Mansoura Engineering Journal, Vol.19, No.3, September, 1994 M.41

A SLAM II NETWORK MODELING TO PREDICT JOB SYSTEM TIMES IN A JOB SHOP FOR SETTING JOB DELIVERY DATES UNDER EXTERNALLY IMPOSED REQUIREMENTS

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استخدام شبكات لغة المحاكاة SLAM II في تقدير اوقات انتاج المشغولات في ورشة انتاجية بهدف تحديد مواعيد تسليمها وحسب متطلبات خارجية

خلاصة

يقدم هذه الدراسة أسلوبا لتمثيل الورش الانتاجية كنماذج شبكات بواسطة استخدام نسخة الحاسوب الشخصي للغة المحاكاة SLAM II لغرض التنبؤ بالوقت اللازم لانتاج المشغولات في الورش من أجل تحديد مواعيد تسليمها . أن تحديد موعد تسليم المشغولة من قبل جهة خارجية دون أي اعتبار للمتطلبات الزمنية لتشغيلها ولمدى اكتظاظ الورشة ولسياسات التشغيل فيها ، يشكل تحديا لادارة الورشة لتسليم المشغولة في الموعد المحدد . وغالبا ما يحدث هذا في حالة تقديم المناقصات على العروض المقدمة من الزبائن لطلبات التشغيل . كما ويبين البحث توضيحا وافيا لهذا الاسلوب عن طريق بناء شبكة نموذج محاكاة لورشة انتاجية ، وكيفية الاستفادة من تحليل نتاج محاكاة هذا النموذج من قبل ادارة الورشة في تقدير الوقت اللازم لانهاء تشغيل المشغولات فيها ، واستخدامه في تحديد مواعيد التسليم للمشغولات الجديدة ومراجعة مواعيد التسليم للمشغولات تحت التشغيل في ضوء الامكانات المتاحة لادارة الورشة والشروط المفروضة عليها من الخارج .

ABSTRACT

This study presents a network modeling methodology for tackling the problem of enforcing job delivery dates which are set by an external agency, and without regard to the job processing characteristics and the shop status or the priority rule to be used. In a job shop having multiple jobs with multiple routings and unique machine processing times for each job, etc., it becomes virtually impossible to apply analytical approaches to solve the problem. In this paper a network modeling approach using the microsoft version of SLAM II simulation language is used for developing reasonable estimates of job system times in a job shop for the purpose of setting and/or asserting job delivery dates to meet externally imposed conditions. This approach does not only generate estimates to verify whether the suggested job delivery dates are reasonable and attainable, but also provides a model which is easily constructed, communicated to, and interpreted by all parties involved in the bidding process, i.e. job shop management and customers. Further, system time distributions are generated by simulating the model and utilized to construct confidence intervals on the mean job delivery dates, and to estimate the probabilities of meeting established delivery dates in the light of job shop management acceptable level of risk and customers' requirements. A job shop consisting of six unique machines, and a set of ten jobs; seven in process (partially completed) jobs and three incoming (in the bidding process) jobs are used to demonstrate this approach. In addition, experimentation with the network model is carried out for different scenarios of job shop operation to illustrate the usefulness of the network modeling in enabling job shop management to exercise continuous monitoring and effective controlling over the job shop operations. Thus, corrective actions can be implemented in early stages to avoid late jobs and resulting penalties and/or lost sales for the job shop, especially if the job shop produces to order under externally imposed conditions in a bidding environment.

Received 21st. March, 1994.

INTRODUCTION

The problem of job shop scheduling and control has received considerable attention in the literature. But most of the effort has dealt extensively with algorithms and heuristics for scheduling jobs and simulation studies evaluating the efficiency of various sequencing rules, namely the order in which jobs should be arranged for processing on individual machines, under various assumed conditions with the objective of optimizing job shop operation in terms of certain performance measures. Most oftenly used performance measures in the literature are: mean flow time, mean lateness, mean tardiness, and percentage of jobs completed tardy. Review papers by Panwalker et al. [12], Graves [10], Browne et al. [3], Blackstone et al. [4], and Ramasesh [17] provide an excellent reference on this subject.

The development of methods for estimating job throughput time (job system time or job flow time), being the time elapsed from the job arrival to its departure time from the shop, has relatively received less attention by job shop researchers. Reasonable estimation of job system time is, however, one of the most crucial aspects of most job shop operations. Conway et al. [5] pointed out that if one could exactly predict the system times of various jobs under a certain sequencing procedure, one could assign an allowance equal to the system time so that the completion time of each job would be exactly equal to its due date (which is the prespecified date for completion of the job, sometimes called "delivery date"). Further, it was noted that the estimation of job flow time to meet delivery dates is extremely difficult and depends not only on the individual job characteristics and the sequencing rule used, but also on the nature and status of other jobs being processed at the time the job under consideration arrives to the job shop system.

Job scheduling and sequencing can be approached from either the viewpoint of the job shop management that will process the job, or the customer placing the order for processing the job. If the job shop management point of view is taken, the objective of the schedule determination is likely to be related to the minimization of one or more cost factors. When approached from the customer viewpoint, the objective, most likely, will be related to the delivery date. Delivery dates are usually highly important in the schedule determination, especially when certain outside conditions have to be met, except perhaps when production is made to stock.

In the job scheduling literature, delivery dates are treated in one of two ways: 1) externally imposed or 2) internally determined. Externally imposed delivery dates are outside the control of the job shop management and are assumed to be determined by an order entry or marketing department in agreement with the customer placing the order. In this situation, current shop status information is not normally considered in setting the delivery dates. Research in this setting has focused on evaluating the efficiency of sequencing rules to identify those which yield good due date performance. Due date or delivery date performance is usually measured by job lateness, job tardiness, and percentage of tardy jobs. Internally determined delivery dates are established by shop system management as each job arrives to the shop. The early research in this setting did not focus explicitly on predicting individual job system times, but rather on identifying simple due date assignment heuristics which provide good due date performance in conjunction with a variety of sequencing rules. Conway [6] defines four methods of assigning due dates to arriving jobs: 1) constant (CON), delivery dates are quoted by salesman at a uniform period in the future, 2) random (RAN), due dates are established by the buyer, 3) due dates are based on job total work content (TWK), and 4) due dates are based on the number of operations (NOP). The first two methods set externally imposed due dates, while the last two methods establish internally determined due dates. In the total work content method, the due date is set to equal the arrival time of the job plus a multiple, k, of the job total processing time. While the due date set by the (NOP) method is equal to the arrival time of the job plus a multiple of the number of operations required for the job. In addition, the manner in which job characteristic information is included has been found to affect performance. For example, the multiplier used in TWK method may be varied [7, 9], or processing time may be raised to some power in a TWK-like method [8], and a combination of TWK and NOP methods may be used [1].

Moreover, researchers have considered the use of shop status information in setting due dates. Eilon and Chowdhury [8], and Weeks [19] used expected waiting times and current queue lengths to more accurately estimate job flow time. Baker and Bertrand [13] suggested using current work load in the due date assignment procedure. Ragatz and Mabert [15, 16] demonstrated a methodology to include both job characteristics and shop status information for establishing job due dates. Sawaqed [18] investigated the effect of using simulation based due date assignment procedures on the performance of sequencing rules in terms of due date related performance measures.

The forecasting of job system times is of crucial importance to shop system management for the purpose of establishing job delivery dates especially in a bidding environment. The vendor representing the job shop must know, in advance, within reasonable limits the ability of his firm to meet exogenously imposed delivery dates. The lack of such information can not only result in a weak position for the vendor in the bidding process, but can also result in substantial costs that may incur due to unmet promises, such as capital invested in finished goods and in process inventory, lateness penalties, and lost customers. Again, as pointed by Conway et al.. [5], "scheduling procedures of sufficient power to enforce a completely arbitrary set of due dates do not yet exist". Therefore, job delivery dates must be jointly established by job shop management and customers based upon customer's requirements and the job shop forecasted capacity and ability to keep up with these requirements.

The purpose of this paper is to demonstrate a network modeling methodology of a job shop, using the network builder and processor of the microsoft PC version of SLAM II simulation language (the Simulation Language for Alternative Modeling) [13, 14], for developing reasonable estimates of job system times for the purpose of setting job delivery dates that meet externally imposed conditions. These estimates of system times obtained by network modeling are not only to verify whether the suggested job delivery dates are reasonable and attainable, but also to provide a model which is easily constructed, communicated to, and interpreted by all parties involved in the bidding process, i.e. job shop management and customers. Further, system time distributions can be generated by simulating the model and be utilized by job shop management to construct confidence intervals on the mean job delivery dates, and to estimate the probabilities of meeting established delivery dates in the light of management acceptable level of risk.

The approach presented in this paper is proposed for job shops that receive three to five job orders per week, with job duration time ranging from one to eight weeks. Since job shops of this type of operation is quite common, a time period of one to two days spent in collecting data and developing a network model to obtain job system duration time estimates would be feasible. The network modeling capabilities of SLAM II simulation language, the procedures for model development, and the analysis and application of model simulation results will be demonstrated using a case example.

NETWORK MODELING PROCEDURE

Network modeling using network builder of the microsoft version of the SLAM II simulation language has been selected as the vehicle for estimating job completion times. Basically, network modeling of job shops provides a visual aid in the interpretation of the job shop system under analysis. Through network modeling, as the case when PERT (project evaluation and review technique) or CPM (critical path method) network is used for project analysis, the job shop system under consideration becomes more easier to understand and to communicate with by all participants who are concerned with the system analysis, rather than mathematical algorithms or computer models. Thus, parties involved in the bidding process do not need to have a comprehensive knowledge of a simulation language or mathematical modeling and algorithms. At the same time, at least one person must be technically proficient enough to collect data, construct and simulate the network model.

SLAM II is capable of modeling a variety of systems. Systems can be depicted using an unlimited combination of network symbols, discrete event or continuous representations. Network symbols provide a graphical framework for developing simulation models. Entities (jobs) traverse these symbols to simulate system operation. SLAM II network diagrams simplify the modeling process, and provide a graphical way to communicate the operation of the model and system to others. By using the basic seven network symbols of SLAM II, entities (jobs) by the system are created, enter queues for resources, release resources, assign values to themselves (i.e. attributes) or system variables, add to statistics, select alternative routes through the system, and exit the system. A large number of models representing a wide range of systems can be built with these symbols. Other capabilities for system modeling are also available in SLAM II, such as system variables that can be used to define the logic of the model and maintain system status, status variables to collect statistics useful for decision making, ten standard random variables with ten random number streams to allow a model to replicate the variability of the real system, and user variables which are entirely under the user control can be used in network models. In addition, SLAM II provides an interactive execution environment which helps the user to understand how a running model is behaving. It also provides output reports which include comprehensive statistics on all modeling components.

Because of the recent rapid technological development in microcomputers, their prices are drastically in decline and almost any job shop can afford to be equipped with a PC on which a microsoft version of SLAM II can be installed and utilized for system modeling and operation analysis with great deal of simplicity and practicality. The PC version of SLAM II simulation language is capable of building network models with a complete graphics capability for all network symbols, and is menu driven through microsoft Windows software application.

DESCRIPTION OF THE JOB SHOP MODELED

The job shop which was chosen contains six single processing facilities (machines). Each machine is different from any of the others and each can work on one and only one job at a time. The type of operation performed by each machine is unique, i.e. milling, drilling, turning, grinding, etc.

Once the job shop management has decided to bid on or accept through arrangement with customers a set of jobs for manufacturing, each job has first to undergo certain design and specification setting procedures in the engineering design stage. In this stage, specialists working in the engineering department of the job shop assign the proper machine sequence (job routing), machine processing times, and job number for each job. Upon completion of this stage, each job is routed to the first machine on its routing which can be any of the six available machines in the shop. However, in most cases the initial operations on jobs are typically performed by certain machines such as lathes, grinders, and surface shapers, while other machines perform intermediate and finishing operations. After the first operation is completed a job is routed to the next machine on its routing which can be any of the remaining machines, and so on until the job is completed by its last operation and then exited from the system.

It is natural that at the time of bidding on or accepting a set of jobs (incoming jobs) for production, there will be a number of jobs already exist in the system and have only partially completed their machine operation sequence. In such a situation more than one job may be waiting for processing in a machine queue, and because of the variability inherent in machine processing times, it becomes very difficult to determine which job will arrive first at a machine for processing.

Ten jobs are considered for processing in the job shop considered. Each job is identified by a job number ranging from 1 to 10. Jobs numbered 1 to 7 are considered as in process jobs (partially completed jobs), while jobs numbered 8, 9, and 10 are jobs to be introduced to the shop for processing (incoming jobs). The times (in days) to be spent by the incoming jobs; job # 8, job #9, and job #10, in the engineering design stage are drawn from a normal probability distribution using different distribution parameters for each job. These parameters are shown in Table 1. The machine processing times (in days) for each of the ten jobs are drawn from a triangular probability distribution using different distribution parameters for each job-machine combination. These parameters and job attribute numbers in which machine processing times are stored in are presented in Table 2. The job machine sequences and job transport and handling times (in days) between machines are shown in Table 3.

Job #	Normal Distribution	
	Mean	Standard deviation
8	4.0	1.0
9	6.0	1.5
10	3.0	0.5

Table 1: Parameters for engineering design stage times.

In a job shop having multiple jobs with multiple routings and unique machine processing times for each job and built-up queues at machines, etc., it becomes virtually impossible to apply analytical approaches to solve the problem. Therefore, simulation has become very appealing to researchers in tackling the job shop scheduling problem. However, due to the recent development in computer technology and the introduction of high speed, high capacity personal microcomputers, along with the advancement of microsoft simulation languages in terms of capabilities, affordable computer requirements and enhanced interactive mode, complex job shop systems can now be dealt with in a relatively more effective and productive manner. The PC version of SLAM II simulation language with its many unique and innovative capabilities now provides job shop management with an efficient and effective approach to model and simulate such systems at an affordable cost and moderate technical requirements.

Job status	Job #	Machine #	Triangular Distribution minimum	mode	maximum	Attribute # stored in
IN PROCESS JOBS	1	6	7.0	10.0	16.0	6
	2	6	5.0	8.0	14.0	6
	3	5	8.0	10.0	20.0	5
	4	4	4.0	5.0	9.0	4
		6	5.0	8.0	15.0	6
	5	3	5.0	9.0	15.0	3
	6	2	2.0	4.0	7.0	2
		3	1.0	3.0	7.0	3
	7	2	7.0	11.0	20.0	2
		4	2.0	5.0	10.0	4
INCOMING JOBS	8	1	2.0	4.0	7.0	1
		3	10.0	20.0	32.0	3
		5	6.0	9.0	16.0	5
	9	1	1.0	2.0	4.0	1
		2	3.0	9.0	15.0	2
		4	5.0	7.0	13.0	4
		5	3.0	4.0	8.0	5
	10	2	3.0	6.0	8.0	2
		4	10.0	25.0	34.0	4
		6	4.0	6.0	11.0	6

Table 2: Parameters for machine processing times.

Job status	Job #	Machine # sequence with transport and handling times shown on arrows between machine numbers
IN PROCESS JOBS	1	6
	2	6
	3	5
	4	$4 \xrightarrow{0.2} 6$
	5	3
	6	$2 \xrightarrow{0.3} 3$
	7	$2 \xrightarrow{0.2} 4$
INCOMING JOBS	8	$1 \xrightarrow{0.2} 3 \xrightarrow{0.2} 5$
	9	$1 \xrightarrow{0.3} 2 \xrightarrow{0.1} 4 \xrightarrow{0.2} 5$
	10	$2 \xrightarrow{0.3} 4 \xrightarrow{0.1} 6$

Table 3: Machine sequence with transport and handling times.

DESCRIPTION OF THE SLAM II NETWORK MODEL

The SLAM II network of the job shop considered in this paper is shown in Fig. 1. In this description network nodes will be referred to by their labels which are shown at the bottom side of each node. Observing this network, nodes CR1, CR2, CR3, CR4, CR5, CR6, CR7, CR8, CR9, and CR10 are CREAT nodes representing the introduction of the 10 jobs to the system. Nodes CR8, CR9, and CR10 are used to create the three incoming jobs, while the other CREAT nodes are used to create the 7 in process jobs. The delivery dates of

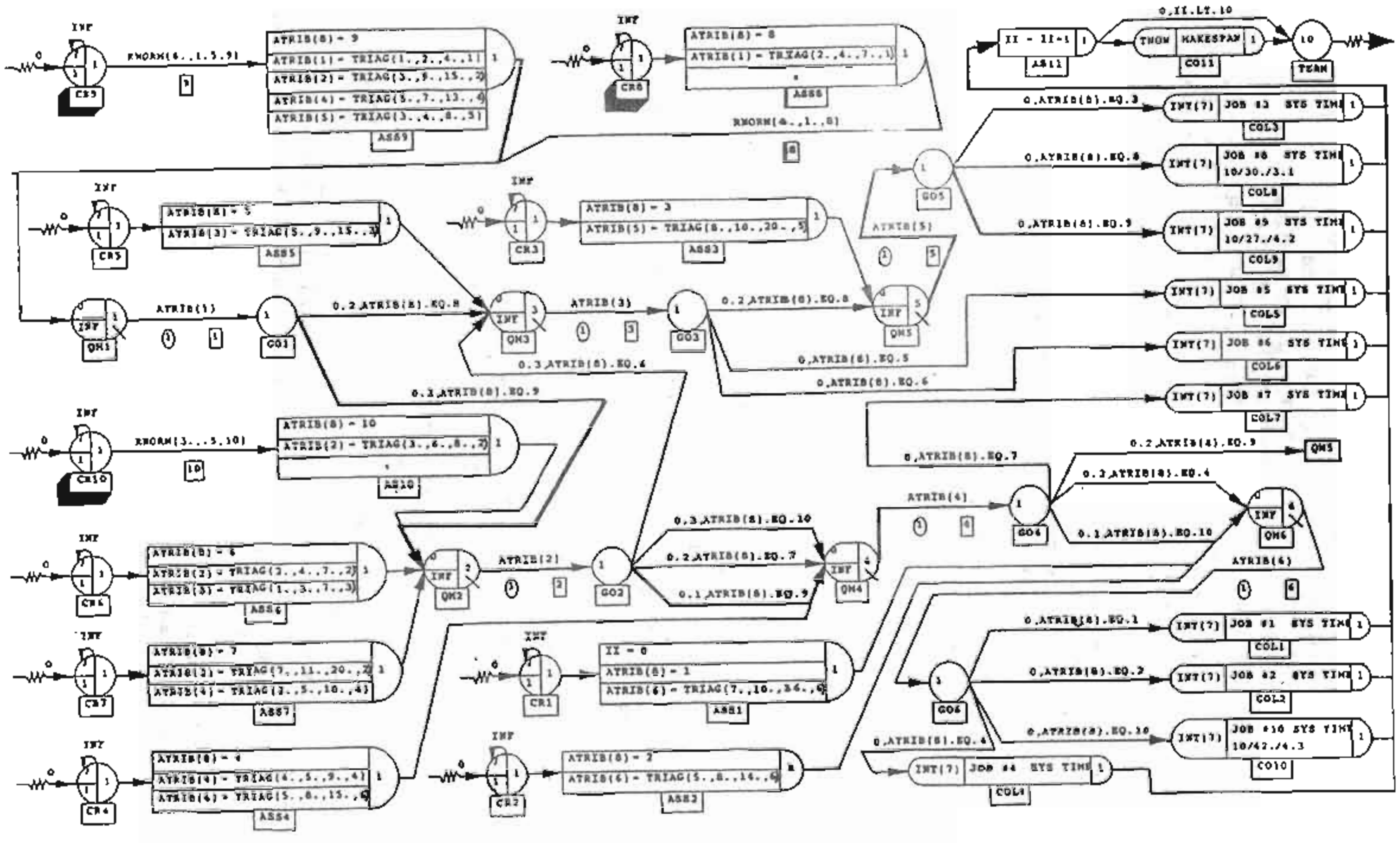

Figure 1 : A SLAM II network of the job shop.

the in process jobs are assumed to be already agreed upon. While the three incoming jobs, namely job #8, job #9, and job #10, are the jobs which management is primarily concerned with in predicting their system times for bidding purposes on the determination of their delivery dates with the customers placing their orders. Note that the job numbering in the model is based on the job entry time to the system. Thus, job #1 is the job that has been in the system first, and job #10 is the last job to enter the job shop. Branches or arrows connecting nodes in the network represent activities carried out on jobs passing through them. Only at branches are explicit activity duration prescribed for jobs flowing through them. Activities emanating from QUEUE nodes, i.e. QM1, QM2, QM3, QM4, QM5, and QM6 are referred to as service activities. These nodes represent the queues of machines 1, 2, 3, 4, 5, and 6 respectively. Service activities restrict the number of concurrent jobs flowing through them to be equal to the number of servers represented by the activity. In this model each service activity has only one server represented by a machine. An activity is mainly described by the number of parallel servers (machines or workers) for a service activity, an activity number, the duration specified for the activity, a probability specification for selecting the activity, a condition for selecting the activity if it is not a service activity, and the end node label which is only required if the end node is not connected directly to it. If an activity appears without a description, then it has the default values of zero duration, no condition, probability of 1 for taking the activity, no activity number, and it requires no servers.

Nine attributes have been assigned to each job and one SLAM global integer variable, namely II is used in the model as a counter. Job attributes #1 (ATRIB(1)), #2 (ATRIB(2)), #3 (ATRIB(3)), #4 (ATRIB(4)), #5 (ATRIB(5)), and #6 (ATRIB(6)) are used to store job processing times on machines 1, 2, 3, 4, 5, and 6 respectively. While job attributes #7, and #8 are used to store the job arrival time to the shop and job number, respectively.

The nodal notation and activities of the network model will be described by referring to the routing of job #9 from its entry time to the shop until it completes processing on the last machine on its routing and dispatched from the system by the TERMINATE node TERM. The routing of job #9 is marked by bold thick branches. Starting with node CR9, job #9 is created by this node at time zero as shown on the zigzag arrow on the left hand side of the node, and only one job (entity) is to be created by this node as indicated by the value of 1 in the lower left hand side and the time between creations as prescribed by INF (infinite time) on the return branch located at the top side of the node. The value of 1 in the right hand side of the node indicates that only one job can leave the node every time it is released. The value of 7 in the upper left hand side designates that the job arrival time (mark time) is to be stored in job attribute #7. After job #9 is introduced to the shop, it is routed to ASSIGN node ASS9 through activity number 9. This activity represents the time spent by the job in the engineering design stage. This time is shown on the top of the activity branch which is drawn from a normal probability distribution with a mean of 6.0 days and a standard deviation of 1.5 days using the SLAM random number stream #9. The activity number is shown below the activity branch in a rectangle. ASSIGN node ASS9 describes the assignments to be made for job #9 in the engineering department including job number and job processing times on the machines specified on the routing of the job. The job number is assigned to job attribute #8 (ATRIB(8)=9), and machine processing times are drawn from a triangular probability distribution (TRIAG) with the parameters shown inside the node, i.e. the processing time of job #9 on machine 1 is assigned in the statement ATRIB(1)=TRIAG(1.,2.,4.,1).

Upon completion of the engineering design stage, job #9 is routed to the first machine on its routing which is machine 1. Thus, it joins machine 1 queue represented by QUEUE node QM1 through the activity branch joining nodes ASS9 and QM1. If service activity #1 (i.e. machine 1) is idle, then job #9 undergoes this activity representing the job processing time on machine 1 as specified by the value stored in job attribute #1 (ATRIB(1)) and shown on the top of the activity branch. A QUEUE node is distinguished from other nodes by a slash on the lower right side of the node. QUEUE node QM1 has zero initial queue length and infinite capacity (INF), and node number 1. As soon as job #9 finishes processing on machine 1, it is routed to GOON node GO1. GOON nodes are included in the network as continue type nodes, and are used in the modeling of activities in series or in parallel, especially when conditional branching exists following a QUEUE node. From node GO1, job #9 is routed to the next machine on its routing, which is machine 2, through the activity joining nodes GO1 and QM1 since the condition on this activity is satisfied by the job. The time delay of this activity is 0.3 days representing the transport and handling time of job #9 between machine 1 and machine 2. Again, job #9 starts processing on machine 2 if the machine is idle, and the processing time is represented by the activity #2 duration time which is specified by job attribute #2. Otherwise, job #9 waits in machine 2 queue QM2 until the machine becomes available. Once job #9 is processed by machine 2, its routed to node GO2. Then according to the conditional branching emanating from node GO2, Job #9 flows through the lower activity joining nodes GO2 and QM4 with a delay time of 0.1 days. Similarly, if machine 4 is available, then it starts working on job #9 with a processing time delay as specified by ATRIB(4) on service activity #4, and then job #9 is routed to node GO4 where it leaves this node to QUEUE node QM5 through the upper activity emanating from node GO4 with a time delay of 0.2 days, since job #9 meets only the condition specified on this activity. Note that this activity is not directly connected with node QM5, therefore an end node label $\boxed{\text{QM5}}$ has been used. As described before, job #9 finishes processing on machine 5 and routed to node GO5 where it has to undergo conditional testing by which it is routed to the COLCT node COL9. COL9 node is a statistics collection node, and it collects statistics on time spent in the system (SYS TIME) by job #9 as specified by INT(7), which means that statistics must be collected on the time between the job completion time and the time the job entered the system (which is stored in job attribute #7). In addition, a histogram for job #9 system time is requested to be presented in the simulation output summary report according to the specifications stated inside node CO19, i.e. 10 cells with an upper cell limit of 27.0 and a cell width of 4.2. After statistics requested are performed by node CO19, job #9 is routed without any time delay to ASSIGN node AS11. This ASSIGN node increases the counter II by one each time a job is released from it, thereby counting the number of jobs being completed in each of the 400 simulation runs. If job #9 is the tenth job to be completed in a run, then it is routed to the COLCT node CO11 where statistics are collected on the makespan, i.e. the time required to complete all the ten jobs in the shop in each run, and then the job is routed to the TERMINATE node TERM where job #9 is dispatched from the system. The TERM node terminates the simulation of each simulation run after all of the ten jobs in the system completed processing, and this is indicated by the value of 10 inside the node. On the other hand, if job #9 is not the last job to be completed by a run based on the condition (II.LT.10) specified on the activity linking AS11 with TERM, then job #9 is routed from AS11 node directly to TERM node. A similar nodal notation and routing description that demonstrates the construction of the network model including other jobs can be applied, and the remainder of the network reflects the routings of the other nine jobs.

SIMULATION RESULTS AND ANALYSIS

The network model of the job shop was simulated under different sequencing rules: the first in system first served rule (FISF), the shortest processing time rule (SPT), and the first in queue first served rule (FIQF). The FISF rule gives the highest priority for machine processing to the job having the longest time in the system, i.e. the job that was first to enter the system is served first. This type of rudimentary sequencing procedure is what realistically occurs in many shops, and it was shown in the literature to have good performance in minimizing the variance of job mean time in the system. While the SPT rule assigns the highest job priority for processing on a machine to the job that has the shortest processing time on that machine. This sequencing rule has been shown in the literature to have a powerful performance in reducing job mean system time. The FIQF rule assigns the highest priority for processing to the job in a machine queue which has first joined that queue, i.e first come at a machine is first served by that machine. The reason for using these three sequencing rules is primarily for the purpose of comparison between these rules through experimentation with the simulation network model of the job shop. Such an experimentation will provide job shop management with a better insight on the effect of using different sequencing rules in predicting job system time.

Tables 4, 5, and 6 present the final SLAM II summary report for 400 independent simulation runs of the network model of the job shop under the FISF, SPT, and FIQF sequencing rules. Each of these tables shows the job mean system time statistic for jobs #1, #2, #3, #4, #5, #6, #7, #8, #9, and #10, with the expected total time required to complete all of these 10 jobs in the job shop, i.e. the makespan. Figs. 2, 3, and 4 give histograms for the simulated relative frequency and cumulative frequency distributions of the job system time for job #10 under the FISF, SPT, and FIQF sequencing rules respectively. Similar histograms for the other jobs considered in the network were also obtained but are not reported here. Table 7 gives the results of the simulation on the mean job system times for the ten jobs when job #10 is being rushed through the system, i.e. when job #10 is given the highest priority for processing on all machines on its routing, under the FISF sequencing rule. Again, experimentation with the model whenever an emergency emerges for rushing certain jobs provides management with an effective way to explore the consequences and the effect of job expediting on the status of the jobs being processed and on the performance of the job shop as a whole system. Job expediting is very common in produce to order production systems.

Referring to Tables 4, 5, and 6, it can be observed that the sequencing rule used has an impact on mean job system times. However, this effect may vary from job to job, but as can be seen the mean system times for certain jobs are highly affected by the sequencing rule used. For example, the mean system time for job #10 has a value of 43 days under the SPT rule and a maximum value of 65.1 days under the FISF rule. A reduction of 22.1 days (34%) in mean job system time has been achieved by using the SPT rule instead of the FISF rule. Obviously, this is reflected as well in the system time distribution for job #10 which has less variability (variance) as shown in Fig. 3. Moreover, the mean system time for job #8 has not been affected largely by the sequencing rule employed, but the mean system time for job #9 favored the FISF sequencing rule, and a reduction of 17.9 days and 10.6 days were obtained by using this rule over the use of the FIQF and the SPT rule, respectively.

Observing Table 7, the mean system time for job #10 has been reduced to 42.8 days, even though the FISF sequencing rule was used. This reduction is attributed to rushing job #10 over the other jobs in the system. This result should not lead management to exercise expediting for a certain job without considering the effect of such expediting on the other jobs being processed in the system. For example, the mean system time for job #7 has been increased, due to rushing job #10, from 22.9 days to 37.7 days, and this will affect the agreed upon delivery date for job #7. Hence, the policy of job expediting

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO OF OBS
JOB #1 SYS TIME	.110E+02	.188E+01	.171E+00	.734E+01	.155E+02	400
JOB #2 SYS TIME	.200E+02	.272E+01	.136E+00	.140E+02	.275E+02	400
JOB #3 SYS TIME	.126E+02	.262E+01	.208E+00	.823E+01	.192E+02	400
JOB #4 SYS TIME	.294E+02	.342E+01	.116E+00	.211E+02	.388E+02	400
JOB #5 SYS TIME	.958E+01	.211E+01	.220E+00	522E+01	.147E+02	400
JOB #6 SYS TIME	.132E+02	.240E+01	.181E+00	.719E+01	.188E+02	400
JOB #7 SYS TIME	.229E+02	.326E+01	.143E+00	145E+02	.309E+02	400
JOB #8 SYS TIME	.454E+02	.589E+01	.130E+00	.307E+02	.609E+02	400
JOB #9 SYS TIME	.432E+02	.624E+01	.145E+00	.275E+02	.646E+02	400
JOB #10 SYS TIME	.651E+02	.724E+01	.111E+00	.424E+02	.847E+02	400
MAKESPAN	.654E+02	.682E+01	.104E+00	.488E+02	.847E+02	400

Table 4. SLAM II summary report on mean job system times and makespan of 400 simulation runs under the FISF sequencing rule.

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
JOB #1 SYS TIME	.110E+02	.188E+01	.171E+00	.734E+01	.155E+02	400
JOB #2 SYS TIME	.239E+02	.595E+01	.249E+00	.140E+02	.388E+02	400
JOB #3 SYS TIME	.126E+02	.262E+01	.208E+00	.823E+01	.192E+02	400
JOB #4 SYS TIME	.245E+02	.596E+01	.243E+00	.139E+02	.384E+02	400
JOB #5 SYS TIME	.958E+01	.211E+01	.220E+00	.522E+01	.147E+02	400
JOB #6 SYS TIME	.132E+02	.240E+01	.181E+00	.719E+01	.188E+02	400
JOB #7 SYS TIME	.392E+02	.832E+01	.212E+00	.145E+02	.605E+02	400
JOB #8 SYS TIME	.448E+02	.566E+01	.126E+00	.307E+02	.609E+02	400
JOB #9 SYS TIME	.538E+02	.634E+01	.118E+00	.326E+02	.714E+02	400
JOB #10 SYS TIME	.430E+02	.599E+01	.139E+00	.287E+02	.702E+02	400
MAKESPAN	.548E+02	.531E+01	.969E-01	.423E+02	714E+02	400

Table 5: SLAM II summary report on mean job system times and makespan of 400 simulation runs under the SPT sequencing rule.

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
JOB #1 SYS TIME	.110E+02	.188E+01	.171E+00	.734E+01	.155E+02	400
JOB #2 SYS TIME	.200E+02	.272E+01	.136E+00	.140E+02	275E+02	400
JOB #3 SYS TIME	.126E+02	.262E+01	.208E+00	.823E+01	.192E+02	400
JOB #4 SYS TIME	.294E+02	.342E+01	.116E+00	.211E+02	.388E+02	400
JOB #5 SYS TIME	.958E+01	.211E+01	.220E+00	.522E+01	.147E+02	400
JOB #6 SYS TIME	.135E+02	.330E+01	.244E+00	.719E+01	.397E+02	400
JOB #7 SYS TIME	.229E+02	.326E+01	.143E+00	145E+02	.309E+02	400
JOB #8 SYS TIME	.447E+02	.554E+01	.124E+00	307E+02	.609E+02	400
JOB #9 SYS TIME	.610E+02	.606E+01	.993E-01	.458E+02	.770E+02	400
JOB #10 SYS TIME	.542E+02	.614E+01	.113E+00	.368E+02	.701E+02	400
MAKESPAN	.610E+02	.604E+01	.990E-01	458E+02	.770E+02	400

Table 6. SLAM II summary report on mean job system times and makespan of 400 simulation runs under the FIQP sequencing rule.

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
JOB #1 SYS TIME	.110E+02	.188E+01	.171E+00	.734E+01	.155E+02	400
JOB #2 SYS TIME	.200E+02	.272E+01	.136E+00	.140E+02	.275E+02	400
JOB #3 SYS TIME	.126E+02	.262E+01	.208E+00	823E+01	.192E+02	400
JOB #4 SYS TIME	.294E+02	.357E+01	.121E+00	.211E+02	.466E+02	400
JOB #5 SYS TIME	.958E+01	.211E+01	.220E+00	522E+01	.147E+02	400
JOB #6 SYS TIME	.132E+02	.240E+01	.181E+00	719E+01	.188E+02	400
JOB #7 SYS TIME	.377E+02	.737E+01	.195E+00	.145E+02	.536E+02	400
JOB #8 SYS TIME	.448E+02	.560E+01	.125E+00	307E+02	.609E+02	400
JOB #9 SYS TIME	.552E+02	.520E+01	.942E-01	.423E+02	714E+02	400
JOB #10 SYS TIME	.428E+02	.580E+01	.136E+00	280E+02	.682E+02	400
MAKESPAN	.654E+02	682E+01	.104E+00	.488E+02	.847E+02	400

Table 7: SLAM II summary report on mean job system times and makespan of 400 simulation runs with rushing job #10 under FIFS rule.

```
OBSERVATION  RELATIVE   CUMULATIVE  UPPER
FREQUENCY    FREQUENCY  FREQUENCY   CELL LIMIT 0        20        40        60        80       100
                                               +    +    +    +    +    +    +    +    +    +    +
   0          .000       .000       .420E+02   +                                                 +
   3          .007       .007       .463E+02   +                                                 +
   9          .023       .030       .506E+02   +*                                                +
  20          .050       .080       .549E+02   +***C                                             +
  46          .115       .195       .592E+02   +******   C                                       +
  82          .205       .400       .635E+03   +**********         C                             +
  91          .228       .628       .678E+02   +***********                   C                  +
  79          .197       .825       .721E+02   +**********                              C        +
  50          .125       .950       .764E+02   +******                                        C  +
  16          .040       .990       .807E+02   +**                                               C
   4          .010      1.000       .850E+02   +                                                 C
   0          .000                    INF      +                                                 C
 ---                                           +    +    +    +    +    +    +    +    +    +    +
 400                                           0        20        40        60        80       100
```

Figure 2: A histogram for job #10 system time under the FISF sequencing rule.

```
OBSERVATION  RELATIVE   CUMULATIVE  UPPER
FREQUENCY    FREQUENCY  FREQUENCY   CELL LIMIT 0        20        40        60        80       100
                                               +    +    +    +    +    +    +    +    +    +    +
   0          .000       .000       .280E+02   +                                                 +
   6          .015       .015       .323E+02   +*                                                +
  37          .093       .108       .366E+02   +*****                                            +
 105          .262       .370       .409E+02   +*************     C                              +
 138          .345        715       .452E+02   +*****************                  C             +
  70          .175       .890       .495E+02   +*********                                   C    +
  22          .055       .945       .538E+02   +***                                           C  +
  10          .025       .970       .581E+02   +*                                               C+
   7          .018       .988       .624E+02   +*                                               C+
   2          .005       .993       .667E+02   +                                                 C
   3          .007       1.00       .710E+02   +                                                 C
   0          .000                    INF      +                                                 C
 ---                                           +    +    +    +    +    +    +    +    +    +    +
 400                                           0        20        40        60        80       100
```

Figure 3. A histogram for job #10 system time under the SPT sequencing rule.

```
OBSERVATION  RELATIVE   CUMULATIVE  UPPER
FREQUENCY    FREQUENCY  FREQUENCY   CELL LIMIT 0        20        40        60        80       100
                                               +    +    +    +    +    +    +    +    +    +    +
   0          .000       .000       .360E+02   +                                                 +
   4          .010       .010       .396E+02   +                                                 +
  12          .030        040       .432E+02   +*C                                               +
  33          .083       .123       .468E+02   +**** C                                           +
  58          .145        268       .504E+02   +*******     C                                    +
  91          .228       .496       .540E+02   +***********             C                        +
  80          .200       .696       .576E+02   +**********                        C              +
  71           177       .873       .612E+02   +*********                                  C     +
  35          .087        960       .648E+02   +****                                           C +
  10           025       .985        684E+02   +*                                               C+
   6          .015      1.000        720E+02   +*                                                C
   0          .000                    INF      +                                                 C
 ---                                           +    +    +    +    +    +    +    +    +    +    +
 400                                           0        20        40        60        80       100
```

Figure 4: A histogram for job #10 system time under the FIQF sequencing r.le.

should be considered by job shop management in a global framework, taking into account all possible payoffs and drawbacks through a situational based management.

Furthermore, if the expected total time for completing all jobs existing in the shop is of interest to job shop management, especially in the case in which the job shop system functions according to periodically planned horizons, management must recognize the impact of sequencing rules employed on the makespan. As can be observed from Tables 4, 5, and 6, the SPT sequencing rule produced the minimum makespan of 54.8 days.

Now, consider job #10 system time to illustrate how the simulation results and output can be utilized and analyzed for the purpose of predicting job system time for setting and/or reviewing job delivery dates. The data presented by any of the Tables 4, 5, and 6 may be used for the demonstration to follow. This demonstration can also be applied to the other incoming and in process jobs. Suppose the data shown in Table 4 is used. The mean job system time for job #10 is 65.1 days. That is the probability of completing job #10 in 65.1 days or less is 0.50. In other words, if the externally imposed delivery date for Job #10 is 65.1, then the probability of completing the job on time is 0.50. The relative frequency and cumulative frequency for Job #10 system times are shown in Fig. 2 (this histogram corresponds to the simulation results presented in Table 4). From this histogram and the others shown in Figures 3 and 4, one can clearly observe that the distribution of the system times for job #10 follows closely the normal distribution. Similar behavior was observed for the system times for jobs #8 and #9. In addition, based on the central limit theorem [19], the sampling distribution of the system time for job #10 will be approximately normally distributed. Since each of the 400 simulation runs (observations) of the system time for job #10 were performed in an independent manner, an estimate of the standard deviation of the mean system time for job #10 is equal to the standard deviation of the distribution of the system time for job #10, which is 7.24 (from Table 4), divided by the square root of 400 (the number of observations, i.e the sample size). That is the standard deviation of the mean system time for job #10 is $(7.24/20)=0.36$. Thus, a 95% confidence interval on the mean system time can be constructed as $(65.1 \pm 1.96*0.36)$, where 1.96 is the critical value of the normal distribution corresponding to a 95% confidence. The critical value of the normal distribution is used even though the estimate for the standard deviation is employed since the number of observations is large. The limits for the confidence intervals are (64.39, 65.81). This means that at least 95% of the population of mean system times for job #10 generated from the model should be in the tolerance interval (64.39, 65.81), which also indicates that the mean of job #10 system time from the network model is expected to be in a narrow range. Other confidence intervals on the mean system time can be constructed based on the confidence level that job shop management may consider acceptable.

Moreover, from the cumulative frequency distribution shown in Fig. 3, estimates of the probability that job #10 will be completed by a certain time can be made. Thus, it is estimated that the probability of job #10 being completed by 59.2 days is 0.195 and hence, the probability of job #10 taking more than 59.2 days is $(1-0.195)=0.805$. This indicates that if the externally imposed delivery date for job #10 is 59.2 days, then the probability of the risk involved of not completing the job on time is 0.895. Obviously, this is a very high risk level and job shop management must recognize the resulting potential loss and penalties if the job does not meet its delivery date. On the other hand, if the externally specified delivery date for job #10 is 72.1 days, then there is a probability of 0.825 that the job can be completed on time. If this probability is within the shop's risk range then the job should be considered for bidding.

In addition, each time the job shop is simulated for the determination of a system time estimate for a job being under consideration for bidding, an update of estimates for jobs already in the job shop such as jobs #1, #2, #3, etc. can be obtained. This provides management with information that can be useful to ascertain if promised delivery dates will be met or not. If not, necessary actions must be taken by shop management to avoid late jobs such as rescheduling, use of overtime and increasing job shop capacity.

CONCLUSIONS

The results of this study showed that both sequencing rules and job expediting have significant impact on mean job system time. This leads to recommend that whenever a job shop management has already specified certain operating policies based on job shop conditions and prior planning and auditing for a given planning horizon, any changes in these policies will produce significant impacts on the results expected. Thus, th rough revision and assessment must be carried out before implementing such changes. This must be of a major concern , especially in the situations in which shop management is committed to externally imposed conditions such as job delivery dates. As can be noted, network modeling and simulation present a viable vehicle to deal with understanding the effect of manipulating the many factors that may affect the performance of job shops.

The problem of enforcing job delivery dates which are set by an external agency, and without regard to the job processing characteristics and the shop status or the priority rule to be used, is to find a procedure that is capable of enforcing such set of delivery dates. Previous research, to date, suggested that none of the standard and obvious scheduling procedures is particularly powerful in this regard. It has been shown in this study that network modeling using the PC version of SLAM II simulation language is a viable approach for tackling this job shop scheduling problem with moderate technical efforts and affordable costs. This approach provides job shop management with valuable information on estimates of job system times which can be used in setting and assessing job delivery dates for incoming jobs as well as for in process jobs, respectively. Furthermore, the possibility of periodical experimentation by simulating network models under a wide possible varieties of scenarios enables job shop management to exercise continuous monitoring and effective controlling over the job shop operations. This eventually results in better performance, less production costs and higher productivity. It is worth noting that the network model of the job shop considered in this study was constructed by using only six types of SLAM II nodes without any computer programing, and was simulated under an interactive mode on a personal computer. In a more complex job shop setting such as dual-constrained job shops (shops with limited workforce capacity, i.e. the number of workers is less than the number of available machines) the network modeling approach demonstrated can also be applied by embellishing the model with few other types of nodes such as the AWAIT, and FREE nodes which assign limited resources to service activities and release them as required.

Finally, network modeling and analysis is a valuable aid for enabling job shop management to better understand their system. The network itself presents a visual aid in showing job flows, bottleneck machines/facilities, resources allocation and utilization, etc. While, on the other hand, model experimentation is useful for system design, operations planning and control, and system redesign.

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