Scheduling in the dynamic job shop under auxiliary resource constraints: A simulation study

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Abstract:

Traditionally, job shop research has only considered constraints related to machine and labour availability. With the advent of flexible manufacturing systems and just-in-time manufacturing, practitioners have recognized the importance of auxiliary resources (e.g. tooling) in production activity control and shop scheduling. In recent years, it has been recognized that theory and practice based on labour-constrained job shops cannot be generalized to auxiliary resource-constrained job shops. This paper presents a study of scheduling in the dynamic job shop under auxiliary resource constraints. Local and lookahead dispatching and resource assignment rules, and a global Contingency Based Scheduling (CBS) approach are developed and evaluated in a dynamic job shop constrained by auxiliary resources. Several traditional measures of performance are employed, including root mean square of tardiness, average system time and percentage of auxiliary resource changes. As shop utilization increases, the study reveals that the CBS algorithm is the only scheduling mechanism that consistently provides high performance on all three measures.

Keywords: manufacturing systems | auxiliary resources | performance | Contingency Based Scheduling (CBS)

Article:

1. Introduction

Shop floor management includes not only the scheduling of labour and machines directly involved in production, but also the scheduling of other needed resources, e.g. maintenance equipment and tooling. Resources required to make labour and machines productive are called auxiliary resources or adjunct resources (Blackstone 1989). Auxiliary resources can be viewed as equipment and special fixtures that the Production Activity Control (PAC) system employs and uses during setup, maintenance and operation of a machine, or an assembly process. Auxiliary resources include not only those attachments and accessories needed during production and maintenance, but also supporting equipment needed for transport (e.g. forklifts, cranes, automated guided vehicles and pallets). This research investigates dynamic job shop scheduling in the presence of auxiliary constraints.

In this paper, a constraint is defined as a resource that limits, restricts or regulates output of the system and impacts shop performance. In addition, the following definitions are used:

(1) Multiple resource-constrained job shop: a job shop in which two or more resources are constraining output. The resources may include machines, labour and auxiliary resources. Dual-constrained job shops are constrained by two resources (machines and labour, machines and auxiliary resources, or labour and auxiliary resources). Dual-constrained job shops are thus a specific type of multiple resource-constrained job shops.

(2) Machine-only-constrained job shop: a job shop in which machines are the only constraints. There are no constraints on labour and auxiliary resources.

(3) Labour-constrained job shop: a type of dual-constrained job shop in which machines and labour are the constraining resources.

(4) Auxiliary resource-constrained job shop: a type of dual-constrained job shop in which machines and auxiliary resources are the constraining resources.

During the last few years, particularly in view of investment in flexible manufacturing systems and highly integrated just-in-time manufacturing (with reduced setup times), production managers have started to realize that the planning and control of auxiliary resources is as important as the management of machines and manpower (Melnyk et al. 1989). In a dynamic machine-only-constrained job shop, machines are sometimes idled due to the stochastic nature of the shop. In an auxiliary resource-constrained job shop, a machine can also be idle due to the non- availability of the auxiliary resource. Gargeya (1994) demonstrated that in auxiliary resource-constrained job shops (as well as all dual resource-constrained job shops), the average job ¯ ow time is not only impacted by the degree of constraint imposed by each resource, but also by the interaction effect of the resource constraints. In general, auxiliary resource-constrained job shops present problems somewhat similar to those encountered in labour-constrained shops. However, theory and practice based on labour constraints cannot be generalized to auxiliary constraints. In studies pertaining to labour constraints, the labour force has usually been treated as homogeneous (i.e. when a machine is manned, it can process any job in the queue). However, auxiliary resources, and in particular tools, have a heterogeneous characteristic. A job order in the queue at a work centre does not simply require one type of tooling or auxiliary resource; it requires a specific tool or auxiliary resource. Auxiliary resource scheduling is distinctly different from machine-only scheduling based on simultaneity in usage (i.e. an auxiliary resource and a machine are required at the same time, whereas usually two machines are not). Thus, scheduling in a job shop with machines and auxiliary resources presents a more complex resource matching problem than scheduling in a machine-only-constrained job shop, or in a labour-constrained job shop. A detailed analysis of the scheduling research in labour- and auxiliary resource-constrained job shops has been provided by Gargeya and Deane (1996).

In both machine-only- and labour-constrained systems, the execution phase of scheduling includes priority sequencing and resource allocation. In machine-only- constrained shops, dispatching rules are sufficient for executing a schedule (i.e. choosing jobs at machine centres). In labour-constrained systems, a combination of a job dispatching rule (for prioritizing jobs at machine centres) and a labour assignment rule (for assigning labour to machine centres) is required (Treleven 1982). Thus, the level of complexity of shop floor control in the execution phase is greater in a dual-constrained shop as compared to a machine-only-constrained shop.

Job shop scheduling in a machine-only-constrained shop presents enormous combinatorial complexities. Consideration of auxiliary constraints, e.g. tooling, presents an even more increased level of complexity. A typical job shop includes small tools which can be manually carried by individual workers, and large pieces of equipment (e.g. cranes) for maintenance. These resources may be required for a very short period of time (e.g. a few minutes), or for very long periods of time. Complexity of the machine- and auxiliary resource-constrained job shop scheduling problem increases with more machine centres, routings, and number of tools and maintenance equipment. For scheduling in such an environment, mathematical programming techniques are typically not feasible. In such instances, heuristics may be required. Heuristic methods are an important technique for solving large scale, combinatorial decision problems. The use of heuristic methods, which involve the application of simple decision rules, can provide a means of obtaining near-optimum solutions to a decision problem. In the past, dynamic job shop scheduling has primarily been focused on local dispatching and auxiliary resource assignment rules that make use of local information (i.e. information that is available at that resource at that specific moment in time). Curiously, `look-ahead' dispatching and auxiliary resource assignment rules have not been applied in an attempt to improve shop performance in the auxiliary resource-constrained job shop. Look-ahead dispatching and auxiliary resource assignment rules make use of global shop information at each decision point. In this research, it is hypothesized that look-ahead dispatching rules combined with auxiliary resource assignment rules should perform significantly better than combinations involving local dispatching and auxiliary resource assignment rules in an auxiliary resource-constrained job shop. In addition to combinations of local and look-ahead dispatching rules, a Contingency-Based Scheduling (CBS) approach is developed in this research. The CBS approach first makes use of indicators or measures of resource constraint for scheduling the machines/jobs. The basic premise of the CBS approach is to give scheduling priority to the most con- strained resources at any point in time.

The major objectives of this research are: (1) to develop local and look-ahead dispatching rules for scheduling jobs in a job shop with auxiliary constraints; (2) develop local and look-ahead auxiliary resource assignment rules for an auxiliary resource-constrained job shop; (3) develop an adaptive, contingency-based scheduling approach for a dynamic job shop with auxiliary constraints; and (4) compare and evaluate the performance of the contingency-based scheduling approach developed in this research with combinations of local and look-ahead dispatching and auxiliary resource assignment rules. In the next section, existing literature on the subject is reviewed. In section 3, a contingency-based scheduling approach is described. Sections 4-6 present the research design, analysis and results, and conclusions, respectively.

2. Literature review

Machine and labour constraints have been considered extensively in the shop scheduling literature. A shop with constraints only on auxiliary resources, or labour (with no constraints on machines) in the long term is probably unrealistic. In the short term, however, a shop may be primarily constrained by auxiliary resources or labour. With the exception of studies by Melnyk et al. (1989) and Ghosh et al. (1992), there is little research reported on job shop scheduling under machine and auxiliary resource constraints (Gargeya and Deane 1996).

As in labour-constrained job shops, auxiliary resource-constrained job shops (i.e. job shops that are constrained by machines and auxiliary resources) must have a job dispatching rule (for prioritizing jobs at machine centres) and an auxiliary resource assignment rule (for assigning auxiliary resources to machine centres). Melnyk et al. (1989) state that: ``tooling assignment rules are similar to dispatching rules. They determine how jobs will compete for tooling and what to do with the tooling on completion of a job'' (p. 73).

However, this definition of tooling assignment rules given by Melnyk et al. does not focus on the issue of how tooling will be assigned to the various machine centres. They simulated a simple job shop based on one type of operation, one machine, one type of tool for all jobs, and a single work centre operating. The remainder of the shop was simulated in aggregate to provide competition for four different auxiliary resources (in the form of tools) available in the shop. It should also be noted that Treleven's (1989) review of the scheduling research in dual (labour)-constrained job shops reported that previous labour-constrained studies employed from two to 1000 machines, and from one to 500 workers. Such studies are very different from the simplified model used by Melnyk et al., which had the following restrictive assumptions: (a) no penalty for tool changes; (b) tooling had infinite life; (c) only production tooling was considered; and (d) simple dispatching rules were used.

In their study, Melnyk et al. (1989) employed a shop in which both machines and tools had the same relatively high level of utilization (85%). As discussed by Gargeya (1994), in a multi-machine, multi-tool, auxiliary resource-constrained job shop simulation, utilization levels higher than 65% for all resources are diffcult to attain due to the interaction effects of the resource constraints. Gargeya and Deane (1996) have also provided a detailed discussion on the limitations on utilization levels in multiple resource-constrained job shops. Melnyk et al. may have been able to attain a utilization level of 85% due to the fact that a `one-machine' shop simulation was con- ducted. As such, the applicability of their results is questionable. Melnyk et al. also evaluated the interaction between tooling assignment rules, job priority rules and the level of tooling available. The four tooling assignment rules were: (a) job priority; (b) job priority subject to tool availability; (c) avoid tool change; and (d) modified avoid tool change. The tool assignment rules suggested by Melnyk et al. (1989) not only differ in principle, but also are somewhat contradictory to the labour assignment rules suggested by Treleven (1982). While Treleven used labour assignment rules in determining which machine would be first served by an idle worker, Melnyk et al. used tool assignment rules somewhat interchangeably with job dispatching rules (for prioritizing jobs at machines) based on availability of tools. The `avoid tool change' rule is the only tool assignment rule (used by Melnyk et al.) that would come close to the type of labour assignment rules used by Treleven (1982). The definition of tool assignment rules given by Melnyk et al. did not focus on the issue of how tools will be assigned to machines. The decision of which machine will be served by a tool arises in situations where there is more than one machine waiting for a tool at any moment in time. Melnyk et al. considered only one machine centre with four tools. As such, the issue of how tooling will be assigned to the various machine centres does not arise.

With different definitions for dispatching rules and resource assignment rules being used by different researchers, it is essential to adopt a common definition of dispatching rules and resource assignment rules. In this paper, dispatching rules are the means by which jobs are prioritized for machines, and auxiliary resource assignment rules are mechanisms by which an auxiliary resource is assigned to machines waiting for the auxiliary resource.

While a substantial amount of research has been undertaken in machine- and labour-constrained job shops, there is a dearth of research involving scheduling in auxiliary resource-constrained job shops. In recent years, shop loading algorithms have been applied to labour-constrained shops (Miller and Berry 1974, Park 1987). However, there has been no research applying loading algorithms in job shops constrained by machines and auxiliary resources, or in shops constrained by more than two resources. Some of the gaps in the previous literature, which have been addressed in this paper, include: (1) do local job dispatching and resource assignment rules perform as well as global dispatching and resource assignment rules in job shops constrained by machines and auxiliary resources? and (2) can shop loading algorithms, similar to those developed by Miller and Berry (1974), and Park (1987), in labour-constrained job shops, be effectively used in auxiliary resource-constrained job shops?

3. Contingency-Based Scheduling approach

A bottleneck is a resource that limits throughput. A bottleneck could be a machine, scarce labour or a specialized tool. Industry observations have shown that there are only a few bottlenecks in a shop at any given moment (Goldratt and Fox 1986). The same resources may not be bottlenecks all the time. Various resources become bottlenecks at one time or another depending on shifting demand patterns. It is the task of the shop manager to identify current bottlenecks and accordingly schedule the shop. It may be futile to give priority to a non-bottleneck machine, as it can produce more than is needed to supply critical bottleneck resources.

In previous research, a dual-constrained shop has been characterized as one which makes use of machines and labour, or machines and auxiliary resources (Melnyk et al. 1989). However, the mere presence of two resources may not necessarily make a shop dual constrained. For example, a shop with a machine utilization of 85%, and an auxiliary resource utilization of 5% is not auxiliary resource con- strained for practical purposes. Such a shop would be more of a machine-only- constrained shop in the long run. On various performance measures (e.g. average mean lateness, average mean tardiness, root mean square of tardiness, number of tardy jobs, average flow time and average work-in-process), a shop with 5% auxiliary resource utilization may not perform significantly different than a shop with no constraint on auxiliary resources. On the other hand, a shop having 85% machine utilization and 85% auxiliary resource utilization would certainly be dual constrained.

Even high utilization of a particular resource in the long run may not guarantee that it is constrained by that resource at any given point in time. There are periods of time in which a high utilization resource may not be as much of a constraint as a low utilization resource. Based on this logic, average resource utilization alone is ineffective as a measure of resource constraint (Lawrence and Buss 1994). Gargeya (1994) described the Resource Criticality Factor (RCF) as an effective measure of resource constraint. The RCF takes into account shop information that relates to a specific time span (i.e. `longitudinal' data). The RCF of any resource is given as

$$\mathrm{RCF} = \frac{\text{Total resource requirement in the given time period}}{\text{Number of units of resource available.}} \qquad (1)$$

This research is based on the premise that schedule generation should focus on the type of current shop resource constraint. It is hypothesized that such a contingency- based scheduling approach should perform better than conventional dispatching and auxiliary resource assignment rules in an auxiliary resource-constrained job shop with varying degrees of resource constraint. A CBS approach is developed in this section.

The CBS algorithm provides a `quasi-global' procedure by which jobs are prioritized at each resource. The CBS procedure includes three distinct phases: the Forward Finite Loading Updating phase, the Critical Resource Determination and Reloading phase, and the Job Priority Setting phase. In the first phase, forward finite loading and updating are conducted at the time of arrival of every incoming job. In this process, each incoming job is loaded into a schedule (similar to a GANTT chart) using the forward finite loading mechanism. In the second phase, the critical resource is determined (based on the RCF of each resource) at fixed intervals of time. The critical resource is the resource with the highest RCF. If the critical resource has changed, all jobs in the shop are reloaded (using the forward finite loading mechanism) and re-prioritized (using the least critical ratio rule) at each resource. The critical ratio of job *i*, CR_i is computed as follows

$$CR_i = (Di - TNOW)/RPT_i \qquad (2)$$

where D_i = due date of job *i*; NOW = current time; and RPT_i = remaining processing time for job *i*.

In the re-prioritization, preference is given to those jobs that make use of the critical resource. The third and last phase of the CBS procedure is executed at the shop floor control stage. The purpose of this phase is to set dispatching priorities for jobs waiting in queues or for prioritizing machines for tool assignment. This phase is executed just prior to jobs being dispatched onto machines or tools assigned to jobs. Job dispatching and tool assignment is based on the least critical ratio rule. Priority is given to those jobs that require the current critical resource. Amongst those jobs that require the critical resource, the priority is determined using the least critical resource-critical ratio in lieu of the least critical ratio. The critical resource-critical ratio of job *i*, $CRCR_i$ is computed as follows

$$CRCR_i = (S_i - TNOW)/RPTCR_i, \qquad (4)$$

where S_i = projected starting time for the next operation requiring the critical resource for job i, this is obtained from the forward finite loading (performed either in the first or second phase); TNOW =current time; and $RPTCR_i$ =remaining processing time (for job *i*) prior to the next job operation requiring the critical resource.

The rationale for using the CRCRi priority for jobs requiring the critical resource, and the CRi priority for jobs not requiring the critical resource is that the CBS approach attempts to schedule the jobs on a contingency basis depending upon the criticality of each job with regard to the critical resource.

4. Research design

One of the objectives of this research is to compare the performance of the CBS approach with local dispatching rules and look-ahead dispatching rules in a job shop constrained by machines and auxiliary resources. A computer simulation research methodology was employed. A discrete event simulation model for a machine and auxiliary resource-constrained job shop environment was developed using the SIMAN simulation language (Pegden 1989).

4.1. *The job shop simulation model*

The model in this research considered a job shop that is machine and tooling constrained. There were no labour constraints in the job shop model. While this research made use of tooling as the auxiliary resource, the results are generalizable to other auxiliary resources as well. In this research, both production and setup tooling were considered. Only a single tool is required for setup or production. Job dispatching at machine centres and tool assignment is carried out through centralized control, and the tools are stored and assigned from a tool crib. The number of operations per job is drawn from a uniform distribution with a range of from two to four operations per job (giving an average of three operations per job). Each job operation requires a tool. For each operation, there is a 50% likelihood that the tool is for setup and a 50% likelihood that the tool is a production tool. If the operation requires only setup tooling, the setup time is drawn from a uniform distribution ranging from 40 to 60 time units, and the production time is drawn from a normal distribution with a mean of 90 time units and a standard deviation of 9 time units. If the operation requires production tooling, the production time (i.e. the time period for which the tool is required as well as the length of the entire operation) is drawn from a normal distribution with a mean of 140 time units and a standard deviation of 14 time units. Jobs arriving at a `busy' machine wait in the queue. Once the machine is available, the job `seizes' the required tool. If there are other jobs waiting for the specific tool, the job (and machine) waits in a tool queue. A machine may be idle even though there are jobs in the machine queue, because of tool unavailability. The expected work content in each arriving job is altered during the simulation to provide a more pronounced effect in varying the degree of constraint imposed by each shop resource.

In summary, the job shop model used in this research has the following features, assumptions and limitations:

(1) balanced shop with four machine centres and two tools;

(2) negative exponentially distributed job inter-arrival times (with 210 time units for a 50% utilization shop, 175 time units for a 60% utilization shop and 161.54 time units for a 65% utilization shop);

(3) stochastic setup and production times;

(4) predetermined job routing upon arrival;

(5) operation overlapping and preemption are not allowed;

(6) negligible move time for jobs between machine centres and negligible move time for tools between machine centres;

(7) unlimited queue lengths allowed at machine centres and tools;

(8) machine or tool breakdowns are not explicitly considered;

(9) lot splitting is not allowed;

(10) stochastic- and sequence-independent setup times;

(11) alternative routing is not allowed;

(12) tooling is used for setup and production;

(13) single tooling;

(14) no separate setup or `tear down' time is required to change tools on a machine;

(15) due dates are based on a function of total predicted processing time;

(16) the job shop simulation model described above is representative of shops found in industry and reported in the literature (Gargeya 1994).

4.2. *Experimental design*

4.2.1. *Performance criteria*

Three types of shop performance measures are employed in this study.

(1) Root Mean Square of Tardiness (TRMS) is employed as the specific criterion for the due date performance-related measure, as, in a way, it is a 'combined' measure for average tardiness and variance of tardiness. (TRMS) is computed as follows:

$$T_{RMS} = \left[\sum_{i=1}^{n} \{ \text{Max} \left(0, \left(C_i - D_i \right) \right) \}^2 / n \right]^{1/2} \quad (5)$$

where: C_i = completion time of job i; D_i = due date of job i; and n = number of jobs completed. TRMS is designed to penalize the situation where a few jobs are very tardy from the case where many jobs are a little tardy (Russell and Taylor III 1985).

(2) Average System Time (S_{av}) is used as the specific criterion for the shop flow time performance measure. S_{av} is computed as follows:

$$S_{av} = \left[\sum_{i=1}^{n} (C_i - A_i) \right] \Big/ n \quad (6)$$

where C_i = completion time of job i; A_i = arrival time of job i; and n =number of jobs completed.

(3) Percentage of Tool Changes (p_{tc}) is used to reflect the managerial and operational disruptions associated with frequent transfer of resources, and is computed as:

$$p_{tc} = \frac{\text{Number of tool changes}}{\text{Number of times tools are required}} \times 100. \quad (7)$$

4.2.2. *Experimental factors*

There are two experimental factors employed in this research.

(1) Scheduling methodology employed. In this research, 37 scheduling methodologies have been studied. The first is the Contingency-Based Scheduling (CBS) approach described in section 3. The remaining are the 36 combination of six dispatching rules and six tool assignment rules. The dispatching rules include four local dispatching rules and two look-ahead dispatching rules. Local dispatching/tool assignment rules take into account information that is available at a particular machine/tool crib at the specific moment a dispatching/tool assignment decision is required. Look-ahead dispatching/ tool assignment rules are based on information that is available with reference to the rest of the shop at the specific moment in time (just before the machine operator selects a job to process or a tool is assigned to a machine). It is hypothesized that look-ahead dispatching/tool assignment rules will perform better than local dispatching/tool assignment rules. The first four dispatching/tool assignment rules listed below are local dispatching/tool assignment rules, and the last two are look-ahead dispatching/tool assignment rules. The dispatching/tool assignment rules are as follows.

(i) First Come First Served (FCFS) rule.

(ii) Shortest Processing Time/Shortest Tool Requirement Time (SPT/ STRT) rule.

(iii) Earliest Due Date (EDD) rule.

(iv) Critical Ratio (CR) rule. The critical ratio of job *i*, CR_i is calculated as follows:

$$CR_i = (D_i - TNOW) / RPT_i \qquad (8)$$

where: D_i = due date of job *i; TNOW* = current time; and RPT_i = remaining processing time for job *i*.

Under the CR dispatching rule, the next job selected for processing at the machine is the one in the queue with the lowest critical ratio. Under the CR tool assignment rule, the tool is assigned to the machine which has the job with the lowest critical ratio.

(v) Least Number of Jobs in Queue at Next Machine (LNJQNM) rule. Under the LNJQNM dispatching rule, the next job chosen at a particular machine is the one which has to be processed at its next machine with the fewest number of jobs in the queue. Under the LNJQNM tool assignment rule, the tool is assigned to a machine which has a job that has to be processed at its next machine with the fewest number of jobs in the queue. The LNJQNM rule is illustrated with the following ex- ample: consider three jobs (job A, job B and job C) awaiting processing at a machine 1 at time 0. The routings for job A, job B and job C are Machine 1-Machine 2 (3 jobs)-Machine 3 (1 job)-Machine 4 (2 jobs), Machine 1-Machine 4 (2 jobs), and Machine 1-Machine 3 (1 job)-Machine 2 (3 jobs), respectively. It should be noted that the number of jobs shown in parentheses after each machine in a job's routing sequence is the number of jobs currently (at time 0) waiting in sequence at that machine. This indicates that with the LNJQNM rule, job C (as there is only 1 job at Machine 3, job C's next machine) will be done first at machine 1 at time 0, followed by job B (based on the fact that there are 2 jobs at Machine 4, job B's next machine), and then followed by job A (as there are 3 jobs at Machine 2, job A's next machine).

(vi) Least Number of Jobs in Queue at All Machines on job's route (LNJQAM) rule. Under the LNJQAM dispatching rule, the next job chosen at a particular machine is that which requires machines that have the fewest number of jobs in the queue. Under the LNJQAM tool assignment rule, the tool is assigned to a machine which has a job which requires machines that have the fewest number of jobs in the queue. The LNJQAM rule is illustrated with the example given in the earlier subsection on the LNJQNM rule. With the LNJQNM rule, job B (as there is a total number of only 2 jobs on job B's routing) will be done first at machine 1 at time 0, followed by job C (based on the fact that there are only 4 jobs in total on job C's routing), and then followed by job A (as there are as many as 6 jobs in total on job A's routing).

It should be noted that FCFS, SPT/STRT, EDD and CR are local rules, and LNJQNM and LNJQAM are 'look-ahead' rules.

(2) Utilization levels of resources. Consistent with earlier research (Gargeya 1994) and based on the explanations given in section 2 of this paper, three different long term resource (machine and tool) utilization levels of 50, 60 and 65% are used in this research. The utilization level is a ratio of the total time the resources are in use to the total time the shop is run. For each of the 37 scheduling methodologies (viz. 36 combinations of the six dispatching rules, and the six resource assignment rules and CBS approach) employed, 90 observations (i.e. 30 observations at the 50%

utilization level, 30 observations at the 60% utilization level and 30 observations at the 65% utilization level) were collected. For each of the 37 scheduling methodologies employed, means (for the 90 observations) on the three performance measures were computed.

4.2.3. *Model validation, data collection and statistical procedures*

The simulation model was validated by input/output analysis, by analysing a set of `snapshot' outputs, and through tracing of individual jobs through the system. In order to isolate the effects of experimental factors from sampling errors, multiple observations were used.

Since this research effort involves a stochastic simulation, each observation is one sample from an infinite population. In order to isolate the effects of experimental factors from sampling errors, multiple observations are required. The number of observations (sample size) depends on the variance of key performance measures and the desired precision in estimating mean performance measures. A set of pilot runs has been employed to estimate the variance of each performance measure. To be conservative, the sample size is chosen such that a confidence level of 95% can be established for the performance measure which shows the greatest variability. In addition, in order to reduce the variances of the performance measures, common random number seeds are used as a variance reduction technique.

A problem in collecting data in computer simulation experiments is the determination of when the system has reached steady state. In order to eliminate the initial bias, data from the initial transient period have been discarded. The length of the transient period has been determined by plotting the job flow time against the simulation time. In essence, the shop is considered to be in steady state when the job flow time `stabilizes'. Again, to be conservative, data from a run-in period (1 050 000 time units for the 50% utilization level) which are longer than the transient period have been discarded. In order to avoid a run-in period for each observation the 'batch means' approach is used for collecting multiple observations in one long simulation run. Using this approach, one long simulation run has been broken down into 'batches' or 'sub-runs' (of 1 050 000 time units for the 50% utilization level), such that the end of one simulation sub-run will serve as the starting point for the next sub-run. Each sub-run (which includes approximately 5000 completed jobs) yields one observation for each performance measure. The procedure used to deter- mine this sub-run length is described by Law and Kelton (1982). The run-in period (and length of the sub-run) for the 60% and 65% utilization levels are 875 000 and 807 700 time units, respectively.

As more than one performance criterion is employed in this research, Multivariate Analysis of Variance (MANOVA) is used as the primary statistical procedure for analysing the results from the factorial experimental designs of the research. The use of MANOVA (Greene 1978), rather than a series of Analyses of Variance (ANOVA), is to simultaneously evaluate the impact of factors on the multiple criteria. Interaction effects among factors and the main effects of factors will be first identified. Tukey's multiple comparison method (Neter et al. 1985) is used to answer detailed research questions, e.g. the relative performance of the scheduling approaches.

A full factorial fixed effect MANOVA model was employed to analyse the simulation results. Since different replications (problem sets) are considered as a blocking factor, this MANOVA model represents a randomized block design. It is assumed that there are no interaction effects between the blocking factor and experimental factors.

5. Analysis and results

A preliminary observation of the data indicated that there were several combinations of dispatching rules and auxiliary resource assignment rules that do not perform well on any of the three performance measures. Also, studying all the 37 scheduling methodologies at the same time complicates matters. Hence, it was thought that a reduced number of combinations should be used in the remainder of the research. The five best scheduling methodologies for each of the performance measures (shown in table 1) indicated that only 10 scheduling methodologies appear in the list. The CBS algorithm appears three times (once on each of the performance measures), the CR-EDD and CR-CR methods appear twice, and the remaining eight methods appear only once. Only one of the `look-ahead' dispatching rules (viz. LNJQAM) in combination with the EDD tool assignment rule appears in the list of 'top fives'. These 10 scheduling methodologies were interpreted in the remainder of the research.

Performance measure	Scheduling methodologies employed
Root Mean Square of Tardiness	CR-EDD EDD-EDD CBS CR-CR EDD-CR
Average System Time	CR-EDD CBS CR-CR EDD-EDD LNJQAM-EDD
Percentage of Tool Changes	SPT-STRT EDD-STRT CR-STRT FCFS-STRT CBS

Table 1. Five best scheduling methodologies employed for each performance measure.

Source of variation	Wilks' criterion	F value	Degrees of freedom N†	Degrees of freedom D‡	Pr > F
Scheduling methodology (RULE)	0.2643	54.2073	27	2536	0.0001
Utilization of resources (UTIL)	0.0534	963.2614	6	1736	0.0001
RULE by UTIL	0.3450	20.5643	54	2587	0.0001

Dependent variables: root mean square of tardiness (R_{RMS}); average system time (S_{av}); and percentage of tool changes (p_{tc}).

† N = numerator degrees of freedom.

‡ D = denominator degrees of freedom.

Table 2. Multivariate analysis of variance.

5.1. *Interaction effects and main effects in the MANOVA model*

A MANOVA was conducted with the three performance measures (i.e. root mean square of tardiness, average system time and percentage of tool changes) as dependent variables, and Shop Utilization level and the 10 Scheduling Methodologies employed as independent variables. The results of the MANOVA (provided in table 2) show that, at a level of significance of 0.01, there is an interaction effect between the 10 scheduling methodologies employed and the three levels of resource utilization. Separate Analysis of Variance procedures were carried out using each of the three measures of performance (tables 3-5). The results of the MANOVA and ANOVA show that both the experimental factors, i.e. the scheduling methodology employed and the level of resource utilization, have significant main effects. However, the main effects of the experimental factors cannot be interpreted, as there are significant interaction effects among the experimental factors. It is appropriate to examine the interaction effects among the two experimental factors in greater detail.

Source of variation	DF*	Sum of squares	Mean square	F value	Pr > F
MODEL	29	16 927 560 300.85	583 708 975.89	77.63	0.0001
Scheduling methodology (RULE)	9	4 109 971 792.57	456 663 532.51	60.73	0.0001
Resource utilization (UTIL)	2	7 406 236 999.29	3 703 118 499.03	492.50	0.0001
RULE by UTIL	18	5 411 351 509.00	300 630 639.39	39.98	0.0001
RESIDUAL	870	6 541 552 957.51	7 519 026.81		
TOTAL	899	23 469 113 258.36			

* DF: degrees of freedom.
Dependent variable: Root mean square of tardiness (R_{RMS}).

Table 3. Analysis of variance.

Source of variation	DF*	Sum of squares	Mean square	F value	Pr > F
MODEL	29	2 681 821 546.46	92 476 605.05	132.28	0.0001
Scheduling methodology (RULE)	9	79 160 375.40	8 795 597.27	12.58	0.0001
Resource utilization (UTIL)	2	2 459 253 933.50	1 229 626 966.62	1758.88	0.0001
RULE by UTIL	18	143 407 237.83	7 967 068.77	11.40	0.0001
RESIDUAL	870	608 212 905.78	699 095.29		
TOTAL	899	3 290 034 452.24			

* DF: degrees of freedom.
Dependent variable: Average System Time (S_{av}).

Table 4. Analysis of variance (continued).

Source of variation	DF*	Sum of squares	Mean square	F value	Pr > F
MODEL	29	0.1030	0.0036	275.50	0.0001
Scheduling Methodology (RULE)	9	0.0070	0.0007	60.24	0.0001
Resource utilization (UTIL)	2	0.0955	0.0477	3701.05	0.0001
RULE by UTIL	18	0.0006	0.0000	2.51	0.0001
RESIDUAL	870	0.0112	0.0000		
TOTAL	899	0.1143			

* DF: degrees of freedom.
Dependent variable: Percentage of Tool Changes (p_{tc}).

Table 5. Analysis of Variance (continued).

5.2. *Multiple comparisons of scheduling methodologies employed*

In this section, the detailed performance of the scheduling mechanisms employed, including the CBS approach, is examined using the Tukey method of multiple comparisons (Neter et al. 1985). Tables 6-8 illustrate the relative performance of the scheduling methodology employed under varying levels of resource utilization with respect to the root mean square of tardiness, average system time and percentage of tool changes. Several observations can be made from these tables.

(1) At a resource utilization level of 50%, the CBS approach along with EDD- STRT and CR-STRT, is in the best performing category with respect to each of the main performance measures (T_{RMS}, S_{av} *and* p_{tc}).

(2) At a resource utilization level of 60%, the CBS approach along with CR- STRT, EDD-STRT and FCFS-STRT, is in the best performing category with respect to T_{RMS} and S_{av}. However, with regard to p_{tc}, the CBS approach is dominated by CR-STRT, EDD-STRT and FCFS-STRT.

(3) At a resource utilization level of 65%, only the CBS approach is in the best performance category on every main performance measure (T_{RMS}, S_{av} *and* p_{tc}).

(4) As the resource utilization level increases, the performance of the CBS approach improves with regard *to* S_{av}.

(5) LNJQAM-EDD was found to be in the worst performing category at 50% and 60% utilization levels on T_{RMS} and S_{av}. However, as the utilization level was raised to 65%, LNJQAM-EDD was found to be in the best performing category along with CR-EDD, CBS, CR-CR, EDD-EDD and EDD-CR on each of those measures.

At 50% utilization		At 60% utilization		At 65% utilization	
Scheduling methodology	Mean value	Scheduling methodology	Mean value	Scheduling methodology	Mean value
EDD-CR	709.07	CR-EDD	2007.20	LNJQAM-EDD	4775.00
CR-EDD	714.40	EDD-EDD	2050.40	CR-EDD	4909.00
EDD-EDD	715.73	CR-CR	2092.00	CBS	5033.00
CR-CR	718.86	EDD-CR	2112.30	EDD-EDD	5109.00
EDD-STRT	721.66	CBS	2308.00	CR-CR	5307.00
CR-STRT	723.67	EDD-STRT	2310.20	EDD-CR	5417.00
CBS	785.35	CR-STRT	2315.70	EDD-STRT	6910.00
FCFS-STRT	882.45	FCFS-STRT	2679.00	CR-STRT	7260.00
SPT-STRT	1334.16	SPT-STRT	4977.00	FCFS-STRT	8573.00
LNJQAM-EDD	1473.23	LNJQAM-EDD	5686.60	SPT-STRT	23 763.00

Note: Scheduling methodologies with a side bar are not significantly different at an α level of 0.01.

Table 6. Tukey's range test for root mean square of tardiness (T_{RMS}).

At 50% utilization		At 60% utilization		At 65% utilization	
Scheduling methodology	Mean value	Scheduling methodology	Mean value	Scheduling methodology	Mean value
SPT-STRT	1129.78	CR-EDD	2093.00	LNJQAM-EDD	4152.00
EDD-STRT	1130.48	CR-CR	2142.00	CR-EDD	4233.00
CR-STRT	1134.48	CBS	2143.20	CBS	4312.00
EDD-CR	1145.62	EDD-EDD	2183.10	CR-CR	4539.60
EDD-EDD	1146.98	SPT-STRT	2190.80	EDD-EDD	4667.30
CR-EDD	1149.09	EDD-CR	2209.90	EDD-CR	4954.10
CR-CR	1150.20	CR-STRT	2210.80	SPT-STRT	5478.20
CBS	1156.31	EDD-STRT	2306.80	CR-STRT	5793.30
FCFS-STRT	1202.62	FCFS-STRT	2493.80	EDD-STRT	5999.80
LNJQAM-EDD	1288.29	LNJQAM-EDD	5686.60	FCFS-STRT	6774.20

Note: Scheduling methodologies with a side bar are not significantly different at an α level of 0.01.

Table 7. Tukey's range test for Average System Time (S_{av}).

At 50% utilization		At 60% utilization		At 65% utilization	
Scheduling methodology	Mean value	Scheduling methodology	Mean value	Scheduling methodology	Mean value
CBS	86.66	SPT-STRT	88.26	CR-STRT	89.15
EDD-STRT	86.74	EDD-STRT	88.36	SPT-STRT	89.16
SPT-STRT	86.80	CR-STRT	88.40	EDD-STRT	89.23
CR-STRT	86.87	FCFS-STRT	88.42	FCFS-STRT	89.24
FCFS-STRT	86.90	CBS	88.76	CBS	89.50
EDD-CR	87.26	EDD-EDD	88.91	EDD-CR	89.74
EDD-EDD	87.27	EDD-CR	88.98	EDD-EDD	89.75
CR-EDD	87.33	CR-CR	88.99	LNJQAM-EDD	89.78
CR-CR	87.35	CR-EDD	89.02	CR-CR	89.82
LNJQAM-EDD	87.36	LNJQAM-EDD	89.08	CR-EDD	89.92

Note: Scheduling methodologies with a side bar are not significantly different at an α level of 0.01.

Table 8. Tukey's range test for percentage of tool changes (p_{tc}).

A summary of the rankings of the 10 scheduling approaches with respect to the three performance measures at varying levels of utilization are given in table 9. It was a priori hypothesized that the CBS approach would yield better results than combinations of conventional dispatching rules and auxiliary resource assignment rules. Such a hypothesis is based on the premise that rules or approaches that take into account `look-ahead' information are likely to perform better than rules or approaches that take into account more `local' information. Combinations of `local' dispatching rules and auxiliary resource assignment rules (viz. EDD-EDD approach, SPT-STRT approach, etc.) take into account job-specific information that does not change over time. However, the results indicate that this hypothesis has not been fully supported. Naturally, the inability to reject the null hypothesis raises a question as to why the CBS approach, in particular, and `look-ahead' approaches, in general, do not perform significantly better than combinations of `local' dispatching rules and auxiliary resource assignment rules. Several reasons are advanced in an attempt to explain the `non-performance' of the CBS approach.

(1) The CBS methodology captures to a greater extent the dynamic nature of the shop compared to any of the other rules, e.g. the EDD rule, CR rule or LNJQAM rule. In capturing the dynamic nature of the shop, the CBS approach apparently introduces a greater degree of `nervousness' into the system. Small changes in the job mix tend to immediately change the entire prioritizing schema leading to less than superior performance on the part of the CBS methodology.

(2) Some jobs in the shop require critical resources and some jobs do not. If only a small percentage of jobs in the shop require a critical resource, overall shop performance will not benefit from the CBS approach. In such a situation, the CBS approach does not improve shop performance because only a small percentage of jobs are impacted by the assignment of a higher priority. When only a few jobs are given a high priority in dispatching and assigning auxiliary resources, the job-specific performance criteria for those few jobs do improve, but the overall performance of all jobs is not improved. On the other hand, in a situation where a large percentage of jobs make use of the critical resource, the CBS approach may not improve shop performance because too many jobs are given a higher priority. When all jobs are to be given a high priority in dispatching and assigning the auxiliary resources, the CBS algorithm cannot adequately distinguish among jobs, and the very purpose of the CBS approach is defeated.

(3) Table 7 indicates that the performance of the CBS approach with respect to S_{av} significantly improves as the level of resource utilization is increased. This suggests that as the level of resource utilization in a job shop increases, the CBS approach is likely to perform better than other mechanisms.

6. Conclusions

This research has investigated scheduling procedures in the dynamic job shop with auxiliary constraints. Local and look-ahead job dispatching/tool assignment rules are investigated, and a CBS approach has been developed in this research. The CBS approach makes use of an index of resource constraint, the Resource Criticality Factor (RCF) and `global' information to schedule jobs and assign tools contingent upon the constraining resource. The performance of several scheduling methodologies in an auxiliary resource-constrained job shop under varying levels of resource utilization has been compared using computer simulation experimentation. The results showed that shop performance was affected by the level of resource utilization, irrespective of the scheduling methodology used.

The results of multiple comparison tests showed that the CBS approach is always among the higher performing procedures with respect to root mean square of tardiness and average system time, particularly at higher levels of resource utilization. However, with regard to the percentage of tool changes, the ranking of the CBS algorithm deteriorates with increasing resource utilization levels. It has been found, quite contrary to expectations, that `look-ahead' scheduling approaches do not perform significantly better than simple rules (e.g. EDD, CR, etc.). There have been reports (Jacobs 1983, Meleton 1986) that `OPT' principles (i.e. `look-ahead' scheduling based on `bottleneck' operations) have not performed as well as expected. These reports are, somewhat, in consonance with the findings in this paper. One of the primary reasons why the CBS scheduling methodology does not provide a pronounced improvement over combinations of more conventional `local' dispatching and tool assignment rules is that the CBS approach attempts to react to the dynamic nature of the shop, and in the process introduces systems `nervousness'. Interestingly, the performance of contingency-based approaches may depend on the percentage of jobs making use of critical resources over time. If a large number of jobs make use of the critical resource, then the contingency approaches do not have the ability to `discriminate', thereby leading to futility. If a small number of jobs make use of the critical resource, then the performance of a large percentage of jobs turns out to be unaffected, thus negating the `good' performance achieved by a small number of jobs.

Despite the fact that the CBS approach has not turned out to be significantly better on any one performance measure, it is still advantageous to use the CBS approach because of the fact that in terms of the ranking of all scheduling approaches employed with respect to three performance measures, the CBS approach, unlike any other scheduling methodology, ranks among the better scheduling methodologies on each of the performance measures. As is evident in table 9, the mean ranking (on the three measures of performance) for the CBS approach improves as the level of utilization is increased. If management is interested in developing and implementing only one scheduling methodology so that the shop performs reasonably well on the three measures of performance employed in this research, then it would be appropriate to use the CBS algorithm. This, more than anything else, underscores the importance of the CBS algorithm. This thread of logic emphasizes that future research needs to look at more `global' and multiple criteria in assessing shop performance while using `look-ahead' scheduling approaches.

There are several additional research needs in the area of applying shop loading algorithms and `look-ahead' rules in auxiliary resource-constrained job shops. Some of those needs are enumerated as follows.

(1) One of the vital, and important, aspects of shop floor control is job order releasing. Past research has shown that shop performance can be enhanced by making use of a job order-releasing pool and a job-triggering mechanism. Barring the study by Park (1987), there are no studies that report the impact of a job order-releasing and triggering mechanism in the dual-constrained job shop. Even the study conducted by Park (1987) concentrated on labour-constrained job shops, where the secondary resource (labour) is homogenous in nature. In an

auxiliary resource-constrained job shop, the secondary resource (in the form of an auxiliary resource) is more heterogeneous in nature. Hence, future research should address the impact of a job order- releasing and triggering mechanism on an auxiliary resource-constrained job shop.

(2) In this research, job due dates were set based on the Planned Lead Time, which is a function of total predicted processing time, and is a parameter. There is very little research that has addressed the impact of due date-setting mechanisms on scheduling approaches in dual-constrained job shops, and in particular auxiliary resource-constrained job shops. Hence, future research needs to address the impact of due date-setting mechanisms on the job shop constrained by auxiliary resources.

(3) Future research should focus on more complex situations in which multiple tools may be required for a single job operation.

(4) This research has shown that the CBS approach has turned out to be a consistently `good' performer on all the individual measures of shop performance. It is essential that future research needs should address the issue of developing more `global' measures of shop performance.

(5) Future research should address methods by which contingency-based scheduling approaches could be desensitized to minor changes in job mix or shop conditions. In other words, methodologies should be developed by which the `nervousness' in the CBS approach could be minimized.

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