DETERMINATION OF APPROPRIATE DYNAMIC SLACK SEQUENCING RULES FOR AN INDUSTRIAL FLOW SHOP VIA DISCRETE SIMULATION

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ABSTRACT

This paper presents an application of combined discrete and network simulation modelling to determine and validate an appropriate sequencing technique for a modified flow shop. The research was based upon a study of a modified flow shop at the International Business Machines, Federal Systems Division (IBM/FSD), Manassas, Virginia, manufacturing Facility. The company's concerns were directed towards enhancing the real-time scheduling of a man and machine dependent flow shop where meeting customer due dates was vital. In this manufacturing facility it is necessary to rework all parts that do not initially meet stringent quality control specifications until those parts do meet those quality limits. Therefore another reason for analyzing different sequencing rules was the necessity to better control the rework activity.

The sequencing technique currently used at this facility is based on Earliest Due Date scheduling. With the cooperation of the production control organization at IBM/FSD, Manassas, a simulation study was performed in order to determine if an enhancement to the current system could be found. The objective of the research was to determine which due date based sequencing technique would best meet the overriding production control criteria of the IBM/FSD flow shop. The company's production control objectives were to minimize number of tardy jobs, total amount of job tardiness, and total amount of in-process inventory.

The flow shop was modelled using SLAM simulation language. The flow shop was both machine and man dependent requiring both entities to be modelled. A time-consuming task encountered in the development of this model, and with the development of many other simulation models which attempt to represent real world systems, was the task of obtaining data in the proper format to analytically determine the control parameters for the model. This paper presents and discusses some of the difficulties encountered with the data interpretation.

Also included in the paper is a discussion of the due date based sequencing techniques studied and the usefulness of simulation to determine and validate the appropriate sequencing technique.

Proceedings of the 1982
Winter Simulation Conference
Highland * Chao * Madrigal, Editors

82CH1844-0/82/0000-0223 $00.75 © 1982 IEEE

INTRODUCTION

Effective control of production operations in a job shop or a flow shop has long been one of manufacturing management's most difficult tasks. Typically the control of production operations is guided by one or more basic management performance measure critieria. While all critieria are usually based on economic concerns, these criteria can be partitioned into the following categories:

1. Minimize in-process inventory.
2. Maximize the number of completed jobs.
3. Maximize productivity per job.
4. Meet customer due date.

It is the fourth performance measure criterion which guides many companies. For many companies missed due dates result in lost customers, lost sales, and heavy financial penalties. Therefore, the timely completion of jobs on or before the given due dates is a primary concern to many companies.

The timely completion of jobs is accomplished by performing two major production control tasks. The first, or macro-level task, is typically termed system loading. The system loading task consists of long-term balancing of the aggregate backlog of work and the available manpower and machine resources. This balance is performed to maintain uniform levels of machine and manpower utilization, queue lengths, and completed jobs. This macro-level task is classically posed as one of balancing the cost of missing job due dates and the cost of carrying in-process inventory versus the cost of having idle machines and manpower.

The second, or micro-level task, is the daily or hourly control of the facility. This micro-level control task consists of the sequencing of all jobs in every machine in the facility. In addition, if the facility is manpower dependent, the sequencing must be extended to encompass the control of the appropriate manpower. The sequencing of jobs or manpower is typically driven by a single performance measure. In many instances this measure is inappropriate or inaccurate thereby making the sequence ineffective. Conversely, if the sequencing technique is inappropriate, there will be an adverse effect on the performance measure criterion.

Therefore at the micro-level it is necessary to analyze the basic sequencing task and the associated performance measures. While it would be ideal, on the one hand, to analyze each possible sequencing technique in a real world environment, it is wholly impractical. On the other hand, digital simulation provides a mechanism to analyze numerous sequencing techniques and determine which technique is the most appropriate.

This paper presents an analysis through simulation modelling of several sequencing techniques and their effect on several performance measures based on the desire of the International Business Machines Corporation, Federal Systems Division (IBM/FSD), to enhance the real-time scheduling control system of its Manassas, Virginia manufacturing facility. One of the responsibilities of IBM/FSD's manufacturing facility at Manassas is the final manufacturing, testing and assembly of electronic printed circuit board based equipment. The vast majority of the electronic printed circuit boards flowing through the facility follow a single path. Because of this flow the facility resembles a flow shop. It should be noted that because some circuit boards initially fail the stringent quality control tests, rework and retesting is necessary. Therefore there is some backward flow in the facility resulting in a modified flowshop.

Included in the paper is a statement of the objective of the research, history of sequencing simulation studies, specific IBM/FSD modified flow shop under consideration, the sequencing techniques investigated, the simulation model, the task of data collection for the model, the usefulness of simulation, and the specific results of the simulation analysis which includes the validation of the model.

RESEARCH OBJECTIVE

The objective of the research was to determine and validate a sequencing technique for the IBM/FSD flow shop that would attempt to minimize the following performance measures: number of tardy jobs, total tardiness of all jobs exiting the system, and total amount of in-process inventory. A job is defined as being tardy when the job was completed after the intended due date (intended completion date). Total tardiness is the sum over all tardy jobs of the difference in time between the due date and the completion date. In-process inventory consists of jobs partially completed and queued in the flow shop waiting for process completion. It should be noted that most sequencing techniques cannot minimize more than one performance measure simultaneously. But in this specific industrial situation it was necessary to attempt to minimize all three performance measures, realizing that there would be some compromises.

Because the research was based on a real world system, the solution techniques developed had to be industrially implementable and had to be realistically employed in a real-time environment. Therefore, the sequencing techniques developed and tested were heuristic in nature. Because the objective was to minimize the number of jobs tardy, total tardiness and in-process inventory, both static and dynamic due date sequencing heuristics were studied.

SEQUENCING THE FLOW SHOP

To sequence a number of jobs through a flow shop, it is necessary to determine an order of precedence among the jobs. In other words, priorities must be assigned to the jobs according to a sequencing rule deemed appropriate by the production management. Gere [8] defines a sequencing rule or priority function as a technique which assigns to each waiting job a scalar value, the minimum of which, among jobs waiting at a machine, determines the job to be selected over all others for scheduling.

In the past twenty years, there has been substantial research into the area of sequencing rules and their effect on job tardiness and in-process inventory. Most of this research has been through the use of digital simulation, testing combinations of different sequencing rules, different methods of assigning due dates, and different performance measure criteria. The simulation tool has proven quite valuable in this regard, and has become more effective as computing hardware and software have become more sophisticated. It should be noted, however, that few if any simulations attempt to exactly model a real world system because: (1) collection of the data in the proper format necessary for the modelling is a difficult and time consuming task, (2) the intricacies and interactions found in a complex manufacturing environment result in a very extensive model, and (3) it is very difficult to percieve or determine the informal control found in any real world system. Inherent to the majority of simulation studies that test the effect of sequencing rules in flow shop or job shop environments are the following primary assumptions:

1. No machine may process more than one operation at a time.
2. Each operation, once started, must be performed to completion (no preemption.
3. Each job, once started, must be performed to completion (no order cancellations).
4. No lot-splitting or lot-joining is allowed.
5. Known operation times are determined from classical statistical distributions.
6. Jobs are independent.
7. In-process inventory is allowed.
8. No machine failures are allowed.
9. Material handling and set-up times are included in processing times.
10. Due dates are known and fixed.

11. The job routing is given and no alternative routings are permitted.

These primary assumptions facilitate the simulation process and therefore are common to most of the simulation research to date. However, there is simulation software available today which allows for preemptive priorities, machine breakdowns and the possibility of alternative routings as well as other features which require fewer general assumptions for the simulation process. Assumption number ten states that due dates are known and fixed. This is a simple statement which masks the difficult problem of assigning due dates which are reasonable and attainable. Due dates, according to Conway [3], can be assigned proportional to the processing time of a job, proportional to the number of operations of a job, in a random manner, or by using a constant independent lead time. Each assignment scheme has benefits and shortcomings based upon the performance measure on which it is judged.

Once one, or several, due date assignment methods have been chosen for the simulation study, it is necessary to choose performance measures upon which to judge the effectiveness of the sequencing rules to be studied. Concurrent with the performance measure decision is the decision as to which sequencing rules to study. Conway, Johnson, and Maxwell [4] classified sequencing rules into four categories:

1. Lateness rules - rules that determine priority according to some increasing function of lateness.
2. Arrival order rules - rules that assign priority according to the order in which jobs arrive at the machine under consideration.
3. Property rules - rules that determine priority according to some property of the job itself.
4. Random rules - rules which assign priorities at random.

Measures of shop performance include:

1. Job tardiness with respect to due dates.
2. Percent of jobs tardy with respect to due dates.
3. In-process inventory.
4. Flowtime.
5. Machine utilization.

Of course, none of the lists presented is exhaustive, but they merely represent the common thread of sequencing rule simulations in the recent past.

MODIFIED FLOW SHOP UNDER CONSIDERATION

The IBM/FSD flow shop under consideration is characterized by a fixed product mix of multilayered electronic printed circuit boards or pages built to satisfy four major government contracts. The pages flow through four functionally grouped work centers and may also flow through a fifth work center if any repair work is necessary. Figure 1 presents a schematic of the flow of pages through the manufacturing facility. The five work centers are located in physically adjacent areas. There are approximately 1000-2000 pages in in-process inventory at any one time, with a page recieving an average of six operations including rework before the page is considered completed. The operation times range from thirty minutes to nine hours for different types of pages. Each page of a specific contract follows a similar routing unique to its contract specifications. Though different contract pages may follow different routings, the pages travel to common work centers at which operations are performed that are unique to a specific page. In other words, each work center is capable of setting up and performing unique operations on different contract pages. The work centers are manned by an average of six employees per shift. At this manpower level, the average time required for a page to be completed is three to four weeks.

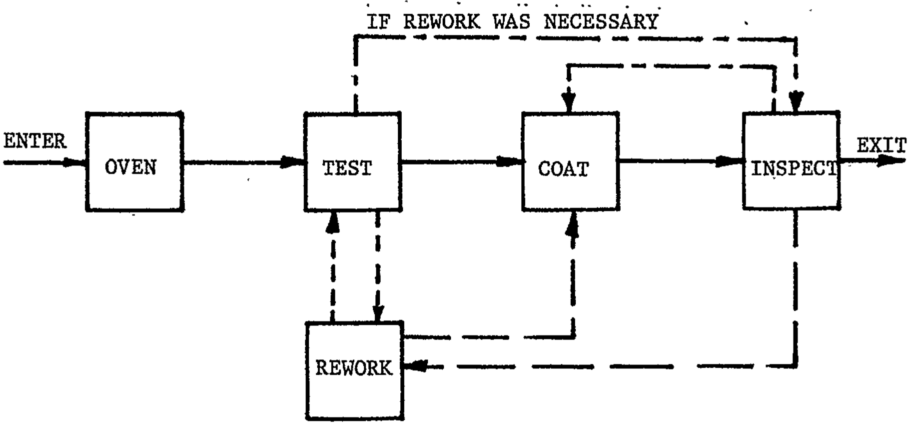

FIGURE 1: SCHEMATIC OF PAGE FLOW THROUGH WORK CENTERS

Currently, a due date for a page is set by the production control management proportional to the sum of the processing times for the necessary operations to complete the page and in accordance with the customer delivery date.

The sequencing technique currently used is based on earliest due date. However, in many cases due to work center employee concern to get the pages through the work centers in the most expedient manner, the sequencing technique has taken on a random influence. In most cases, the employees' desire to perform their jobs well and complete the pages by the due dates has resulted in an acceptable sequencing control system. However, because there are other known sequencing rules available, IBM/FSD decided to investigate the possibility of employing a different sequencing rule.

With the knowledge that there are other sequencing techniques available which could possibly enhance the current system, IBM/FSD provided the data for the simulation model and analysis. Sequencing techniques using due date and processing time data were investigated to determine if a more appropriate sequencing technique was available for the flow shop. Simulation of the real-world system provides the ability to determine which sequencing technique whether the current system or a new technique - is most appropriate without disrupting production or prolonging the analysis phase.

SEQUENCING RULES TO BE INVESTIGATED

The simulation model and the subsequent analysis were performed to analyze a set of sequencing rules to determine which sequencing rule provided the best performance. According to Gere [8], it is reasonable to expect that effective sequencing rules will take into account due dates or processing times or both. In other words, it follows that a good sequencing rule relates explicitly to the available data, where the data involves job routings, operation times, and machine loads. It should be noted that rules which ignore the available data, such as a random rule, do not in general produce a schedule that results in acceptable levels for the performance measures. Furthermore, since each operation is another opportunity for delay as the job waits in queue, the number of operations appears relevant.

Gere, in his 1966 study of heuristics for job shop scheduling, considered job shops with 4 to 6 machines and with 6 to 60 jobs, where each job had one to 16 operations. Operation times were generated rectangularly, with one to 10 hours per operation. The sequencing rules studied included:

1. Job SLACK: Present time minus due date minus remaining processing time.
2. Job SLACK per Operation: Job SLACK divided by remaining number of operations.
3. Job SLACK Ratio: Job SLACK hours divided by hours remaining until the due date.
4. "Modified" job SLACK ratio: Job SLACK Ratio plus expected delay time.
5. Length of next operation (SI): Shortest imminent operation time.
6. SI/Job SLACK Ratio: Length of next operation integrated with job SLACK ratio.
7. FCFS: First come, first served.
8. Random: Jobs sequenced in random order.

The results of Gere's research indicated that if the system under investigation is real world in nature with the performance measure being job tardiness, the selection of a sequencing rule based simply on processing time is not as effective as a sequencing rule that utilizes processing time plus a look-ahead heuristic.

Conway [3], in 1965, used simulation to test the effects on a job shop for several combinations of due date assignment procedures and priority rules. Four methods of assigning due dates were used: TWK due date, allowable shop time proportional to the sum of the processing times of the operations of a job; NOP due date, allowable shop time proportional to the number of operations of a job; and CON due date, a fixed, constant amount of allowable shop time; RDR due date, allowable shop time assigned at random. The simulation modelled a job shop with nine single machine centers and 8700 jobs. The initial simulation emphasized the use of TWK due dates in studying several due date based sequencing rules. The final simulation used TWK due dates exclusively and investigated four sequencing rules which Conway had determined were in fairly common use in industry where job lateness was an important concern.

1. Earliest due date
2. Job SLACK
3. Operation due date: Allowable shop time divided equally among the operations of a job to obtain a due date for each operation.
4. Job SLACK per operation.

Conway's investigation chose the rule which selects the job with the least SLACK per operation remaining. SLACK per operation remaining is the most complicated of the observed due date rules, but the one which exhibits the smallest value of tardiness variance and the smallest proportion of tardy jobs.

Similar techniques to those of Gere and Conway were used by Miyazaki [10] in his 1981 Monte Carlo simulation of hypothetical job shops using an average of 5.7 machines and 4500 jobs. Miyazaki added two additional sequencing rules in his study: minimum ratio of current allowable time to operations remaining and minimum ratio of the current SLACK time to the remaining allowable time. His investigation showed that SLACK per operation and allowable shop time per operation were the most effective sequencing rules.

For the IBM/FSD flow shop the following sequencing rules were chosen for investigation:

1. First come - first served (FCFS) : preference given to job which arrived at queue first.
2. Earliest due date (EDD) : jobs given preference based on earliest due date.
3. SLACK: preference given to the job with the least time remaining to due date after deducting the remaining processing time.

4. SLACK/RPT: slack divided by the remaining processing time where preference is given to the job with the smallest ratio.

5. SLACK/RNO: slack divided by the number of operations remaining where preference is given to the job with the smallest ratio.

6. Operation due date (OPNDD): allowable remaining shop time divided equally among the remaining operations of the job to obtain a due date for each operation. Precedence in a particular queue given to the job with the earliest operation due date.

It is interesting to note some of the finer points of these sequencing rules. The FCFS rule is straight forward to implement and is included in the study primarily for comparison between a due date and a non-due date based sequencing rule. The FCFS rule is not believed to be much better than a random rule in reducing tardiness or in-process inventory because a job is given priority based solely on its arrival time to the queue while available data on due dates and processing times are not considered.

EDD sequencing has been shown to minimize maximum job tardiness. When the EDD sequencing provides either one or no tardy jobs, EDD also minimizes the number of tardy jobs and the mean tardiness of all jobs. However when scheduling a flow shop or job shop, EDD sequencing does not appear tp guarantee the minimum number of tardy jobs, the minimum mean tardiness nor the minimum maximum job tardiness. Edd was included in the analysis to model the control system now in use and to provide a baseline for comparison purposes.

Both the SLACK/RPT rule and the SLACK/RNO rule have an interesting dynamic nature. Bulkin, Colley, and Steinhoff [2] in 1966 implemented the SLACK/RNO rule in sequencing jobs in the El Sequndo Division of Hughes Aircraft Company, a job shop in which there were from 2000 to 3000 orders in in-process inventory at any one time. The dynamic nature of SLACK/RNO and also of the SLACK/RPT rule was noted as follows, ". . . when the SLACK time for two orders are positive and equal, the one having more operations remaining (or more processing time remaining) will have higher priority. The converse is true when the SLACK times are negative and equal." Therefore the order with the lesser amount of remaining processing time or fewer number of operations will have higher priority. These rules actually expedite orders once the SLACK times become negative. Similarly, the last rule investigated, the OPNDD rule, exhibits the above mentioned dynamic property whereby once the time remaining until due date becomes negative, orders are expedited.

In a real world system, it would be virtually impossible to perform an investigation involving all or as many sequencing rules as listed here. First, the results on production of trying any one rule could be disastrous when customer contract due dates must be met. Also, for the effectiveness of a set of sequencing rules to be determined, they must be employed for several production cycles with in a complete investigation taking several years. Lastly, because the real world conditions never exactly repeat overtime, it is totally impossible to perform an accurate comparison. Therefore, simulation modelling provides a basis for the investigation of several applicable sequencing rules to be performed quickly and easily. Intuitively, the last four rules should enhance the current IBM/FSD control system and improve productivity. Specifically, the simulation will provide statistics on each rule's effectiveness of reducing number of tardy jobs, average job tardiness, and total amount of work in-process inventory. Comparing these statistics will lead to the decision of which sequencing technique to implement in the shop, if these statistics show a new sequencing rule will enhance the current control system.

PRESENTATION OF SIMULATION MODEL

The IBM/FSD manufacturing facility was modelled using SLAM® simulation language. SLAM was chosen becuase the authors wished to model the flow shop as a network. A network approach was taken because the flow of the pages through the five work centers indicated a limited number of flow paths. However, the capability of using discrete logic to update and assign the various sequencing rules to be tested was also needed. Most network languages do not allow for involved computations within the network and allow only limited forms of sequencing techniques within the service queue files. Therefore, discrete capability was indicated. SLAM allows for combined network and discrete modelling and was used as the basis for the model.

Figure 2 indicates the detail included in the simulation model. Although this detail is uncommon in most simulation studies of sequencing rules, the authors felt the detail was necesesary to model the real world flow shop and fully represent the intricate interactions of the system.

In general, the body of the simulation program is network logic, modelling the flow of pages from one work center to another as entities flowing from one queue node to another. The discrete logic of the program represents the calculation and updating of the sequencing rules to be used at service activity queues. Also included in the discrete logic is the capability of tracking the entity travel through the network, indicating for example if a page in the rework area is in queue because of failing a quality test or because of failing a final inspection.

The first level of detail modelled in the network is that of the different shift occurences at the IBM/FSD facility. The facility operates with three eight hour shifts, but not all work centers operate for all three shifts. This condition is modelled in the network with gates opening and closing in eight or sixteen hour intervals. These gates indicate the shift schedules in conjunction with await files placed in the network before each service activity, thereby allowing for service to be performed only during the appropriate shifts. The shifts operations are:

AREA	SHIFT
Shipping and Receiving Dock	1st shift
Test: Contract Part Type 1,2	1st and 2nd shifts
Contract Part Type 3,4	2nd and 3rd shifts
Inspection	1st and 2nd shifts
Rework	1st and 2nd shifts
Coat	1st and 2nd shifts

The arrival of the pages was modelled as occurring in specific time intervals with the pages only admitted into the system during the equivalent eight hour first shift. This arrival pattern models the real world batch arrival of pages. All processing times in the network include appropriate set-up times. The processing times are defined as deterministic averages which were determined from the management records of the various manufacturing departments. No material handling times are included due to the adjacency of work centers and the relatively inconsequential travel times between departments. The four different contract page types were modelled as percentages of all entities arriving to the system based on production contract requirements for the 1982-1983 calendar years. Specialty pages within contract types were broken out as separate percentages of those contract types.

An important aspect of the simulation network is the inclusion of both man and machine dependent service activities. For instance, the inspection activity is solely manpower dependent, i.e. an employee must be available to inspect the page. The test area is solely machine dependent because a test machine is required to test a page, and because an employee is always available to run the test machine. The coat area is both man and machine dependent. Some coat activities require manpower resources, and some coat activities require only machine resources. Another special consideration in the coat area is the need to accumulate twenty pages before a spray activity can occur. This was modelled with the use of a gate and an await node.

Finally, the simulation model contains the ability to track the number of times a page fails in test and accordingly assign variable test times and different quality rejection percentages to pages which have been reworked once, twice, three times, or more. This inclusion more accurately reflects the real world system and allows for better model validation.

COLLECTION OF DATA

Collection of data to determine the control parameters for a real world simulation is a major task. More often than not the data collected on a daily basis in a manufacturing facility in , log books (although in proper form for purposes of the effective daily control of the facility) is not in suitable form for direct implementation into a simulation model.

Quite often the available data must be sorted or manipulated to provide the model with the necessary control parameters. As an example, in this simulation model the probability of a page requiring rework was modelled by probabilistic conditional branching from the appropriate test or inspection node. The probability parameters were obtained from the log books where percentages of past jobs passing or not passing a test or inspection were available. It should be noted that the historic data only provided a sample from which a percentage was determined. The percentage was then used as the probability of a page passing or not passing a test, or inspection for the entire population.

Sorting of availalbe data for the simulation model is a very time consuming task. Approximately seventy manhours were required to sort log book data to obtain probabilities for only one test activity. Similar time consuming tasks were performed for all page types for all activities. Fortunately, a considerable amount of the data had been presorted before the simulation study was undertaken by the IBM production engineers. In general, it should not be assumed that the data is available in the appropriate form for a simulation model and time for data collection should be allotted.

The determination and collection of correct processing times can quite often be taken from routing sheets, especially when the process is machine dependent and there is a deterministic job processing time on the machine. In the simulation model all processing times were modelled as deterministic times, although in reality this may not be valid. Job processing times on machines are quite justifiably deterministic, but manual tasks would perhaps be better modelled with a probabilistic distribution. Again the problem is one of collecting the data, in this instance of man dependent processing times so that a distribution can be plotted and fitted to the real world times. This was not done for the initial simulation. Rather, average processing times were used deterministically to represent the man dependent processing times. An extension to the model would include the collection of the data necessary for this distribution.

The discrepancy between using deterministic versus probabilistic processing times leads to the question of model validation. Bulkin et al. [2] who investigated a real life job shop scheduling situation, believe that it is impossible to obtain complete agreement between simulated and actual systems even if the model performance capabilities and its capacities are kept identical to the real world system. Conway [3] suggests that, although complete validity is not attainable, assurance of the model can be established by, ". . . a demonstration that for at least one alternative version, the simulator produces results that are not inconsistent with the known performance of the actual system." Model validation of the IBM/FSD flow shop was considered and is discussed in the results and conclusion section.

USEFULNESS OF SIMULATION

The primary objective of the simulation model is to determine the most effective sequencing technique for the IBM/FSD flow shop without having to disrupt production or utilize several sequencing rules over several years. The most effective sequencing rule to be chosen is the one which gives the minimal or the most acceptable number of tardy jobs, total tardiness, and total amount of in-process inventory. This is not the only application of a simulation model. Effective use of job shop or flow shop simulation, according to Day [4], will help management in the following ways:

1. Establish more realistic scheduling times.
2. Establish more realistic order schedules.
3. Forecast shop load.
4. Plan equipment layout.
5. Test various sets of operating decisions.

The IBM simulation model can be used to forecast the effects of adding new production pages to the area. Other uses could include the forecasting of the effects of new test facilities , additional shift production capability, and possible subcontracting of bottleneck work. Analysis such as this can lead to more effective resource planning. Another significant use of the simulation model could involve the interaction of the simulation model with a data base for job routings and processing times. As with the Bulkin simulation of a real world shop, it is conceivable that simulated dispatch reports could be provided on a daily basis to the manufacturing facility employing the most appropriate sequencing rule. Through interaction with the data base, the simulation model could compute SLACK times and other necessary information and prioritize the daily dispatch reports with little or no programmer interaction necessary.

The possibilities are considerable for using simulation in a planning capacity. Once an accurate model is developed, it can serve to answer almost any question concerning the effects of a change to the manufacturing facility.

RESULTS AND CONCLUSIONS

The simulation analysis of sequencing techniques which is presented and discussed in this paper was based on the plan of International Business Machines Corporation, Federal Systems Division to enhance the production control system in use at the Manassas, Virginia, manufacturing facility. The system currently in place sequences based on earliest due date with the employees of the respective work centers expediting jobs when necessary. The simulation model of the flow shop was developed to determine if a more appropriate sequencing technique existed.

Six sequencing techniques were investigated including earliest due date. Earliest due date was included in the analysis to reflect the current production control system and provide a baseline for comparing the other five sequencing rules. The performance measures employed were total number of tardy jobs, total amount of job tardiness, and total amount of in-process inventory. These measures are presented as ratios of the baseline sequencing technique, earliest due date.

The validity of the simulation model was established by comparing the results of the EDD simulation run with actual production figures over a four month period. Comparison of average cycle processing times through the flow shop, average failure rates through selected test activities, average number of tardy jobs, and average queue lengths for various service activities showed the simulation to be approximately 90% accurate. As mentioned previously, although complete validation of a simulation model of a real world system is not attainable, a demonstration that the model is not inconsistent with the actual system provides the necessary assurance.

The following table presents the results of the simulation analysis. The figures are based on assigning the earliest due date results a norm of one and dividing each of the sequencing techniques' results by the EDD results to obtain a relative improvement index. For example, if EDD sequencing produced 50 tardy jobs and SLACK sequencing produced 23 tardy jobs, EDD index = 1.0, SLACK index = 23/50 = 0.46. The results are based on the simulation of 8640 jobs with one run per sequencing technique. Multiple simulation runs were not necessary because the simulation was entirely deterministic and did not exhibit any random influence.

SEQUENCING RULES	TOTAL NUMBER OF TARDY JOBS	TOTAL JOB TARDINESS	IN-PROCESS INVENTORY	CYCLE TIME
FIFO	1.24	.61	.84	.73
EDD	1.00	1.00	1.00	1.00
SLACK	.24	.08	1.00	.24
SLACK/RPT	.22	.09	0.99	.26
SLACK/RNO	.22	.09	0.98	.26
OPNDD	1.20	.66	.87	.76

From the results, the three sequencing techniques SLACK, SLACK/RPT, and SLACK/RNO show a marked improvement over EDD sequencing based on total number of jobs tardy, and total tardiness. The three rules are comparable to EDD in their effects on in-process inventory. Comparing SLACK, SLACK/RPT, and SLACK/RNO; SLACK has the lowest coefficient of variance based on cycle time through the flow shop. Also, of the three techniques, SLACK is the most straight forward to implement, requiring less calculations, as well as providing a more intuitively understandable priority index. SLACK represents the amount of buffer time a job has before it becomes tardy thus the priority index represents an understandable concept.

Based on these results, the SLACK sequencing technique does enhance the current EDD control system and does exhibit a superiority over the other sequencing rules tested. In general, the three dynamic slack techniques exhibited superiority over the FIFO or non-due based sequencing technique, with

SLACK being the superior of the three. It has been recommended that the IBM/FSD flow shop implement an enhancement of the current production control system using the SLACK sequencing rules.

In conclusion, the authors would like to thank the International Business Machines Corporation for its cooperation in this research endeavor.

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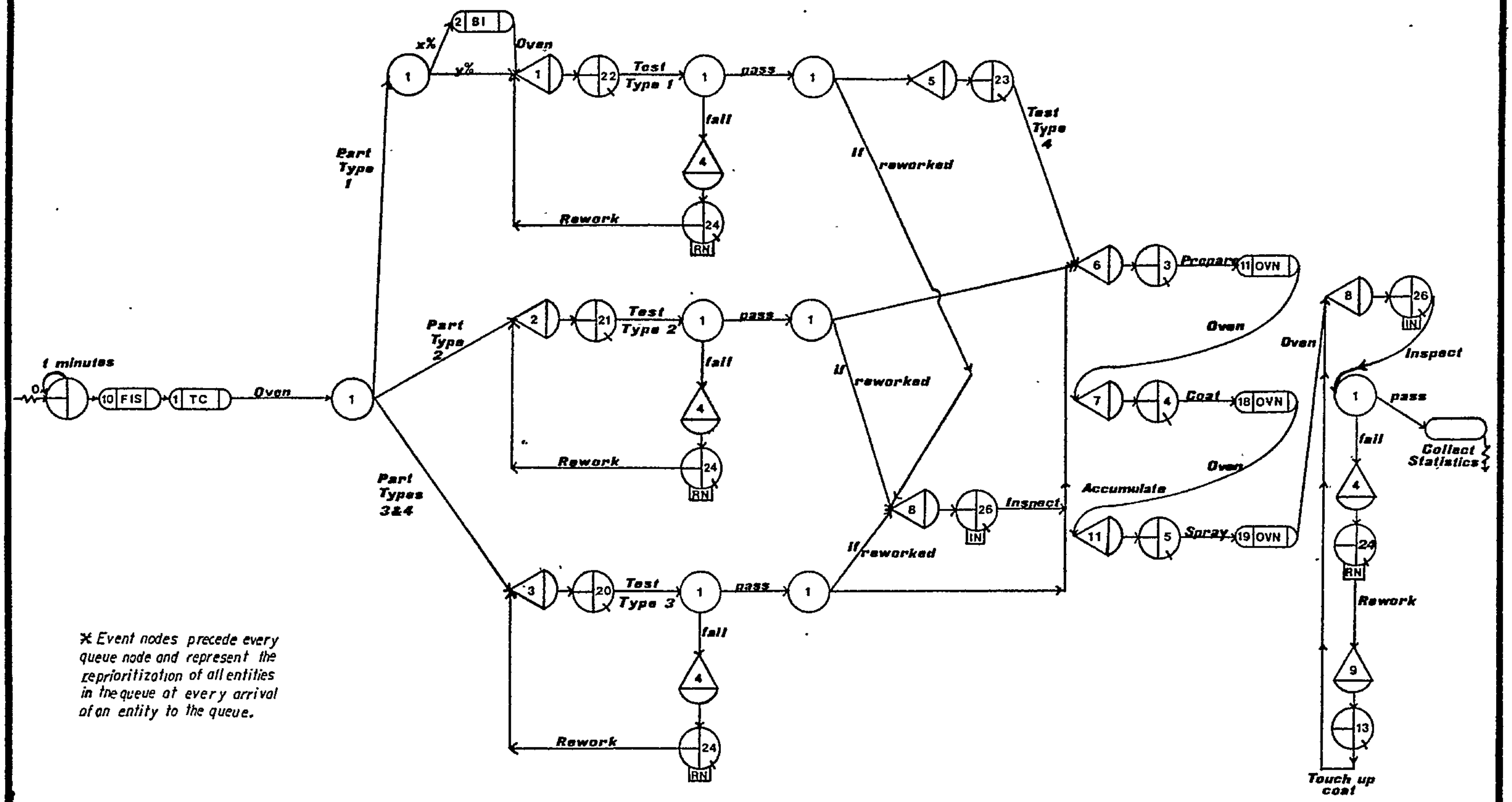

✕ Event nodes precede every queue node and represent the reprioritization of all entities in the queue at every arrival of an entity to the queue.

Arrival | Heat Treatment

Entities (pages) arrive to the system at a fixed arrival rate and are admitted to the system during the equivalent first eight hour shift. All entities travel to the first activity, Heat Treatment, where the activity is monitored by a gate. The gate depicts the occurrence of pages waiting in queue until the previous treatment cycle is complete and the oven is readied for the next batch of pages. After completing this treatment, a percentage of Type I entities travel additionally to an identical heat activity. In both heat treatment activities, there is no restriction on the number of entities which can be processed simultaneously.

Test

The next activity for all entities is a test activity. All entities if they fail their respective tests must be reworked. The probability of failure through the individual tests is unique to each test and is different based on the number of times previously tested and reworked. It is essential to note here that the queue for rework is the same for all tests and final inspection. There is only one queue and one activity for rework, although four queues in total are depicted. Once the entity passes its test, if rework was necessary, it goes through an inspection activity and then to coat. (If the entity is Type I, it travels first to another test then to coat.) If rework was not necessary, the entity passes directly to the coat activity.

Coat

The coat activity consists of several machine and man dependent activities. First, the entity travels through a man dependent activity for purposes of preparing the entity for subsequent processing. Secondly, the entity encounters an oven (machine dependent) activity. Next, it goes through a manual coating activity followed by another oven activity. At this point, the entities are accumulated until a batch of twenty is available for spraying. Finally, the entity travels to a third oven activity and subsequently to the final inspection activity.

Final Inspection | Collect Statistics

The final activity is the final inspection activity. If the entity passes its inspection, it is routed to a set of collect nodes where statistics are collected on time in the system, number of tardy entities, and the total amount of tardiness. If the entity fails in inspection, it must be reworked, routed through a touch up coat activity, then reinspected.

FIGURE 2: BASIC SCHEMATIC OF SIMULATION MODEL