a higher R^2 value.

Under RMS of tardiness, all first order interactions involving job structure are significant, as well as the interaction of labor assignment rule with item sequencing rule and the second order interaction of job structure, labor assignment, and item sequencing rule.

In the sections to follow, each significant interaction is presented graphically and analyzed via Tukey confidence intervals for linear contrasts of specific interest.

AB Interaction

A plot of the first order interaction between factor A, job structure, and factor B, duedate assignment procedure, is shown in figure 5.1. The two separately located line segments indicate significant differences in RMS of tardiness for jobs with different structures, an observation consistent with the significance of factor A main effects. Table 5.11 presents Tukey 95% confidence intervals for linear contrasts of specific interest in the analysis of AB interaction effects.

For flat structured jobs, there is no significant difference between the TWK, LP, and MLP duedate assignment procedures. The MLP procedure, however, does produce a lower tardiness figure. This result is logical since the MLP duedate calculation takes into account the breadth of a job, which is the predominant feature of jobs with flat structures.

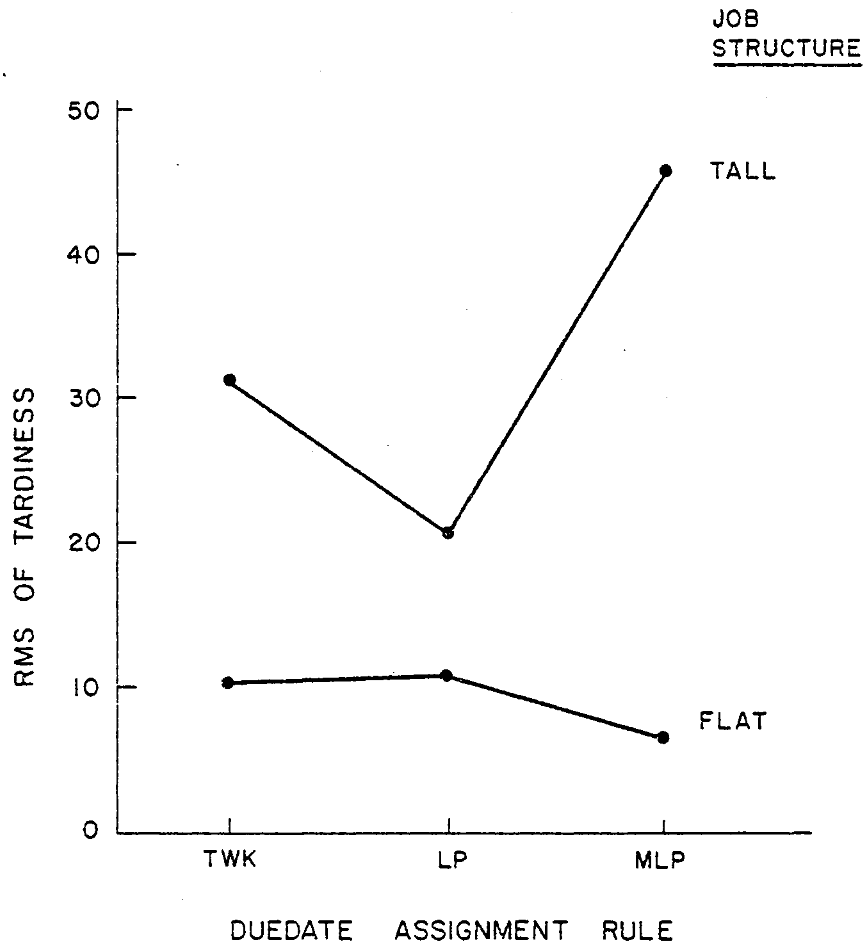


FIGURE 5.1
AB INTERACTION

TABLE 5.11

TUKEY 95% CONFIDENCE INTERVALS FOR SOME SIGNIFICANT COMPARISONS OF AB INTERACTIONS

Lower Confidence Limit	AB Comparison	Upper Confidence Limit
7.36	$\mu_{23..} - \mu_{21..}$	21.21
3.25	$\mu_{21..} - \mu_{22..}$	17.11
17.53	$\mu_{23..} - \mu_{22..}$	31.39

KEY: $\mu_{ij..}$ = mean RMS of tardiness over ten simulation runs for the ith level of factor A and jth level of factor B summed over factors C and D

Factor A = Job Structure
Level 1 = FLAT
2 = TALL

Factor B = Duedate Assignment Rule
Level 1 = TWK
2 = LP
3 = MLP

Differences in duedate procedure are more pronounced for tall structured jobs, as illustrated by the statistically significant contrasts in table 5.11. The MLP rule, the best performer for flat jobs, is the worst performer for tall structured jobs, whose number of components per assembly is small. MLP produces a significantly higher RMS of tardiness than TWK or LP. The TWK rule, which does not discriminate by structure, performs significantly better than MLP, but significantly worse than LP. As expected, the LP rule is the best duedate assignment procedure for tall structured jobs because it concentrates on the length of the job when assigning duedates.

Although duedate tightness was not intentionally varied in the experiment, the AB interaction results do follow the overall tightness of duedates resulting from the different duedate assignment procedures. For example, overall duedate tightness for the flat structured job set varied only slightly with MLP providing the looser duedates. Similarly, for the tall structured job set, LP produced the loosest duedates, followed by TWK and MLP.

The importance of analyzing interaction effects is illustrated by the AB interaction. Previously, a multiple comparison test for factor B tagged the MLP duedate assignment rule as significantly worse than the others tested, when in fact the MLP rule produces the lowest tardiness value for flat structured jobs. These results are not in conflict; they merely point out that the degree of tardiness produced when MLP is used for tall jobs is large enough to negate the slight advantage of its use with flat jobs.

The results of this experiment prompt the following recommendations concerning the calculation of duedates: (1) If the jobs to be processed are flat structured, any of the duedate assignment rules may be chosen. (2) If the jobs to be processed have a tall structure or a mixture of tall and flat structures, assign duedates by the longest path (LP) rule. (3) Do not assign duedates by MLP for tall structured jobs.

The AB interaction is the only significant interaction involving factor B, duedate assignment rule. Thus, selection of a labor assignment rule or item sequencing rule should not be influenced by the method in which duedates are assigned.

AC Interaction

The first order interaction between factor A, job structure, and factor C, labor assignment rule, is graphed in figure 5.2. The two distinct line segments again indicate a significant difference in RMS of tardiness for different job structures. Table 5.12 presents the Tukey 95% confidence intervals for contrasts of particular interest in the analysis of AC interaction effects.

For flat structured jobs, the LNQ rule performs significantly better than LWF, but the difference between LNQ or LWF and ADI,SPT is not significant.

Differences among labor assignment rules for tall structured jobs are more exaggerated. The LWF rule produces a significantly higher tardiness figure than either LNQ or ADI,SPT and should not be used in conjunction with tall structured jobs. The poor performance of LWF is consistent with the analysis of factor C means presented earlier.

Possible reasons for LWF's poor performance were also discussed in the analysis of factor C means. The AC interaction results confirm those observations, and further, illustrate the intensifying effect of a poor resource allocation decision on tall structured jobs where the relationship among items is more complex.

The best labor assignment rule for flat or tall jobs is LNQ, but its performance does not differ significantly from that of ADI,SPT. Since ADI,SPT is more difficult to

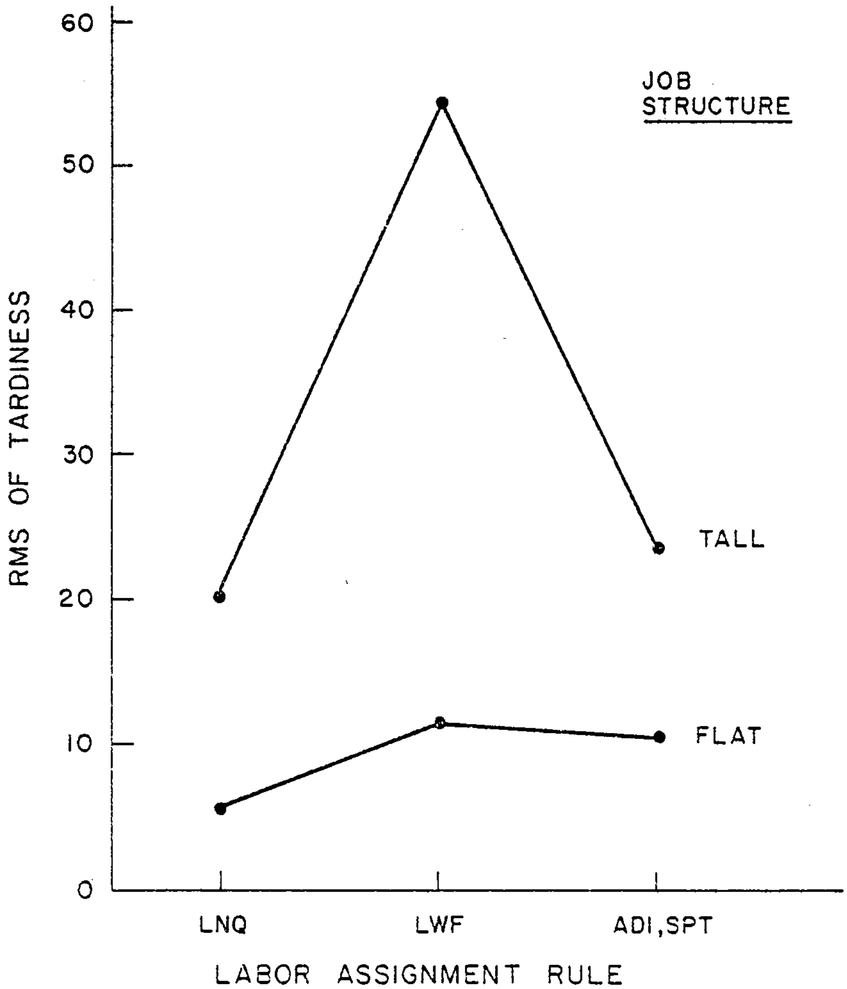


FIGURE 5.2

AC INTERACTION

TABLE 5.12

TUKEY 95% CONFIDENCE INTERVALS FOR SOME SIGNIFICANT COMPARISONS OF AC INTERACTIONS

Lower Confidence Limit	AC Comparison	Upper Confidence Limit
.07	$\mu_{1.2.} - \mu_{1.1.}$	13.00
27.54	$\mu_{2.2.} - \mu_{2.1.}$	40.46
25.33	$\mu_{2.2.} - \mu_{2.3.}$	38.25

KEY: $\mu_{i.k.}$ = mean RMS of tardiness over ten simulation runs for the ith level of factor A and kth level of factor C summed over factors B and D

Factor A = Job Structure
Level 1 = FLAT
2 = TALL

Factor C = Labor Assignment Rule
Level 1 = LNQ
2 = LWF
3 = ADI,SPT

use than LNQ with similar results, the LNQ rule is superior in a practical sense.

Recommendations for the selection of labor assignment rule based on the analysis of AC interactions are: (1) The LNQ labor assignment rule is appropriate for flat or tall job structures. (2) LWF should not be used as a labor assignment rule, especially for tall structured jobs. (3) ADI,SPT is a suitable alternative to LNQ as a labor assignment rule.

AD Interaction

Figure 5.3 graphs the interaction of factor A, job structure, with factor D, item sequencing rule. As before, the two distinct line segments show a significant difference in RMS of tardiness between tall and flat structured jobs. Table 5.13 provides additional statistical information for the analysis of AD interaction effects in the form of linear contrasts.

For flat structured jobs, the $LP+ROPT^2$ sequencing rule results in a significantly higher RMS of tardiness than the other rules. This is a normal result considering that $LP+ROPT^2$ monitors the remaining length of a job structure, and does not consider the breadth of its assemblies or try to coordinate common components of an assembly. The

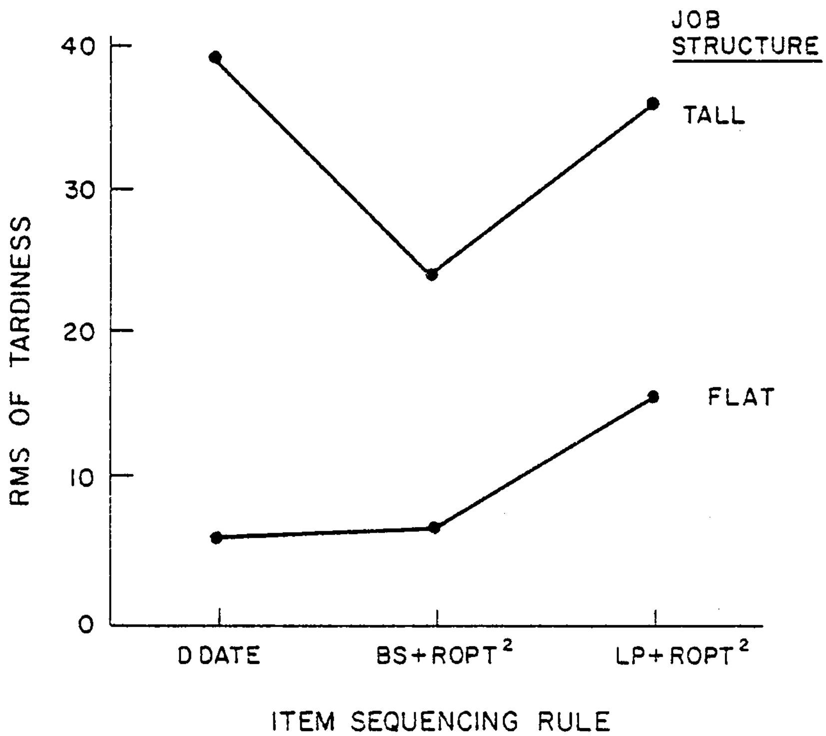


FIGURE 5.3
AD INTERACTION

TABLE 5.13

TUKEY 95% CONFIDENCE INTERVALS FOR SOME SIGNIFICANT COMPARISONS OF AD INTERACTIONS

Lower Confidence Limit	AD Comparison	Upper Confidence Limit
2.88	$\mu_{1..3} - \mu_{1..1}$	17.00
1.77	$\mu_{1..3} - \mu_{1..2}$	15.90
7.83	$\mu_{2..1} - \mu_{2..2}$	21.96
4.16	$\mu_{2..3} - \mu_{2..2}$	18.29

KEY: $\mu_{i..l}$ = mean RMS of tardiness over ten simulation runs for the ith level of factor A and lth level of factor D summed over factors B and C

Factor A = Job Structure
Level 1 = FLAT
2 = TALL

Factor D = Item Sequencing Rule
Level 1 = DDATE
2 = BS+ROPT²
3 = LP+ROPT²

difference in performance between DDATE and BS+ROPT^2 is insignificant. However, because the DDATE rule is easier to apply, it should be preferred.

For tall structured jobs, the BS+ROPT^2 sequencing rule performs significantly better than the other rules tested. The DDATE and LP+ROPT^2 rules do not differ significantly in tardiness performance.

The fine performance of BS+ROPT^2 for both types of job structures is consistent with its superiority in the analysis of factor D means.

To summarize the results of this analysis of AD interactions: (1) For flat structured jobs, DDATE is the simplest and most effective sequencing rule. (2) For tall structured jobs or a mixture of tall and flat jobs, the BS+ROPT^2 sequencing rule is most appropriate. (3) The LP+ROPT^2 rule is not recommended for sequencing flat jobs.

CD Interaction

A plot of the first order interaction between factor C, labor assignment rule, and factor D, item sequencing rule, is shown in figure 5.4. The line segment for LWF located separately from the other line segments shows that LWF is significantly different from the other rules tested. The crossover of line segments for ADI,SPT and LNQ shows

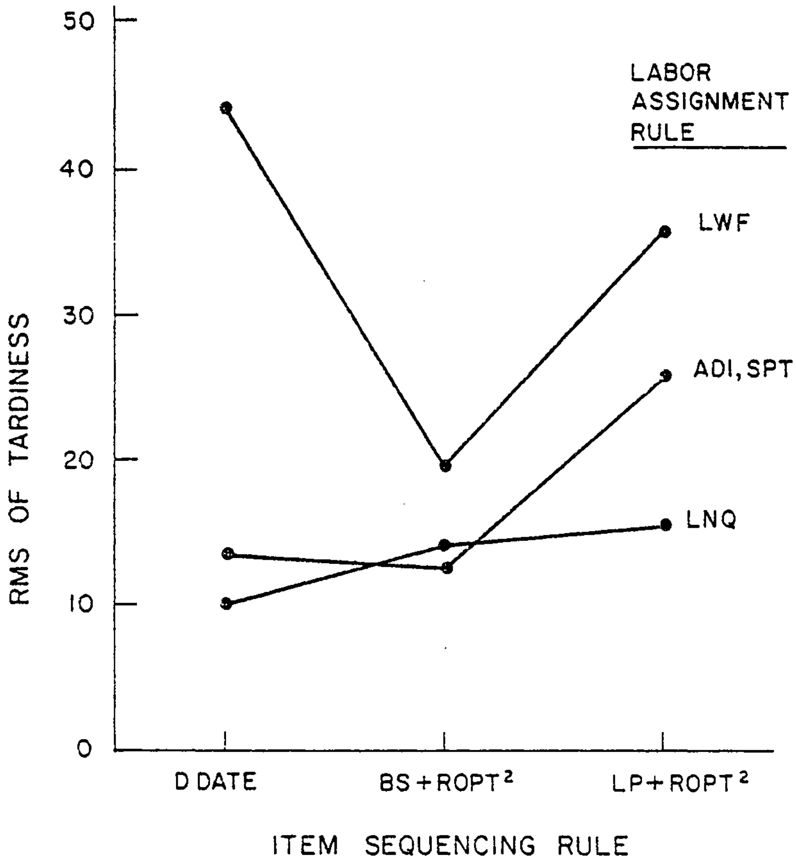


FIGURE 5.4
CD INTERACTION

that there is no significant difference in their tardiness performance. This observation is verified in the analysis of factor C means.

Table 5.14 gives the Tukey 95% confidence intervals for contrasts of specific interest in the analysis of CD interaction effects. They form the basis for the following comments.

There is no significant difference in RMS of tardiness among the sequencing rules tested when the LNQ labor assignment rule is applied. Under the ADI,SPT and LWF labor assignment rules, the BS+ROPT^2 sequencing rule performs significantly better than LP+ROPT^2. The BS+ROPT^2 sequencing rule also performs significantly better than DDATE under the LWF labor assignment rule.

From the perspective of sequencing rule performance, there is no significant difference in RMS of tardiness between LNQ and ADI,SPT for any of the sequencing rules tested. However, LWF performs significantly worse than the other labor rules under the DDATE and LP+ROPT^2 sequencing rules. For the BS+ROPT^2 sequencing rule, there is no significant difference in performance among any of the labor assignment rules.

Every combination of item sequencing--labor assignment rule performs significantly better than DDATE--LWF,

TABLE 5.14

TUKEY 95% CONFIDENCE INTERVALS FOR SOME SIGNIFICANT COMPARISONS OF CD INTERACTIONS

Lower Confidence Limit	CD Comparison	Upper Confidence Limit
15.49	$\mu_{..21} - \mu_{..11}$	30.25
12.86	$\mu_{..21} - \mu_{..12}$	27.62
11.40	$\mu_{..21} - \mu_{..13}$	26.16
8.57	$\mu_{..21} - \mu_{..22}$	23.33
13.13	$\mu_{..21} - \mu_{..31}$	27.89
13.60	$\mu_{..21} - \mu_{..32}$	28.36
5.53	$\mu_{..21} - \mu_{..33}$	20.29
10.08	$\mu_{..23} - \mu_{..11}$	24.84
7.45	$\mu_{..23} - \mu_{..12}$	22.21
5.99	$\mu_{..23} - \mu_{..13}$	20.75
3.16	$\mu_{..23} - \mu_{..22}$	17.92
7.71	$\mu_{..23} - \mu_{..31}$	22.47
8.18	$\mu_{..23} - \mu_{..32}$	22.94
.12	$\mu_{..23} - \mu_{..33}$	14.88
2.58	$\mu_{..33} - \mu_{..11}$	17.34
.22	$\mu_{..33} - \mu_{..31}$	14.98
.69	$\mu_{..33} - \mu_{..32}$	15.45

TABLE 5.14, CONTINUED

KEY: $\mu_{..kl}$ = mean RMS of tardiness over ten simulation runs for the kth level of factor C and lth level of factor D summed over factors A and B

Factor C = Labor Assignment Rule
Level 1 = LNQ
2 = LWF
3 = ADI,SPT

Factor D = Item Sequencing Rule
Level 1 = DDATE
2 = $BS+ROPT^2$
3 = $LP+ROPT^2$

LP+ROPT^2--LWF, and LP+ROPT^2--ADI,SPT. Previous comments concerning the separate performance of labor assignment and item sequencing rules are useful in explaining the CD interaction effects. None of the sequencing rules tested considers queue congestion. Thus, the LNQ and ADI,SPT labor assignment rules, which do take queue congestion into account, tend to bring out the best performance for each sequencing rule, while LWF does not. The DDATE sequencing rule is static, gives all items of a job the same priority, and contains no acceleration factor to complete short jobs quickly. The drastic combination of DDATE with LWF may be explained by the inflexibility of DDATE as a sequencing rule and the redundancy of LWF as a resource allocation rule for items already sequenced in part by a measure of their shop residence time. Similarly, the BS+ROPT^2 sequencing rule is the most adaptable of the rules tested, and thus is not significantly affected by a combination with LWF.

In summary, the findings related to the CD interaction effects are: (1) When sequencing jobs by DDATE or LP+ROPT^2, do not assign labor by LWF. (2) When sequencing jobs by BS+ROPT^2, any of the labor assignment rules tested is sufficient. (3) The LNQ labor assignment rule is appropriate for use with all of the sequencing rules tested. (4) The BS+ROPT^2 sequencing rule should be used when labor is assigned according to ADI,SPT or LWF.

ACD Interaction

The presence of a three factor interaction implies that at least some two factor interactions differ depending on the level of the third factor. Thus, to study the second order interaction between factor A (job structure), factor C (labor assignment rule) and factor D (item sequencing rule), two sets of graphs are presented. Figure 5.5 plots the AD interaction for each level of factor C and figure 5.6 plots the AC interaction for each level of factor D. In addition, table 5.15 presents Tukey 95% confidence intervals for contrasts suggested by an analysis of the ACD interaction. Table 5.16 ranks the performance of each item sequencing--labor assignment rule combination for flat and tall job structures.

Performance by Labor Assignment Rule

Referring to figure 5.5, the scheduling rule performance for flat structured jobs follows that of tall structured jobs in direction, though not in magnitude, with two minor exceptions. Under the LNQ labor assignment rule, LP+ROPT^2 results in a higher RMS of tardiness than BS+ROPT^2

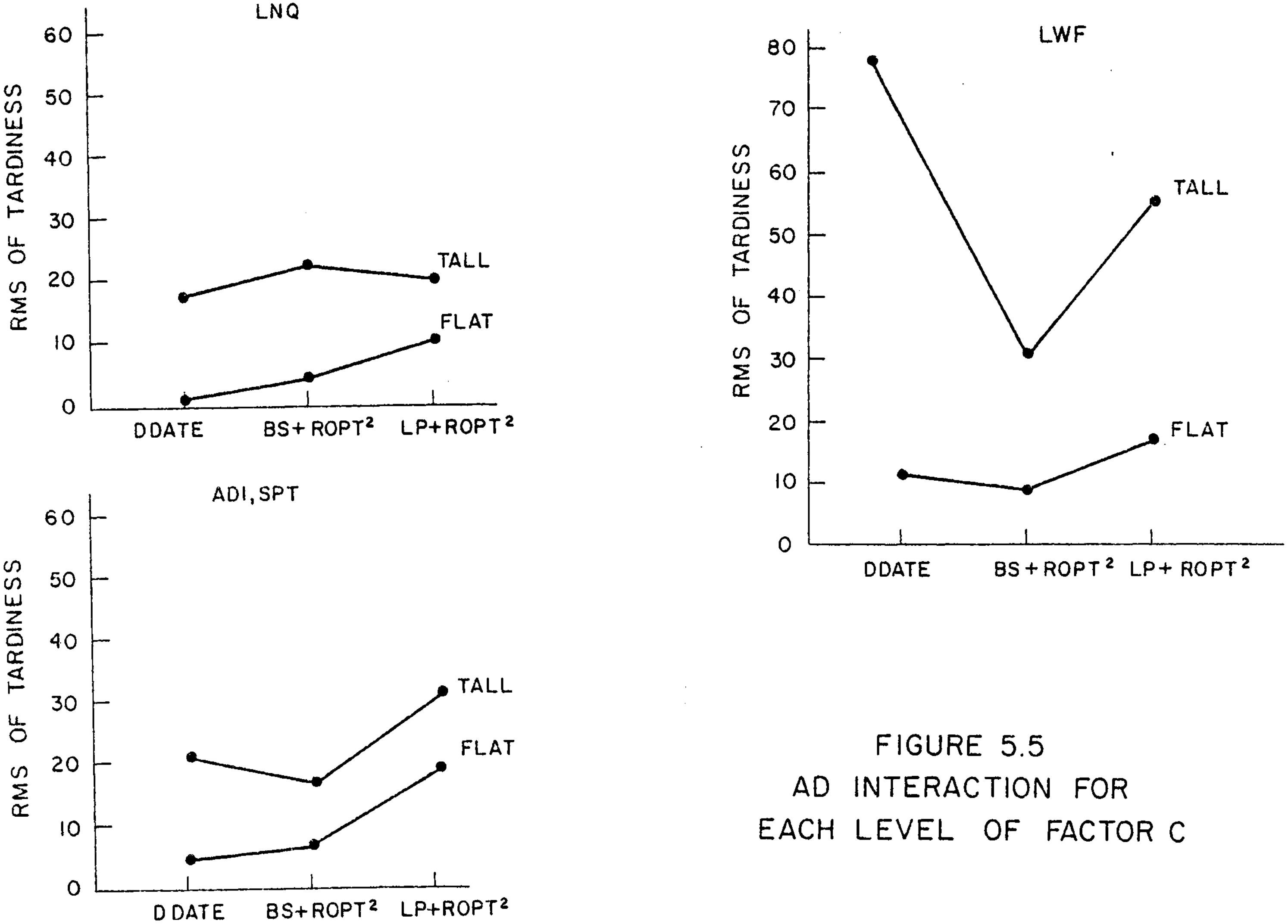
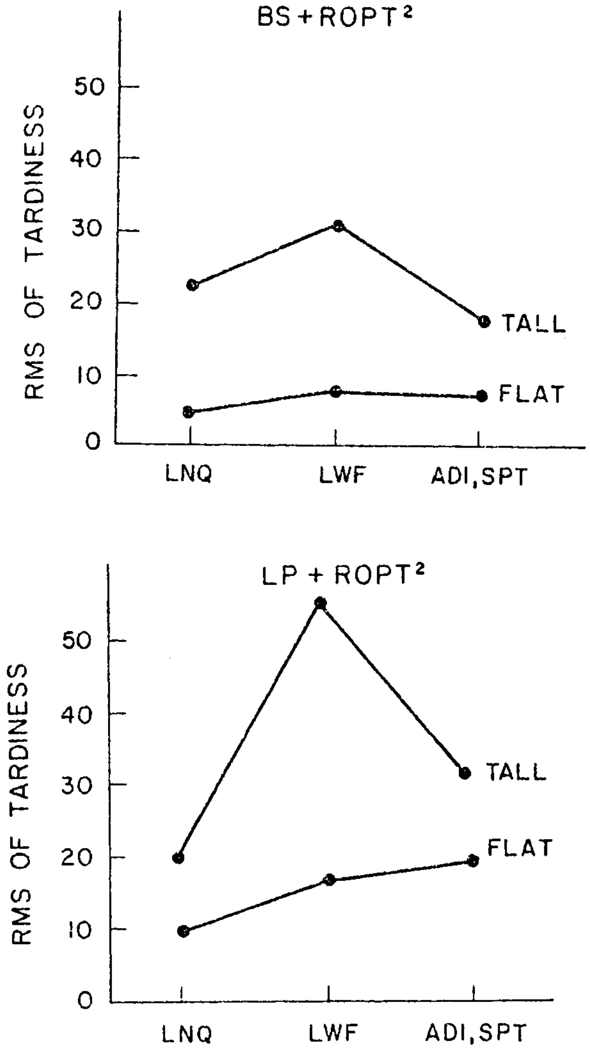


FIGURE 5.5
AD INTERACTION FOR
EACH LEVEL OF FACTOR C



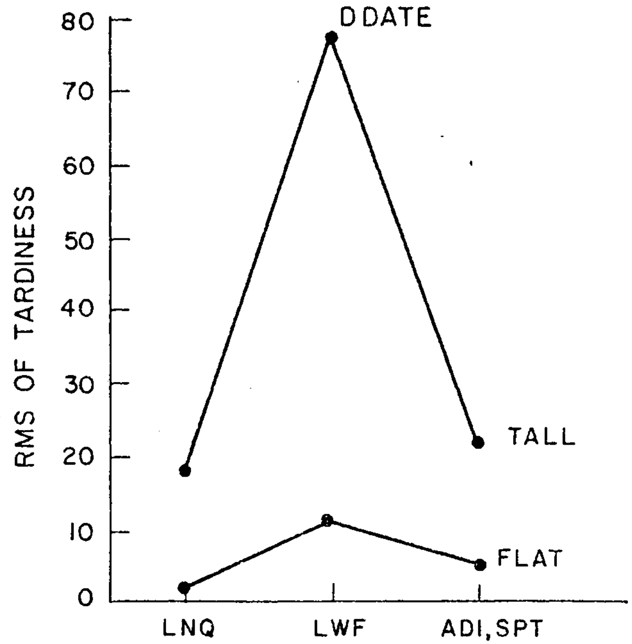


FIGURE 5.6
AC INTERACTION FOR
EACH LEVEL OF FACTOR D

TABLE 5.15

TUKEY 95% CONFIDENCE INTERVALS FOR SOME SIGNIFICANT COMPARISONS OF ACD INTERACTIONS

Lower Confidence Limit	ACD Comparison	Upper Confidence Limit
1.89	$\mu_{1.13} - \mu_{1.11}$	15.60
2.27	$\mu_{1.21} - \mu_{1.11}$	15.99
8.50	$\mu_{1.23} - \mu_{1.11}$	22.22
5.53	$\mu_{1.23} - \mu_{1.12}$	19.25
1.67	$\mu_{1.23} - \mu_{1.22}$	15.39
5.13	$\mu_{1.23} - \mu_{1.31}$	18.85
2.49	$\mu_{1.23} - \mu_{1.32}$	16.20
11.36	$\mu_{1.33} - \mu_{1.11}$	25.07
8.39	$\mu_{1.33} - \mu_{1.12}$	22.10
2.61	$\mu_{1.33} - \mu_{1.13}$	16.33
2.23	$\mu_{1.33} - \mu_{1.21}$	15.94
4.53	$\mu_{1.33} - \mu_{1.22}$	18.24
7.99	$\mu_{1.33} - \mu_{1.31}$	21.70
5.35	$\mu_{1.33} - \mu_{1.32}$	19.06
43.29	$\mu_{2.21} - \mu_{2.11}$	75.68
38.37	$\mu_{2.21} - \mu_{2.12}$	70.76
39.77	$\mu_{2.21} - \mu_{2.13}$	72.16
29.36	$\mu_{2.21} - \mu_{2.22}$	61.76

TABLE 5.15, CONTINUED

Lower Confidence Limit	ACD Comparison	Upper Confidence Limit
6.27	$\mu_{2.21} - \mu_{2.23}$	38.67
39.57	$\mu_{2.21} - \mu_{2.31}$	71.96
43.62	$\mu_{2.21} - \mu_{2.32}$	76.01
31.63	$\mu_{2.21} - \mu_{2.33}$	64.05
20.82	$\mu_{2.23} - \mu_{2.11}$	53.21
15.90	$\mu_{2.23} - \mu_{2.12}$	48.29
17.30	$\mu_{2.23} - \mu_{2.13}$	49.69
6.89	$\mu_{2.23} - \mu_{2.22}$	39.29
17.10	$\mu_{2.23} - \mu_{2.31}$	49.49
21.25	$\mu_{2.23} - \mu_{2.32}$	53.54
9.16	$\mu_{2.23} - \mu_{2.33}$	41.55

KEY: $\mu_{i.kl}$ = mean RMS of tardiness over ten simulation runs for the ith level of factor A, the kth level of factor C, and the lth level of factor D summed over factor B

Factor A = Job Structure
Level 1 = FLAT
2 = TALL

Factor C = Labor Assignment Rule
Level 1 = LNQ
2 = LWF
3 = ADI,SPT

Factor D = Item Sequencing Rule
Level 1 = DDATE
2 = BS+ROPT[2]
3 = LP+ROPT[2]

TABLE 5.16

RANKINGS OF ITEM SEQUENCING--LABOR ASSIGNMENT RULES

FLAT STRUCTURED JOBS

Rule	RMS of Tardiness[1]	Significant Differences[2]
DDATE--LNQ	1.62	*
BS+ROPT²--LNQ	4.78	*
DDATE--ADI,SPT	4.98	*
BS+ROPT²--ADI,SPT	7.62	*
BS+ROPT²--LWF	8.43	*
LP+ROPT²--LNQ	10.35	**
DDATE--LWF	10.74	**
LP+ROPT²--LWF	16.97	***
LP+ROPT²--ADI,SPT	19.83	***

TALL STRUCTURED JOBS

Rule	RMS of Tardiness[1]	Significant Differences[2]
BS+ROPT²--ADI,SPT	18.08	*
DDATE--LNQ	18.41	*
LP+ROPT²--LNQ	20.74	*
DDATE--ADI,SPT	22.13	*
BS+ROPT²--LNQ	23.33	*
BS+ROPT²--LWF	31.01	*
LP+ROPT²--ADI,SPT	31.93	*
LP+ROPT²--LWF	55.43	**
DDATE--LWF	77.90	**

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[1] Averaged over factor B (duedate assignment rule) and 10 simulation runs.

[2] Those rules with the same number of asterisks are statistically the same according to a 5% Tukey multiple comparison test.

for flat structured jobs and a lower tardiness figure for tall structured jobs. Similarly, under the ADI,SPT labor assignment rule, the RMS of tardiness increases when the DDATE sequencing rule is replaced by BS+ROPT^2 for flat jobs, and decreases for tall jobs.

Under the LNQ labor assignment rule, the DDATE sequencing rule performs significantly better than LP+ROPT^2 for flat structured jobs, but produces no significant difference in performance for tall structured jobs.

Under the LWF labor assignment rule, the BS+ROPT^2 sequencing rule produces a significantly lower RMS of tardiness than LP+ROPT^2 for flat structured jobs. For tall structured jobs, BS+ROPT^2 performs significantly better than either the DDATE or LP+ROPT^2 sequencing rules, and LP+ROPT^2 performs significantly better than DDATE.

Under the ADI,SPT sequencing rule, there is no significant difference in performance among sequencing rules for either flat or tall structured jobs.

Performance by Item Sequencing Rule

Figure 5.6 and table 5.15 provide information on the interaction of job structure and labor assignment rule under the three types of item sequencing rules.

Under the DDATE sequencing rule, the LNQ labor assignment rule performs significantly better than LWF for both flat and tall structured jobs. In addition, ADI,SPT performs significantly better than LWF for tall jobs.

There is no significant difference in tardiness performance among labor assignment rules under the BS+ROPT^2 sequencing rule for either type of job structure.

Under the LP+ROPT^2 sequencing rule, the LNQ labor assignment rule performs significantly better than ADI,SPT for flat structured jobs. For tall structured jobs, both LNQ and ADI,SPT produce significantly lower RMS of tardiness figures than LWF.

Overall Performance

The relative performance of each item sequencing--labor assignment rule combination is given in table 5.16. The RMS of tardiness averaged over factor B and ten simulation runs is also provided. Significant differences in tardiness, presented in the form of confidence intervals in table 5.15, are indicated in table 5.16 by a changing number of asterisks.

The LP+ROPT^2--ADI,SPT and LP+ROPT^2--LWF scheduling rules are the worst performers for flat structured jobs. With the exception of LP+ROPT^2--LWF, every scheduling rule performs significantly better than LP+ROPT^2--ADI,SPT on flat structured jobs. Likewise, except for LP+ROPT^2--ADI,SPT, LP+ROPT^2--LNQ, and DDATE--LWF, every scheduling rule performs significantly better than LP+ROPT^2--LWF. The highest RMS of tardiness within each labor assignment category for flat structured jobs occurs when the LP+ROPT^2 sequencing rule is used.

For tall structured jobs, DDATE--LWF and LP+ROPT^2--LWF are the worst scheduling rules. Every other scheduling rule performs significantly better than these two rules. The highest RMS of tardiness overall and within each sequencing rule category for tall structured jobs occurs when the LWF labor assignment rule is used.

Overall, the best performer for flat structured jobs is DDATE--LNQ. Its performance, however, does not differ significantly from that of DDATE--ADI,SPT or any of the BS+ROPT^2 scheduling rules.

Overall, the BS+ROPT^2--ADI,SPT scheduling rule results in the lowest RMS of tardiness for tall structured jobs. However, its performance is not significantly different from the performance of the other ADI,SPT scheduling rules, the LNQ scheduling rules, or BS+ROPT^2--LWF.

Recall that the analysis of AD interaction effects found the DDATE sequencing rule inappropriate for tall jobs. This premature conclusion was reached based on data that included the DDATE--LWF scheduling rule, a combination that produced the highest RMS of tardiness of any rule tested for tall jobs. With LWF eliminated from consideration, the performance of DDATE with the other labor assignment rules is among the best scheduling rules tested.

Summary of ACD Interaction Effects

Of the nine scheduling rules tested, DDATE--LNQ is the simplest to apply. The sequencing rule portion is static, and identical for all items of a job. The labor assignment portion requires no job related calculation, merely a comparison of queue length. The rule performs well for both flat and tall structured jobs. As such, its use is recommended for scheduling in assembly shop environments similar to the hypothetical one presented in this study.

Many of the scheduling rules produced similar RMS of tardiness values, but the performance of certain item sequencing and labor assignment rules, $LP+ROPT^2$ and LWF for example, was particularly sensitive to the structure of the jobs being processed.

In summary, the analysis of ACD interaction effects showed that: (1) The LWF labor assignment rule should not be used for processing tall structured jobs. (2) The LP+ROPT^2 sequencing rule should be avoided when processing flat structured jobs. (3) The DDATE--LNQ scheduling rule is appropriate for both types of job structures.

SUMMARY OF RESULTS

An analysis of variance was performed to analyze the significance of job structure, duedate assignment, labor assignment, and item sequencing rule on the operation of an assembly shop. The ANOVA model and all factor means were judged significant at the .0001 level for the RMS of tardiness performance measure. In addition, all first order interactions involving job structure and a second order interaction of job structure, item sequencing rule and labor assignment rule were found significant. An ANOVA was also run for mean flowtime and mean tardiness measures of performance.

The chapter contains specific recommendations based on analyses of significant factor means and interactions. General conclusions that may be drawn from the results of the experiment include: (1) Job structure, duedate assignment rule, labor assignment rule, and item sequencing rule all significantly affect job tardiness in the assembly shop. (2) The selection of duedate assignment, labor assignment, and item sequencing rule depends on the structure of the jobs being processed. (3) The selection of item sequencing rule should be made in tandem with the selection of labor assignment rule.

Chapter 6 concludes this study by summarizing the research performed, indicating some practical implications garnered from the research results, and suggesting further research possibilities in the area of assembly shop scheduling.

CHAPTER 6

SUMMARY AND CONCLUSIONS

This research has investigated scheduling policies for the production of assembled products. The specific policies examined were duedate assignment procedures, labor assignment procedures, and item sequencing rules. The sensitivity of these policies to product structure was also addressed.

A SLAM II simulation model of a hypothetical assembly shop operation was used to generate the data for analysis. A multifactor ANOVA model was designed to assess the impact of four factors, job structure, duedate assignment rule, labor assignment rule, and item sequencing rule on the mean flowtime, mean tardiness, and root mean square of tardiness of jobs completed by the assembly shop. The significance of these factors may be summarized as follows:

(1) Each of the four main effects has a highly significant impact on the root mean square of tardiness of jobs completed by the assembly shop. Mean job flowtime is significantly affected by the main effects of job structure, labor assignment, and item sequencing rule. Similarly, mean tardiness is significantly influenced by the main effects of job

structure and item sequencing.

(2) The first order interactions of job structure with labor assignment rule, job structure with item sequencing rule, and labor assignment with item sequencing rule are significant for all measures of performance. In addition, the first order interaction of job structure with duedate assignment rule significantly affects root mean square of tardiness.

(3) The second order interaction of job structure, labor assignment rule, and item sequencing rule significantly affects mean flowtime and root mean square of tardiness.

(4) No other first, second or third order interactions have a significant impact on mean flowtime, mean tardiness, or root mean square of tardiness for jobs processed by the assembly shop.

These results suggest the following observations:

(1) The structure of jobs processed, as well as labor assignment and item sequencing policies, affect the flowtime and tardiness of jobs completed by the assembly shop. Job tardiness is also affected by

duedate assignment procedures.

(2) The type of product structure influences duedate assignment, labor assignment, and item sequencing decisions.

(3) The labor assignment rule chosen further affects the selection of item sequencing rule.

(4) The method by which job duedates are assigned does not affect the selection of labor assignment rule or item sequencing rule.

PRACTICAL GUIDELINES

Several practical guidelines may be drawn from a more detailed analysis of the experimental results. They are:

(1) More care should be exercised in selecting scheduling policies if the jobs to be processed have tall versus flat structures. In this experiment, tall structured jobs required more processing time and were tardy more often than their corresponding flat structured jobs. Tall jobs were also more sensitive to variations in the other factors tested. For instance,

different duedate assignment procedures had no significant affect on the processing of flat structured jobs, whereas every duedate assignment procedure produced significant results for tall structured jobs. In terms of labor assignment, the longest queue (LNQ) labor assignment rule outperformed the longest waiting time (LWF) rule for both flat and tall structured jobs, but the difference for tall jobs was more exaggerated. The difference in RMS of tardiness between LNQ and LWF for flat jobs was 6.54; while for tall jobs, it soared to 33.99. Similarly, the difference in RMS of tardiness between the best and worst item sequencing rule was 14.90 for tall jobs, but only 9.94 for flat jobs.

(2) Beware of the strong interaction of labor assignment rule and item sequencing rule. LWF consistently produced higher tardiness values than the other labor assignment rules, but its combination with certain item sequencing rules dramatically worsened its performance. Under the DDATE sequencing rule and tall job structure, mean RMS of tardiness increased from 18.41 to 77.90 when LWF replaced LNQ as the labor assignment rule. Likewise, mean flowtime increased from 3.21 to 8.62.

(3) Certain scheduling policies should be avoided based on job structure. For example, the longest path combination sequencing rule ($LP+ROPT^2$) should not be used to sequence flat jobs, and longest waiting time (LWF) should not be used to assign labor nor modified longest path (MLP) to determine duedates for tall jobs.

(4) Several scheduling rules produce good results regardless of the product structure or other scheduling policies employed. The branch slack combination sequencing rule ($BS+ROPT^2$), longest path (LP) duedate assignment rule and longest queue (LNQ) labor assignment rule performed well for any job structure or combination of scheduling policy. The DDATE sequencing rule also performed well in combination with any scheduling policy other than LWF.

RECONCILIATION WITH PREVIOUS RESEARCH

The experiment performed in this research included more extensive scheduling policies than had been considered in previous studies of assembly shop scheduling. Even so, there is some basis for comparison of the results from this study with the existing body of scheduling literature in both simple job shops and assembly shops.

In terms of sequencing rules, the preliminary experimentation of eleven sequencing rules revealed some interesting results. The poor performance of SPT was confirmed in studies by Maxwell [56] and Goodwin and Goodwin [39], but conflicted with the sequencing rule rankings of Siegel [80]. In addition, the good performance of the DDATE sequencing rule in both the preliminary and full factorial experiments reinforced the findings of Siegel [80] and Goodwin and Goodwin [39]. Also, RWK and $ROPT^2$ performed well as reported in Miller, Ginsberg, and Maxwell [60] and Siegel [80]. The combination rules involving shop congestion did not produce the dramatic performance predicted by Siegel. However, these results do not necessarily refute Siegel's claim because different weights for the shop congestion factor were not examined in this study.

In terms of duedate assignment rule, the strong interaction of duedate assignment rule with item sequencing rule reported by Baker and Betrand [5], Eilon and Hodgson [30], Elvers [32], and Weeks and Fryer [91] did not materialize. This may be due to the fact that the different duedate assignment rules tested in this study were based on job content and duedate tightness was not an issue. Although the total duedate allowance for the set of jobs tested varied under the three duedate rules, the padding of duedates was not uniform for all jobs in a particular job structure set.[1] Job duedates may not have been tight enough to produce significant differences in sequencing rule performance.

For labor assignment, the LNQ rule performed better than LWF, as reported by Nelson [67] and Huang, et al. [48]. However, the LWF rule performed much worse in comparison to other labor rules in the assembly shop than in the simple job shop, particularly in combination with certain sequencing rules. Thus, although the discovery of an interaction among labor assignment and item sequencing rules [35] was verified in this study, the severe results of the DDATE--LWF combination had not been previously disclosed.

Finally, job structure had a greater impact on scheduling policy in this research than previous studies indicated. Siegel [80] tested various sequencing rules on three sets of job structures and found no difference in the rankings of sequencing rules for any of the distinct structure sets. In this research, however, job structure

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[1]Refer to table 3.3.

interacted strongly with every scheduling policy in the model, including sequencing rule, duedate assignment rule, and labor assignment rule. These conflicting results may be attributed to the polarized flat and tall job structures tested in this research versus the generality of job structure sets established by Siegel.

LIMITATIONS AND FURTHER RESEARCH

The assembly shop simulated in this research operated under several limiting assumptions. Processing times were known with certainty, assembly operations required no processing time, and shop load was set at only one level. There were no common assemblies among products, the quantity per assembly for all items was one, and lot sizing was not considered. In addition, the distribution of jobs chosen from each job structure set (i.e., product mix) was not varied. Further research might address these limitations by varying the accuracy of processing times, including non-zero assembly times in varying proportions to the operation processing times of a job, testing under different shop loads, developing more commonality in product bills of material, allowing product mix to vary, and considering lot sizing rules as an additional factor.

As initially stated, this research investigated scheduling policies for an assembly shop unencumbered by the operating constraints of an MRP system. The assembly shop operation in this study differs from an MRP run manufacturing facility in two basic ways: (1) Jobs arrive to the assembly shop continuously and randomly; jobs are released in an MRP system by a master schedule at discrete pre-determined time intervals. (2) Component items are released to the shop by an MRP system according to a release date determined by offsetting their leadtime from their duedate; in the assembly shop, all the items at the lowest level of a product structure are loaded into the shop simultaneously as the job arrives to the system, regardless of its duedate. These differences presumably have the following effect on scheduling policies: (1) Job tardiness for the assembly shop operation should be less than that of an MRP run facility. (2) Item sequencing should have a greater impact on the assembly shop than on the MRP shop. (3) Duedate assignment methods (or release date methods) should be more important for the MRP based systems than for simple assembly shops. In view of these differences and recognizing that most manufacturers of assembled products use MRP, a prime area for further research would be a comparison of scheduling policies in assembly shops with similar scheduling policies under MRP.

Several questions were raised in the course of this research that invite further investigation. The preliminary testing of sequencing rules showed the SPT rule to be the worst sequencing rule for assembled products. Unfortunately, only flat structured jobs were included in the testing at that point. In light of SPT's superior performance in job shops, a thorough study of SPT on progressively more complex assembly structures is needed. The study might also test variations of SPT, such as different truncated SPT rules and composite rules containing SPT. The composite rules involving shop congestion that performed poorly in this study should be re-examined in a detailed study of SPT oriented rules.

As an extension of the present work, additional research is also needed to explain the good performance of the simple DDATE sequencing rule across job structures, the poor performance of the LWF labor assignment rule, and the drastic results of their combination.

Finally, any research performed on hypothetical systems needs to be validated on actual operating systems. The peculiarities of scheduling the production of assembled products provides ample research opportunities.

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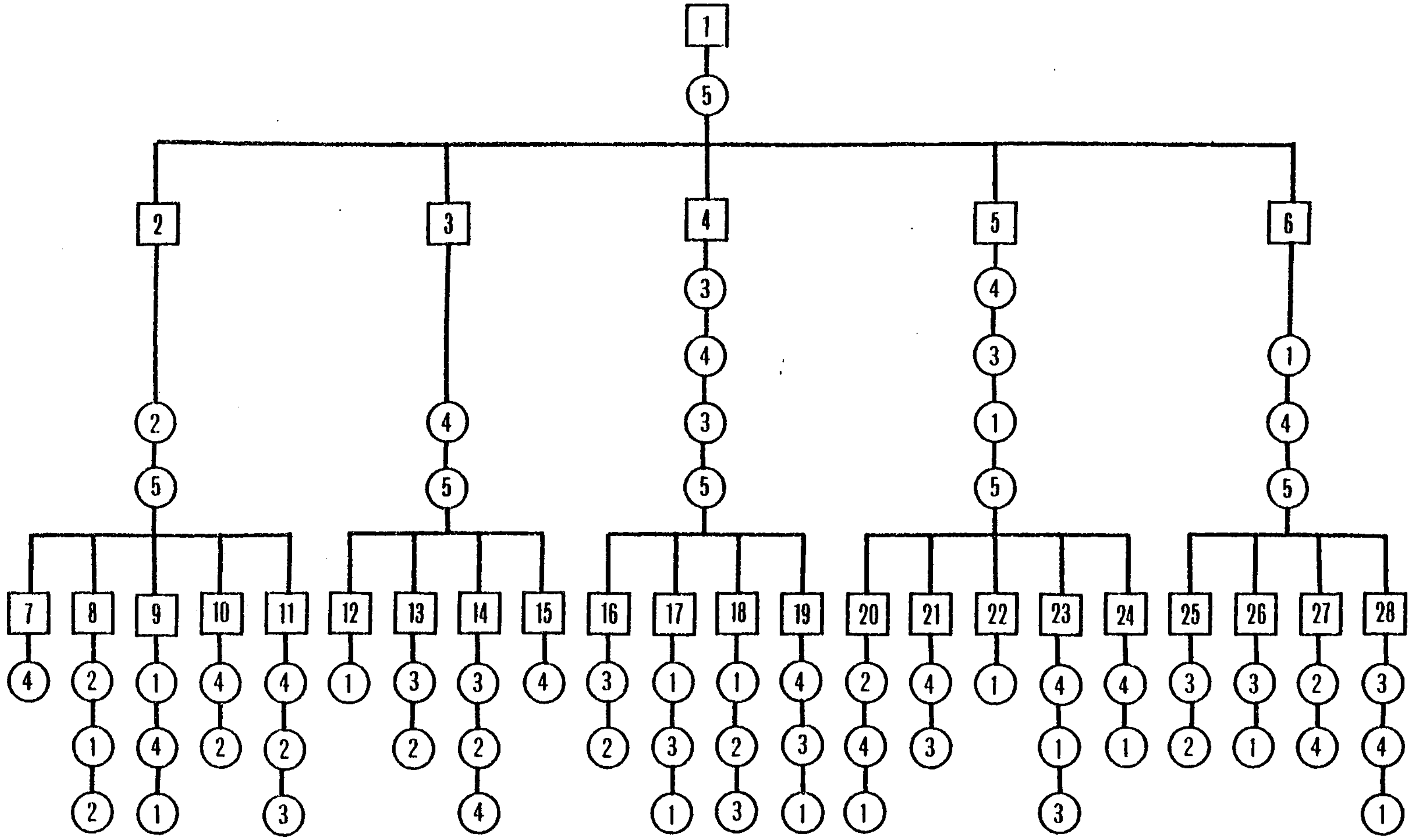
APPENDIX I

FLAT STRUCTURED JOB SET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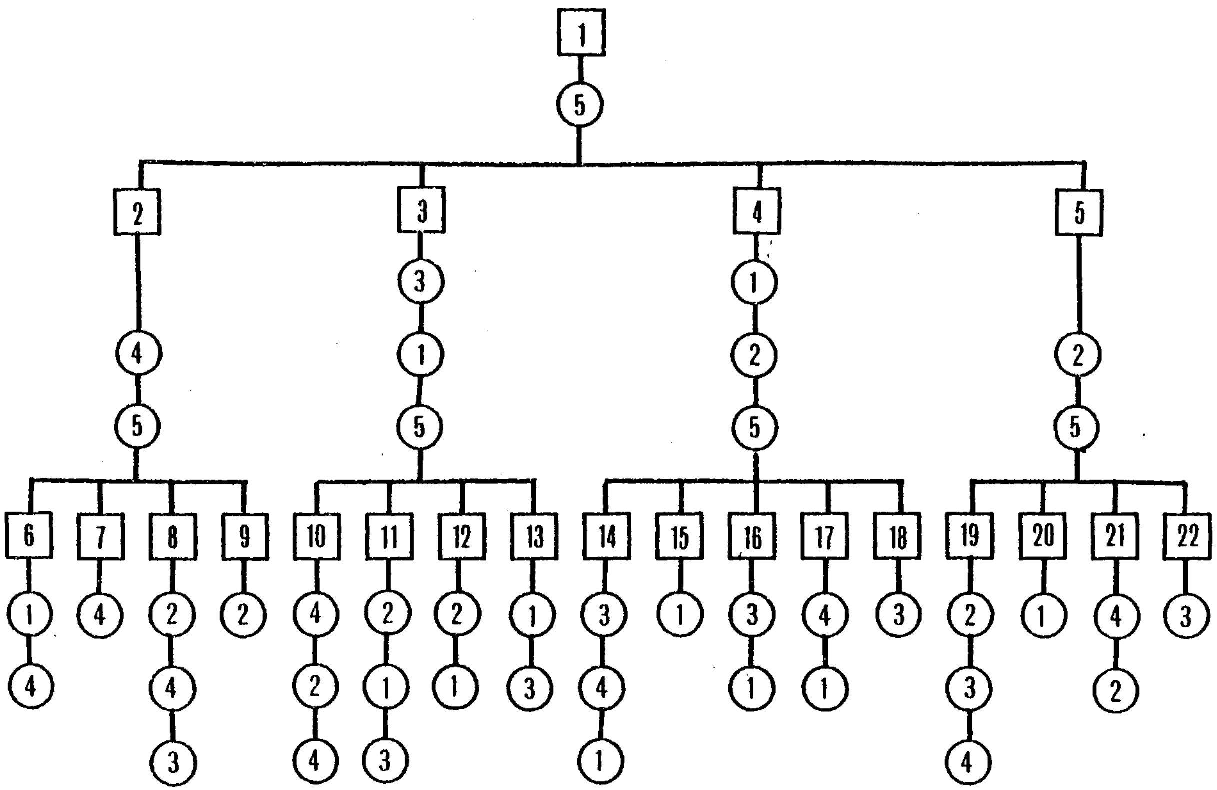

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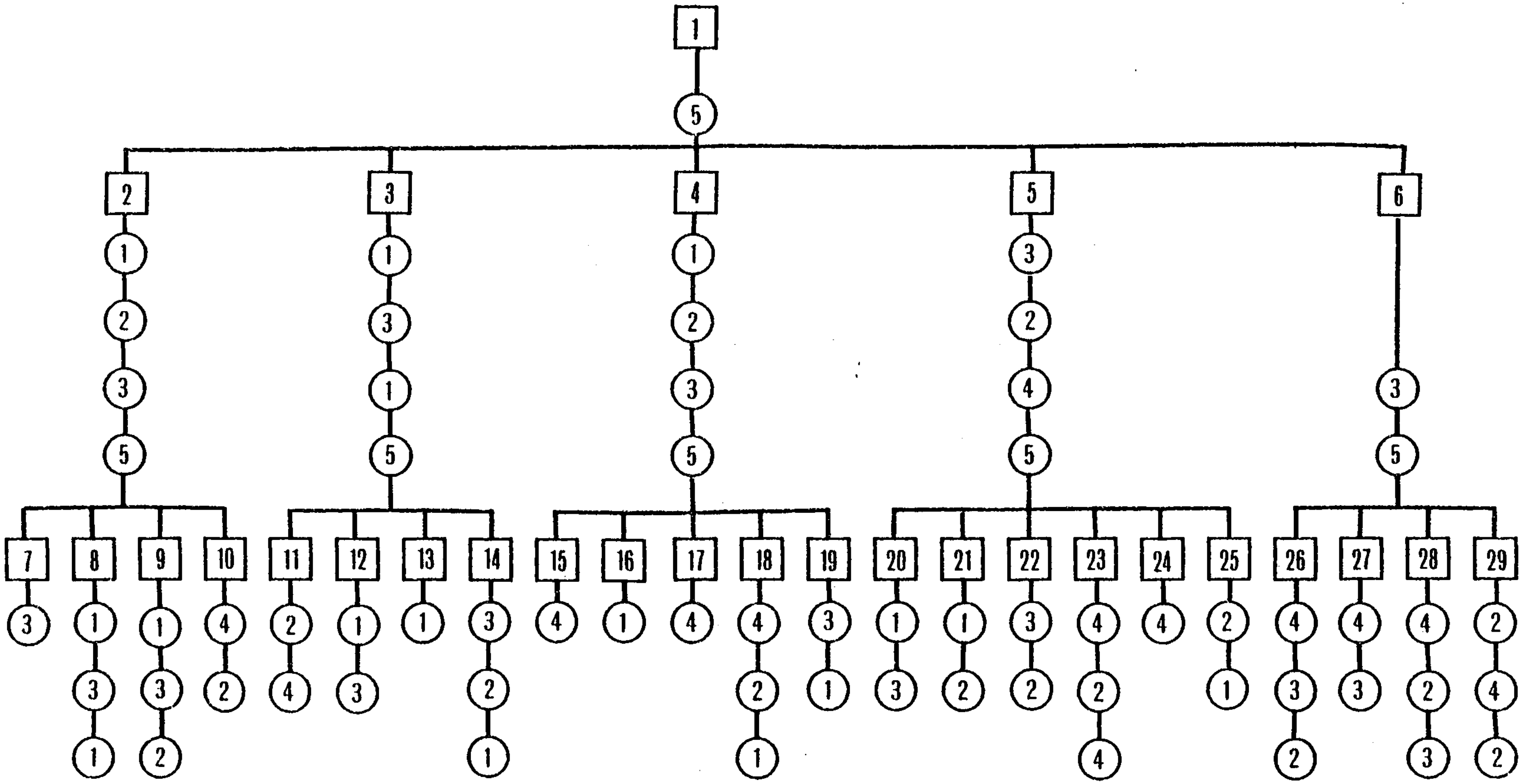

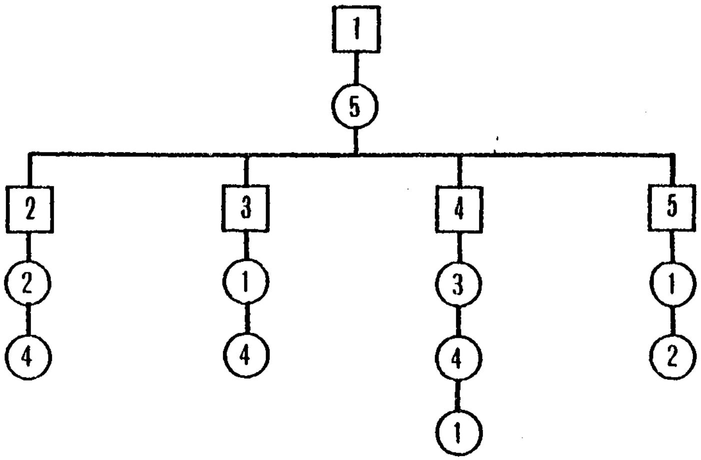
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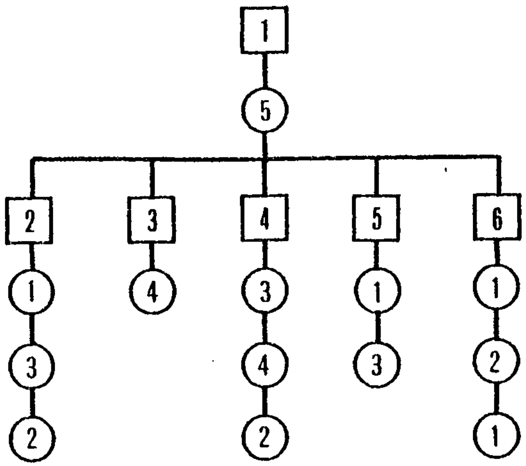
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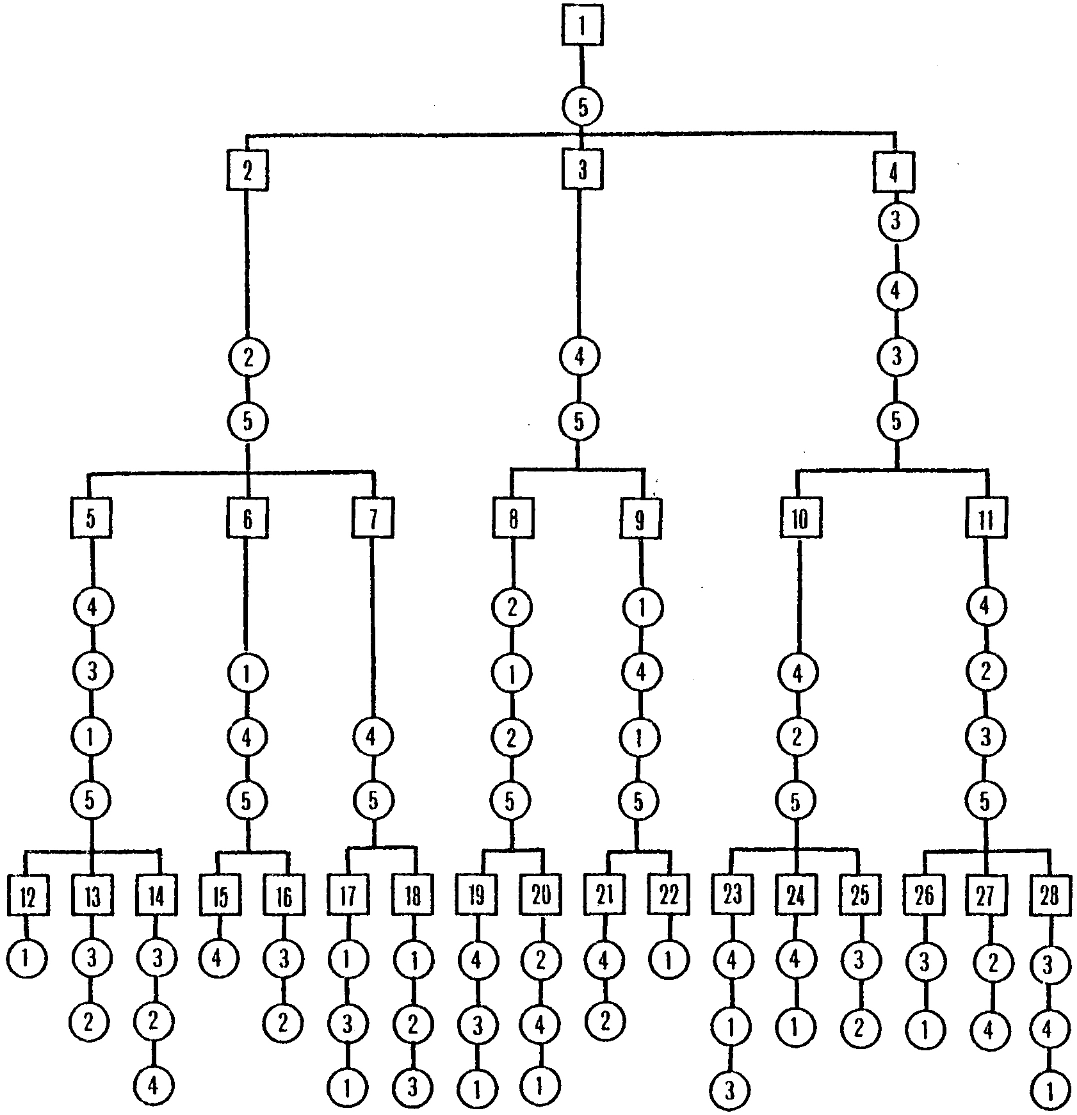
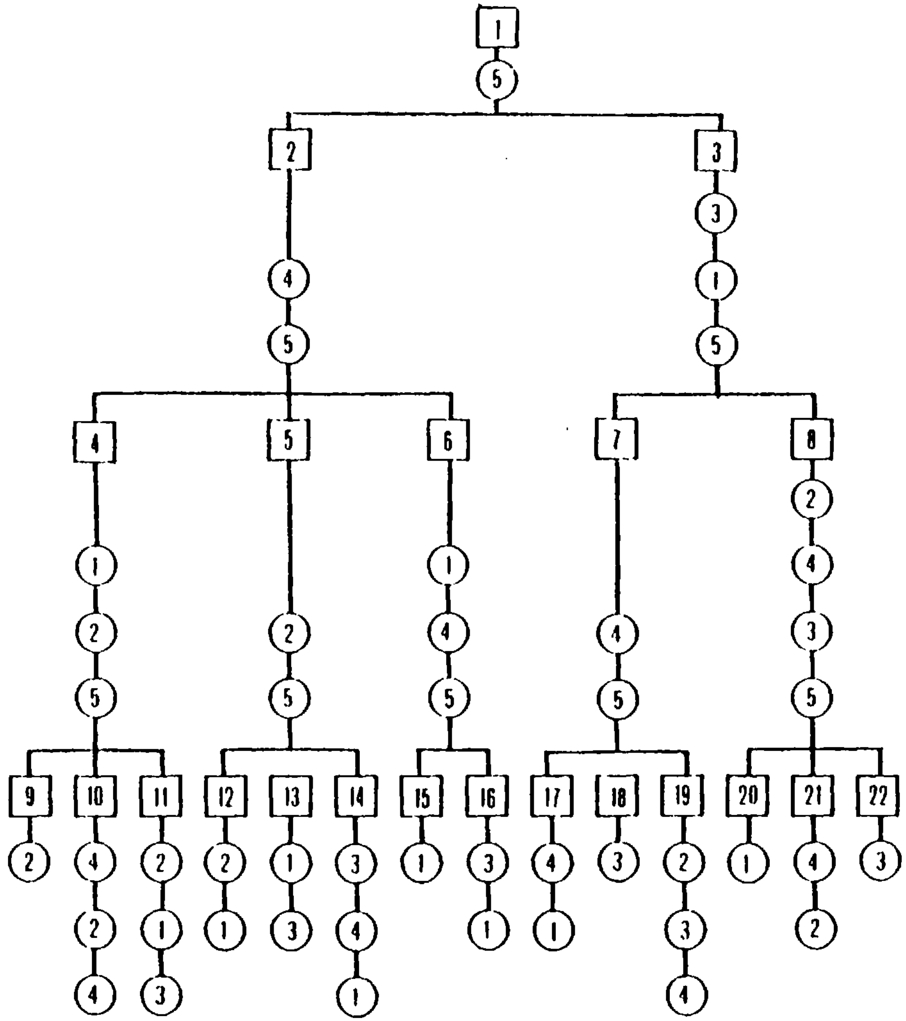
APPENDIX II

TALL STRUCTURED JOB SET

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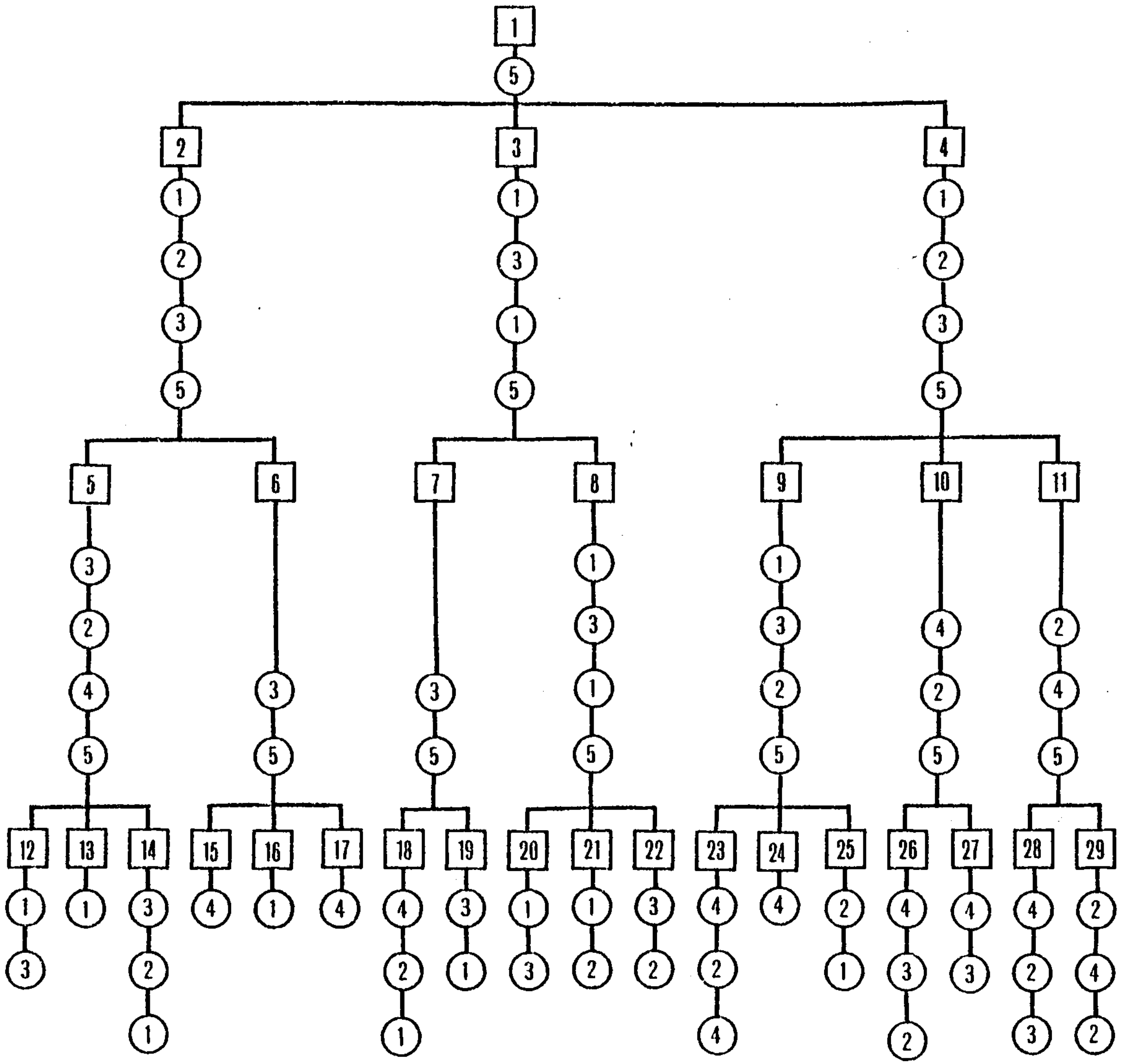
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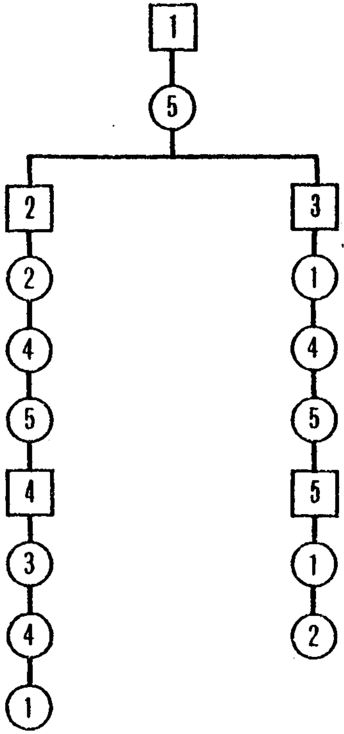
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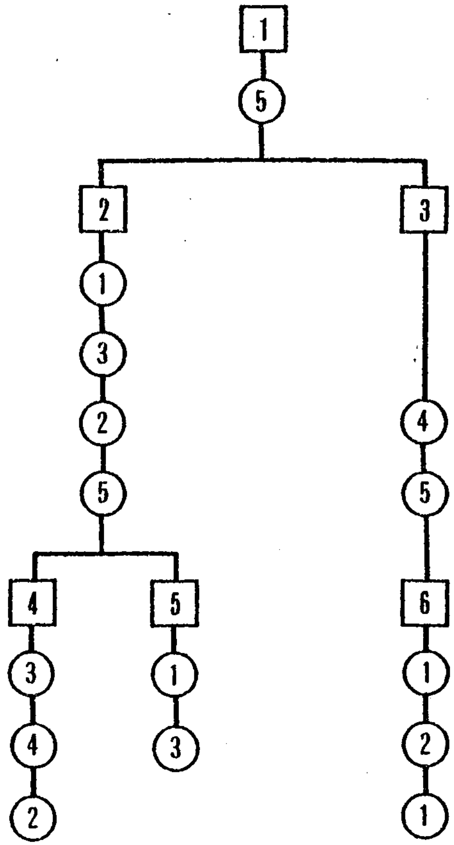

APPENDIX III

LISTING OF BILL OF MATERIAL PROGRAM

```
      DIMENSION NSET(10000)
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON QSET(10000)
      EQUIVALENCE (NSET(1),QSET(1))
      NNSET=10000
      NCRDR=5
      NPRNT=6
      NTAPE=7
      CALL SLAM
      STOP
      END

      SUBROUTINE INTLC
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,CNRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      DIMENSION XCOMP(5,50),XOPER(5,50),XMACH(5,50,4),PT(5,50,4)
     C,JPAR(5,50)
      DIMENSION XVAL(3),FX(2),FY(3),YVAL(4),FZ(4),ZVAL(4),GVAL(3)
      DATA XVAL/2.,3./,FX/.50,1.00/,YVAL/4.,5./,FY/.33,.66,
     11.00/,ZVAL/1.,2.,3.,4./,FZ/.25,.50,.75,1.00/,GVAL/1.,2.,3./
      MM=0
      DO 100 I=1,5
      ITEM=1
      XLEV=DPROB(FX,XVAL,2,1)
      JJ=XLEV-2.
      XCOMP(I,ITEM)=DPROB(FX,YVAL,2,2)
      JPAR(I,ITEM) =0
      XOPER(I,ITEM)=0.
      NUM=XCOMP(I,ITEM)
      IF (JJ.EQ.0) GO TO 51
      DO 10 J=1,JJ
      M=ITEM + 1
      MM=ITEM + NUM
      NUM=0
      NCOMP = MM
      DO 20 K=M,MM
      XCOMP(I,K)=DPROB(FX,YVAL,2,2)
      IBEG=NCOMP+1
      NCOMP=IBEG+XCOMP(I,K)-1
      DO 21 II=IBEG,NCOMP
      JPAR(I,II)=K
   21 CONTINUE
      NUM=NUM + XCOMP(I,K)
      IF(ITEM.EQ.1)JPAR(I,K)=ITEM
   20 CONTINUE
      ITEM=MM
   51 KK=ITEM + NUM
```

```
   10 CONTINUE
      ICOMP=ITEM + 1
      DO 80 J=ICOMP,KK
      XCOMP(I,J)=0.
      IF(JJ.EQ.0)JPAR(I,J)=1
   80 CONTINUE
      NITEM = KK
      DO 30 L=2,KK
      XOPER(I,L)=DPROB(FY,GVAL,3,3)
      NN=XOPER(I,L)
      DO 40 N=1,NN
   50 XMACH(I,L,N)=DPROB(FZ,ZVAL,4,4)
      IF(N.NE.1.AND.XMACH(I,L,N).EQ.XMACH(I,L,N-1)) GO TO 50
      PT(I,L,N)=EXPON(.1,5)
   40 CONTINUE
   30 CONTINUE
      WRITE (6,5) XLEV,NITEM
    5 FORMAT (1X,F10.4,I4)
      DO 35 J=1,KK
      WRITE(6,6) J,JPAR(I,J),XCOMP(I,J),XOPER(I,J)
    6 FORMAT (1X,2I4,2F10.4)
      LIM=XOPER(I,J)
      IF(LIM.EQ.0) GO TO 35
      DO 25 K=1,LIM
      WRITE(6,7) XMACH(I,J,K),PT(I,J,K)
    7 FORMAT (1X,2F10.4)
   25 CONTINUE
   35 CONTINUE
  100 CONTINUE
      RETURN
      END

/*
//GO.FT07F001 DD DSN=&&SEQ1,UNIT=SYSDA,DISP=(NEW,DELETE),
//  SPACE=(TRK,(20,5)),DCB=(LRECL=133,BLKSIZE=1330,BUFNO=1,RECFM=FB)
//GO.SYSIN DD *

GEN,RUSSELL,FINPUT DATA,10/15/1982,,,,,,72;
FIN;
/*
//
```

APPENDIX IV

LISTING OF SIMULATION PROGRAM

```
      DIMENSION NSET(50000)
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/XLEV(5),NITEM(5),PTOT(5),JPAR(5,50),XCOMP(5,50),
     CXOPER(5,50),PITEM(5,50),NASM(5),NCOMP(5,50,5),XMACH(5,50,4),
     CPT(5,50,4),COUNT,ARR,TPT,CPATH(5),PATH(5,50),CPMOD(5),RWK(1000),
     CRASM(1000),ROPT(1000),NOPT(5),ZZ(14),A(15),BD(5,50),QMC(4)
     C,XPATH(5,50)
      COMMON QSET(50000)
      EQUIVALENCE (NSET(1),QSET(1))
      NNSET=50000
      NCRDR=5
      NPRNT=6
      NTAPE=7

C****     INPUT PRODUCT STRUCTURE AND PROCESSING DATA

      TPT=0.
      DO 100 I=1,5
      CPATH(I)=0.
      CPMOD(I)=0.
      KK=1
      PTOT(I)=0.
      NOPT(I)=0
      READ (5,5) XLEV(I),NITEM(I)
    5 FORMAT (F10.4,I4)
      NASM(I)=0
      N=NITEM(I)
      MPAR=0
      DO 60 K=1,N
      READ (5,10) ITEM, JPAR(I,ITEM), XCOMP(I,ITEM), XOPER(I,ITEM)
   10 FORMAT (2I4,2F10.4)
      PITEM(I,ITEM)=0.
      NUM=XCOMP(I,ITEM)
      IF(NUM.EQ.0) GO TO 41
      NASM(I)=NASM(I)+1
      DO 40 J=1,NUM
      KK=KK+1
      NCOMP(I,ITEM,J)=KK
   40 CONTINUE
      IF(JPAR(I,ITEM).EQ.0)GO TO 60
   41 NOPER=XOPER(I,ITEM)
      NOPT(I)=NOPT(I)+NOPER
      DO 50 JJ=1,NOPER
      READ (5,15) XMACH(I,ITEM,JJ), PT(I,ITEM,JJ)
   15 FORMAT (2F10.4)
      PITEM(I,ITEM)=PITEM(I,ITEM) + PT(I,ITEM,JJ)
```

```
   50 CONTINUE
   55 PTOT(I)=PTOT(I) + PITEM(I,ITEM)
      TPT=TPT+PTOT(I)
   60 CONTINUE

C***     CALCULATE LONGEST PATH

      DO 70 IT=2,N
      KIT=JPAR(I,IT)
      XPATH(I,IT)=PITEM(I,IT)*XCOMP(I,KIT)
      PATH(I,IT)=PITEM(I,IT)
      ITEM=IT
   51 JITEM=JPAR(I,ITEM)
      PATH(I,IT)=PATH(I,IT)+PITEM(I,JITEM)
      KITEM=JPAR(I,JITEM)
      XPATH(I,IT)=XPATH(I,IT)+(PITEM(I,JITEM)*XCOMP(I,KITEM))
      ITEM=JITEM
      IF(JITEM.NE.1)GO TO 51
      IF(XPATH(I,IT).GT.CPMOD(I))CPMOD(I)=XPATH(I,IT)
      IF(PATH(I,IT).GT.CPATH(I))CPATH(I)=PATH(I,IT)
   70 CONTINUE

C***     CALCULATE DUEDATES FOR ASSEMBLIES

      DO 20 K=2,N
      IPAR=JPAR(I,K)
      IF(IPAR.NE.1)GO TO 23
      BD(I,K)=CPMOD(I)*3
      GO TO 20
   23 CPBR=0.
      IF(XCOMP(I,K).NE.0.)GO TO 20
      ICOMP=XCOMP(I,IPAR)
      DO 22 J=1,ICOMP
      PTBR=PITEM(I,NCOMP(I,IPAR,J))*ICOMP
      IF(PTBR.GT.CPBR)CPBR=PTBR
   22 CONTINUE
      BD(I,K)=CPBR*3.
   20 CONTINUE
      IF(XLEV(I).LE.3.)GO TO 100
      ICO=XCOMP(I,1)
      IICO=ICO+1
      DO 28 K=2,IICO
      IICOM=XCOMP(I,K)
      CPBR=0.
      DO 26 LL=1,IICOM
      MID=NCOMP(I,K,LL)
      TCPBR=BD(I,NCOMP(I,MID,1))+PITEM(I,MID)*3.*IICOM
      IF(TCPBR.GT.CPBR)CPBR=TCPBR
   26 CONTINUE
      DO 25 L=1,IICOM
      MID=NCOMP(I,K,L)
      BD(I,MID)=CPBR
   25 CONTINUE
   28 CONTINUE
  100 CONTINUE
```

```
C****     DETERMINE MEAN INTERARRIVAL TIME

      ARR=.75

C***      CALL SLAM PROGRAM

      CALL SLAM
      STOP
      END

      SUBROUTINE INTLC
      COMMON/GCOM5/IISED(10),JJBEG,JJCLR,MMNIT,MMON,NNAME(5),NNCFI,
     1NNDAY,NNPT,NNPRJ(5),NNRNS,NNSTR,NNYR,SSEED(10),LSEED(10)
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,CNRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/XLEV(5),NITEM(5),PTOT(5),JPAR(5,50),XCOMP(5,50),
     CXOPER(5,50),PITEM(5,50),NASM(5),NCOMP(5,50,5),XMACH(5,50,4),
     CPT(5,50,4),COUNT,ARR,TPT,CPATH(5),PATH(5,50),CPMOD(5),RWK(1000),
     CRASM(1000),ROPT(1000),NOPT(5),ZZ(14),A(15),BD(5,50),QMC(4)

C****     CALL SUBROUTINE LOAD TO BEGIN SIMULATION

      II=0
      COUNT=0.
      QMC(1)=0.
      QMC(2)=0.
      QMC(3)=0.
      QMC(4)=0.
      WRITE(6,10) SSEED(2),SSEED(1)
   10 FORMAT(1X,10H ARR SEED=,F20.4,12H JTYPE SEED=,F20.4)
      CALL SCHDL(1,0.,ATRIB)
      RETURN
      END

      SUBROUTINE EVENT(I)
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,CNRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/XLEV(5),NITEM(5),PTOT(5),JPAR(5,50),XCOMP(5,50),
     CXOPER(5,50),PITEM(5,50),NASM(5),NCOMP(5,50,5),XMACH(5,50,4),
     CPT(5,50,4),COUNT,ARR,TPT,CPATH(5),PATH(5,50),CPMOD(5),RWK(1000),
     CRASM(1000),ROPT(1000),NOPT(5),ZZ(14),A(15),BD(5,50),QMC(4)

      GO TO (1,2,3,4,5,6),I

C****     GENERATE JOB ARRIVALS

    1 TBA=EXPON(ARR,2)
      IF(TBA.LT..10)TBA=.10
      CALL SCHDL(1,TBA,ATRIB)
      CALL LOAD
      RETURN

C****     ROUTE COMPONENT ITEMS THROUGH THE SHOP
```

```
    2 CALL ROUTE
      RETURN
C****    ASSEMBLE COMPONENTS INTO PARENT ITEM
    3 CALL ASSMBL
      RETURN
C****    CALCULATE STATISTICS
    4 CALL OUTPUT
      RETURN
C**** REMOVE DUMMY ITEM FROM LABOR QUEUE
    5 M=ZZ(10)
      NRANK=NFIND(1,M,4,0,100.,0.)
      IF(NRANK.LT.1)RETURN
      CALL RMOVE(NRANK,M,ZZ)
      RETURN
    6 IF(ZZ(10).EQ.2.AND.NNACT(2).GE.2.AND.NNRSC(1).GT.0)GO TO 11
      IF(ZZ(10).EQ.1.AND.NNACT(1).GE.2.AND.NNRSC(1).GT.0)GO TO 12
      IF(ZZ(10).EQ.4.AND.NNACT(4).GE.2.AND.NNRSC(2).GT.0)GO TO 13
      IF(ZZ(10).EQ.3.AND.NNACT(3).GE.2.AND.NNRSC(2).GT.0)GO TO 14
      RETURN
   11 ZZ(10)=1.
      CALL ENTER(1,ZZ)
      GO TO 10
   12 ZZ(10)=2.
      CALL ENTER(2,ZZ)
      GO TO 10
   13 ZZ(10)=3.
      CALL ENTER(3,ZZ)
      GO TO 10
   14 ZZ(10)=4.
      CALL ENTER(4,ZZ)
   10 CALL SCHDL(5,.0001,ZZ)
      RETURN
      END

      SUBROUTINE LOAD
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,CNRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/XLEV(5),NITEM(5),PTOT(5),JPAR(5,50),XCOMP(5,50),
     CXOPER(5,50),PITEM(5,50),NASM(5),NCOMP(5,50,5),XMACH(5,50,4),
     CPT(5,50,4),COUNT,ARR,TPT,CPATH(5),PATH(5,50),CPMOD(5),RWK(1000),
     CRASM(1000),ROPT(1000),NOPT(5),ZZ(14),A(15),BD(5,50),QMC(4)
      DIMENSION XVAL(5),FX(5)

      DATA XVAL/1.,2.,3.,4.,5./,FX/.20,.40,.60,.80,1.00/

C****    ASSIGN JOB NO., JOB TYPE AND DUEDATE TO EACH ARRIVAL.
C****    SET REMAINING WORK AND REMAINING NO. OF OPERATIONS TO
C****    ORIGINAL LEVEL.
```

```
      II=II+1
      JTYPE=DPROB(FX,XVAL,5,1)
      RWK(II)=PTOT(JTYPE)
      ROPT(II)=NOPT(JTYPE)
      RASM(II)=NASM(JTYPE)
      DDATE = TNOW+3.*CPMOD(JTYPE)

C****     LOAD LOWEST LEVEL ITEMS AND ASSIGN ATTRIBUTES. ENTER NETWORK AT
C****     MACHINE CENTER WHERE THE FIRST OPERATION IS PERFORMED.

      N=NITEM(JTYPE)
      DO 10 I=2,N
      IF(XCOMP(JTYPE,I).NE.0.) GO TO 10
      M=XMACH(JTYPE,I,1)
      QMC(M)=QMC(M)+ATRIB(7)
      ATRIB(1)=JTYPE
      ATRIB(2)=TNOW
      ATRIB(3)=DDATE
      ATRIB(4)=I
      ATRIB(5)=1
      ATRIB(7)=PT(JTYPE,I,1)
      ATRIB(8)=TNOW
      ATRIB(9)=II
      ATRIB(10)=M
      ATRIB(11)=ATRIB(2)+BD(JTYPE,I)-PITEM(JTYPE,I)+.01*(ROPT(II)**2)
      ATRIB(12)=PITEM(JTYPE,I)
      CALL ENTER(M,ATRIB)
   10 CONTINUE
      RETURN
      END


      SUBROUTINE ROUTE
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,CNRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/XLEV(5),NITEM(5),PTOT(5),JPAR(5,50),XCOMP(5,50),
     CXOPER(5,50),PITEM(5,50),NASM(5),NCOMP(5,50,5),XMACH(5,50,4),
     CPT(5,50,4),COUNT,ARR,TPT,CPATH(5),PATH(5,50),CPMOD(5),RWK(1000),
     CRASM(1000),ROPT(1000),NOPT(5),ZZ(14),A(15),BD(5,50),QMC(4)

C****     DETERMINE ITEM, PARENT OF ITEM, AND OPERATION.
C****     IF ITEM IS AN END ITEM, LEAVE THE SHOP.
C****     IF THAT WAS THE LAST OPERATION, CALL SUBROUTINE ASSMBL.

      ITEM=ATRIB(4)
      IF(ITEM.EQ.100)RETURN
      JTYPE=ATRIB(1)
      JOB=ATRIB(9)
      IF(ITEM.EQ.1) GO TO 5
      ATRIB(8)=TNOW
      IF(ATRIB(4).EQ.ATRIB(7))GO TO 15
      RWK(JOB)=RWK(JOB)-ATRIB(7)
      ROPT(JOB)=ROPT(JOB)-1
      I=ATRIB(10)
```

```
      QMC(I)=QMC(I)-ATRIB(7)
      ATRIB(12)=ATRIB(12)-ATRIB(7)
      IF(RWK(JOB).EQ.0)GO TO 25
C***  CALL RULE

   25 IF(ATRIB(5).GE.XOPER(JTYPE,ITEM))GO TO 10

C****    OTHERWISE, UPDATE OPERATION NO. AND DETERMINE THE NEXT MACHINE
C****    IN ROUTING SEQUENCE.  RE-ENTER NETWORK AT THAT POINT.

      ATRIB(5)=ATRIB(5)+1.
   20 NOPER=ATRIB(5)
   21 ATRIB(7)=PT(JTYPE,ITEM,NOPER)
      M=XMACH(JTYPE,ITEM,NOPER)
      QMC(M)=QMC(M)+ATRIB(7)
      ATRIB(11)=ATRIB(2)+BD(JTYPE,ITEM)-ATRIB(12)+.01*(ROPT(JOB)**2)
      ATRIB(5)=NOPER
      ATRIB(10)=M
      CALL ENTER(M,ATRIB)
      IF(NNQ(M).GE.500)MSTOP=-1
      RETURN
    5 CALL SCHDL(4,0.,ATRIB)
      RETURN
   10 CALL SCHDL(3,0.,ATRIB)
      RETURN
   15 ATRIB(5)=1.
      ATRIB(12)=PITEM(JTYPE,ITEM)
      NOPER=1
      RASM(JOB)=RASM(JOB)-1
      GO TO 21
      END

      SUBROUTINE ALLOC(IAC,IFLAG)
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/XLEV(5),NITEM(5),PTOT(5),JPAR(5,50),XCOMP(5,50),
     CXOPER(5,50),PITEM(5,50),NASM(5),NCOMP(5,50,5),XMACH(5,50,4),
     CPT(5,50,4),COUNT,ARR,TPT,CPATH(5),PATH(5,50),CPMOD(5),RWK(1000),
     CRASM(1000),ROPT(1000),NOPT(5),ZZ(14),A(15),BD(5,50),QMC(4),TIME
     C,ASSGN(4),B(15)

C****    GO TO PROGRAM SEGMENT ACCORDING TO MACHINE CENTER
      GO TO (1,2,3,4),IAC

C****    ALLOCATE WORKER RESOURCE TO MACHINE CENTER WHOSE FIRST ITEM
C****    IN LINE HAS BEEN WAITING THE LONGEST.

    1 IF(NNRSC(1).LE.0)GO TO 15
      IF(TNOW.NE.ATRIB(2).AND.TIME.EQ.TNOW.AND.N.EQ.1)GO TO 15
      IF(NNACT(1).GE.2.AND.NNQ(2).LE.0)GO TO 15
      IF(NNACT(1).GE.2.AND.NNQ(2).GT.0)GO TO 5
      CALL COPY(1,1,A)
      CALL COPY(1,2,B)
C***  CALL LABOR
      IF(NNACT(2).LT.2.AND.A(8).GT.B(8))GO TO 5
```

```
      M=1
      TIME=TNOW
      N=1
      GO TO 10
    5 ZZ(10)=2.
      ZZ(11)=1000.
      ZZ(4)=100.
      CALL ENTER(2,ZZ)
      CALL SCHDL(5,.0001,ZZ)
      CALL SCHDL(6,.0001,ZZ)
      GO TO 15

    2 IF(NNACT(2).GE.2.OR.NNRSC(1).LE.0)GO TO 15
      IF(TNOW.NE.ATRIB(2).AND.TIME.EQ.TNOW.AND.N.EQ.2)GO TO 15
      CALL COPY(1,1,A)
      CALL COPY(1,2,B)
C***  CALL LABOR
      IF(TIME.NE.TNOW.AND.NNACT(1).LT.2.AND.B(8).GT.A(8))GO TO 7
      M=1
      TIME=TNOW
      N=2
      GO TO 10
    7 ZZ(10)=1.
      ZZ(11)=1000.
      ZZ(4)=100.
      CALL ENTER(1,ZZ)
      CALL SCHDL(5,.0001,ZZ)
      CALL SCHDL(6,.0001,ZZ)
      GO TO 15

    3 IF(NNRSC(2).LE.0)GO TO 15
      IF(TNOW.NE.ATRIB(2).AND.TIME.EQ.TNOW.AND.N.EQ.3)GO TO 15
      IF(NNACT(3).GE.2.AND.NNQ(4).LE.0)GO TO 15
      IF(NNACT(3).GE.2.AND.NNQ(4).GT.0)GO TO 6
      CALL COPY(1,3,A)
      CALL COPY(1,4,B)
C***  CALL LABOR
      IF(NNACT(4).LT.2.AND.A(8).GT.B(8))GO TO 6
      M=2
      TIME=TNOW
      N=3
      GO TO 10
    6 ZZ(10)=4.
      ZZ(11)=1000.
      ZZ(4)=100.
      CALL ENTER(4,ZZ)
      CALL SCHDL(5,.0001,ZZ)
      CALL SCHDL(6,.0001,ZZ)
      GO TO 15

    4 IF(NNACT(4).GE.2.OR.NNRSC(2).LE.0)GO TO 15
      IF(TNOW.NE.ATRIB(2).AND.TIME.EQ.TNOW.AND.N.EQ.4)GO TO 15
      CALL COPY(1,3,A)
      CALL COPY(1,4,B)
C***  CALL LABOR
```

```
      IF(TIME.NE.TNOW.AND.NNACT(3).LT.2.AND.B(8).GT.A(8))GO TO 8
      M=2
      TIME=TNOW
      N=4
      GO TO 10
    8 ZZ(10)=3.
      ZZ(11)=1000.
      ZZ(4)=100.
      CALL ENTER(3,ZZ)
      CALL SCHDL(5,.0001,ZZ)
      CALL SCHDL(6,.0001,ZZ)
      GO TO 15

C****    MACHINE IS FREE, WORKER IS AVAILABLE, AND LABOR ASSIGNMENT
C****    RULE IS MET, SO SEIZE WORKER

   10 CALL SEIZE(M,1)
      IFLAG=1
      RETURN

C****    WORKER IS NOT AVAILABLE OR CONDITIONS ARE NOT MET

   15 IFLAG=0
      RETURN
      END

      SUBROUTINE LABOR
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,CNRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/XLEV(5),NITEM(5),PTOT(5),JPAR(5,50),XCOMP(5,50),
     CXOPER(5,50),PITEM(5,50),NASM(5),NCOMP(5,50,5),XMACH(5,50,4),
     CPT(5,50,4),COUNT,ARR,TPT,CPATH(5),CPMOD(5),RWK(1000),ROPT(1000),
     CRASM(1000),NOPT(5),ZZ(14),A(15),B(15),BD(5,50),QMC(4),PATH(5,50),
     CASSGN(4)

C****     DETERMINE WHICH QUEUE'S FIRST ITEM IN LINE HAS A PARENT IN
C****     ASSEMBLY DELAY.  IF NONE OR BOTH ARE IN DELAY, CHOOSE ITEM
C****     BY SPT.

      MACH=A(10)
      ITEM=A(4)
      JTYPE=A(1)
      JOB=A(9)
    5 XJOB=JOB
      IPAR=JPAR(JTYPE,ITEM)
      XPAR=IPAR
      ICOMP=XCOMP(JTYPE,ITEM)
      DELAY=1.

C****     SEARCH ASSEMBLY QUEUES FOR COMPONENTS OF SAME JOB AND PARENT.
C****     CHOOSE QUEUES BY NO. OF COMPONENTS TO BE ASSEMBLED.

      GO TO (20,30,40,50),ICOMP
   20 N=16
      GO TO 60
```

```
   30 N=18
      GO TO 60
   40 N=21
      GO TO 60
   50 N=25
   60 NN=N+ICOMP-1
      DO 100 M=N,NN
      J=1
      JJ=1
   10 NRANK=NFIND(J,M,9,0,XJOB,0.)
      IRANK=NFIND(JJ,M,4,0,XPAR,0.)
      IF(NRANK.EQ.0.OR.IRANK.EQ.0.)GO TO 100
      IF(NRANK.EQ.IRANK)GO TO 250
      IF(NRANK.LT.IRANK)J=JJ
      IF(NRANK.GT.IRANK)JJ=J
      IF(J.GE.NNQ(M))GO TO 100
      GO TO 10
  100 CONTINUE
      GO TO 260
  250 DELAY=0.
  260 ASSGN(MACH)=DELAY+A(7)
      IF(MACH.EQ.B(10))RETURN
      MACH=B(10)
      ITEM=B(4)
      JTYPE=B(1)
      JOB=B(9)
      GO TO 5
      END


      SUBROUTINE ASSMBL
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,CNRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/XLEV(5),NITEM(5),PTOT(5),JPAR(5,50),XCOMP(5,50),
     CXOPER(5,50),PITEM(5,50),NASM(5),NCOMP(5,50,5),XMACH(5,50,4),
     CPT(5,50,4),COUNT,ARR,TPT,CPATH(5),PATH(5,50),CPMOD(5),RWK(1000),
     CRASM(1000),ROPT(1000),NOPT(5),ZZ(14),A(15),BD(5,50),QMC(4)

C****    DETERMINE ITEM, PARENT OF ITEM, AND COMPONENT NO. OF ITEM.
C****    ASSIGN LATTER TO ATRIB(6). UPDATE ATTRIBUTES TO PARENT ITEM.

      ITEM=ATRIB(4)
      JTYPE=ATRIB(1)
      J=JPAR(JTYPE,ITEM)
      N= XCOMP(JTYPE,J)
      DO 30 M=1,N
      IF(ITEM.EQ.NCOMP(JTYPE,J,M)) GO TO 32
   30 CONTINUE
      WRITE(6,40)
   40 FORMAT (27X,35H ITEM AND COMPONENT NO. DON'T MATCH)
   32 ATRIB(6)=M
      ATRIB(4)=J
      ATRIB(5)=1.
      ATRIB(7)=J
      ATRIB(11)=ATRIB(1)*10.+ATRIB(7)
```

```
C****     RE-ENTER THE NETWORK ACCORDING TO THE NO. OF COMPONENTS WHICH
C****     MUST BE ASSEMBLED.

      GO TO(10,12,13,14,15),N
   10 CALL SCHDL(2,0.,ATRIB)
      RETURN
   12 CALL ENTER(12,ATRIB)
      RETURN
   13 CALL ENTER(13,ATRIB)
      RETURN
   14 CALL ENTER(14,ATRIB)
      RETURN
   15 CALL ENTER(15,ATRIB)
      RETURN
      END

      SUBROUTINE OUTPUT
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,CNRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/XLEV(5),NITEM(5),PTOT(5),JPAR(5,50),XCOMP(5,50),
     CXOPER(5,50),PITEM(5,50),NASM(5),NCOMP(5,50,5),XMACH(5,50,4),
     CPT(5,50,4),COUNT,ARR,TPT,CPATH(5),PATH(5,50),CPMOD(5),RWK(1000),
     CRASM(1000),ROPT(1000),NOPT(5),ZZ(14),A(15),BD(5,50),QMC(4)
C****
C****     CALCULATE JOB FLOWTIME, JOB TARDINESS, AND SQUARE TARDINESS
C****
      NJOB=ATRIB(1)
      FLOW=TNOW-ATRIB(2)
      CALL COLCT (FLOW,1)
      TARDY=TNOW-ATRIB(3)
      STARD=TARDY**2
      IF(TARDY.LE.0.)GO TO 10
      CALL COLCT(TARDY,2)
      CALL COLCT(STARD,3)
C****
C****     CLEAR STATISTICS AFTER 50 JOBS HAVE LEFT THE SHOP.
C****     STOP THE SIMULATION AFTER 500 ADDITIONAL JOBS HAVE LEFT THE SHOP
C****
   10 COUNT=COUNT+1
      IF(COUNT.EQ.50.)CALL CLEAR
      IF(COUNT.LT.550.)RETURN
      MSTOP=-1
      RETURN
      END

      SUBROUTINE RULE
      COMMON/SCOM1/ ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,CNRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/XLEV(5),NITEM(5),PTOT(5),JPAR(5,50),XCOMP(5,50),
     CXOPER(5,50),PITEM(5,50),NASM(5),NCOMP(5,50,5),XMACH(5,50,4),
     CPT(5,50,4),COUNT,ARR,TPT,CPATH(5),PATH(5,50),CPMOD(5),RWK(1000),
     CRASM(1000),ROPT(1000),NOPT(5),ZZ(14),A(15),BD(5,50),QMC(4)

C****     UPDATE ATRIB(11) FOR ALL ITEMS OF SAME JOB
```

```
      JOB=ATRIB(9)
      XJOB=JOB
      DO 30 I=1,4
      IF(NNQ(I).EQ.0)GO TO 30
    5 J=1
    6 NRANK=NFIND(J,I,9,0,XJOB,0.)
      IF(NRANK.EQ.0)GO TO 30
    7 CALL COPY(NRANK,I,A)
      IF(A(13).NE.TNOW)GO TO 8
      IF(NRANK.GE.NNQ(I))GO TO 30
      J=NRANK+1
      GO TO 6
    8 CALL RMOVE(NRANK,I,A)
      JTYPE=A(1)
      ITEM=A(4)
      JOB=A(9)
      A(13)=TNOW
      A(11)=A(2)+BD(JTYPE,ITEM)-A(12)+.01*(ROPT(JOB)**2)
      CALL FILEM(I,A)
      GO TO 5
   30 CONTINUE
      RETURN
      END

/*
//GO.FT07F001 DD DSN=&&SEQ1,UNIT=SYSDA,DISP=(NEW,DELETE),
//  SPACE=(TRK,(20,5)),DCB=(LRECL=133,BLKSIZE=1330,BUFNO=1,RECFM=FB)
//GO.SYSIN DD *

C****  INPUT JOB STRUCTURE DATA HERE

GEN,RUSSELL,ASSEMBLY SHOP,10/15/1982,1,YES,NO,YES,NO,YES;
LIM,29,13,2500.;
PRI/1,LVF(3)/2,LVF(3)/3,LVF(3)/4,LVF(3);
STAT,1,FLOWTIME;
STAT,2,TARDINESS;
STAT,3,SQ TARDINESS;
;SEEDS,9987654321(1),1123456789(2);
;INIT,,.1;
NETWORK;
;
;        JOB SHOP PORTION OF NETWORK
;
      RES/WKER1(3),1,2;       3 WORKERS AT MACHINE CENTERS 1 AND 2
      RES/WKER2(3),3,4;       3 WORKERS AT MACHINE CENTERS 3 AND 4
      ENTER,1;                ENTER MACHINE CENTER 1
  MC1 AWAIT(1),ALLOC(1);      WAIT FOR MACHINE AND WORKER
   Q5 QUE(5),0,0;             QUEUE FOR MACHINE, WORKER ALLOCATED
      ACT(2)/1,ATRIB(7);      PROCESS ITEM
   F1 FRE,WKER1/1;            FREE WORKER
      EVENT,2;                CALL SUBROUTINE ROUTE
      TERM;
      ENTER,2;                ENTER MACHINE CENTER 2
  MC2 AWAIT(2),ALLOC(2);
```

```
   Q6 QUE(6);
      ACT(2)/2,ATRIB(7);
   F2 FRE,WKER1/1;
      EVENT,2;
      TERM;
      ENTER,3;                ENTER MACHINE CENTER 3
  MC3 AWAIT(3),ALLOC(3);
   Q7 QUE(7);
      ACT(2)/3,ATRIB(7);
   F3 FRE,WKER2/1;
      EVENT,2;
      TERM;
      ENTER,4;                ENTER MACHINE CENTER 4
  MC4 AWAIT(4),ALLOC(4);
   Q8 QUE(8);
      ACT(2)/4,ATRIB(7);
   F4 FRE,WKER2/1;
      EVENT,2;
      TERM;
;
;        ASSEMBLY PORTION OF NETWORK
;
      ENTER,12;                         ASSEMBLE 2 COMPONENTS
      GOON,1;
      ACT,,ATRIB(6).EQ.1.,AA;           SEPARATE BY COMPONENT NUMBER
      ACT,,ATRIB(6).EQ.2.,BB;
   AA QUE(16),,,,MAT2;
   BB QUE(17),,,,MAT2;
 MAT2 MATCH,11,AA/ASM2,BB/ASM2;         MATCH BY PARENT ITEM
 ASM2 ACC,2,2,LOW(8);
      ACT,,,ROUT;
      ENTER,13;                         ASSEMBLE 3 COMPONENTS
      GOON,1;
      ACT,,ATRIB(6).EQ.1.,CC;
      ACT,,ATRIB(6).EQ.2.,DD;
      ACT,,ATRIB(6).EQ.3.,EE;
   CC QUE(18),,,,MAT3;
   DD QUE(19),,,,MAT3;
   EE QUE(20),,,,MAT3;
 MAT3 MATCH,11,CC/ASM3,DD/ASM3,EE/ASM3;
 ASM3 ACC,3,3,LOW(8);
      ACT,,,ROUT;
      ENTER,14;                         ASSEMBLE 4 COMPONENTS
      GOON,1;
      ACT,,ATRIB(6).EQ.1.,FF;
      ACT,,ATRIB(6).EQ.2.,GG;
      ACT,,ATRIB(6).EQ.3.,HH;
      ACT,,ATRIB(6).EQ.4.,II;
   FF QUE(21),,,,MAT4;
   GG QUE(22),,,,MAT4;
   HH QUE(23),,,,MAT4;
   II QUE(24),,,,MAT4;
 MAT4 MATCH,11,FF/ASM4,GG/ASM4,HH/ASM4,II/ASM4;
 ASM4 ACC,4,4,LOW(8);
      ACT,,,ROUT;
```

```
      ENTER,15;                           ASSEMBLE 5 COMPONENTS
      GOON,1;
      ACT,,ATRIB(6).EQ.1.,JJ;
      ACT,,ATRIB(6).EQ.2.,KK;
      ACT,,ATRIB(6).EQ.3.,LL;
      ACT,,ATRIB(6).EQ.4.,MM;
      ACT,,ATRIB(6).EQ.5.,NN;
   JJ QUE(25),,,,MAT5;
   KK QUE(26),,,,MAT5;
   LL QUE(27),,,,MAT5;
   MM QUE(28),,,,MAT5;
   NN QUE(29),,,,MAT5;
 MAT5 MATCH,11,JJ/ASM5,KK/ASM5,LL/ASM5,MM/ASM5,NN/ASM5;
 ASM5 ACC,5,5,LOW(8);
 ROUT COLCT,INT(8),ASSEMBLY DELAY;     COLLECT ASSEMBLY DELAY STATISTICS
      EVENT,2;                            CALL SUBROUTINE ROUTE
      TERM;
      ENDNETWORK;
;MONTR,SUMRY,100.,100.;
;MONTR,TRACE,0.,1.,1,4,5,3,8;
FIN;
/*
//
```

The vita has been removed from
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