Scheduling research in multiple resource constrained job shops: a review and critique

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Abstract:

Over the past several years, a number of survey, classification, and review articles have focused on scheduling research in machine [only] constrained job shops. Barring the work of Treleven (1989), there is no reported research that presents a detailed review of the issues related to scheduling and sequencing in job shops with multiple resource constraints. In his article, Treleven reviewed the research in job shops constrained by machines and labour. Job shops are not only constrained by machines and labour, but by auxiliary resources (in the form of tooling. etc.) as well. This paper extends the work of Treleven by reviewing the literature on scheduling in job shops constrained by more than one resource and comparing the scheduling research in auxiliary resource-constrained job shops with that of labour-constrained job shops. In addition, this article raises some issues for future scheduling research in multiple resource-constrained job shops.

Keywords: scheduling | sequencing | job shops | Treleven | labor | resources

Article:

1. Introduction

Over the past few decades, a number of survey, classification and review articles and books have been written on the subject of sequencing and scheduling in job shops (Sisson 1959, Mellor 1966, Conway *et al.* 1967. Moore and Wilson 1967, Elmaghraby 1968. Spinner 1968. Bakshi and Aurora 1969, Day and Hottenstein 1970, Baker 1974, Coffman 1976, Innogy Kan 1976. Panwalkar and Iskander 1977, Eilon 1978. Godin 1978, Salvador 1978, Graham *et al.* 1979. Schrage 1979. Graves 1981, Blackstone *et al.* 1982, Lawrence and Zanakis 1984, Emmons 1987, Treleven 1989, and Baker and Scudder 1990). In the majority of this literature, the authors have dealt, in an in-depth fashion, with scheduling in job shops constrained by machines only. Barring the work of Treleven (1989), none of this work has addressed, in detail, the issue of scheduling job shops with more than one constraint. It has been long recognized that shop floor management includes not only the scheduling of machines directly involved in production but also the scheduling of other needed resources such as labour, and auxiliary resources (namely, maintenance equipment, and tooling). Resources required to make labour and machines productive are termed auxiliary resources (in this paper) or adjunct resources (Blackstone 19X9). 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. This broad based definition includes not only those attachments and accessories needed during production, and maintenance, but also supporting equipment needed to transport and carry (such as forklifts, cranes, automated guided vehicles, and pallets).

In this paper, a constraint (or bottleneck) 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 in this paper:

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

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

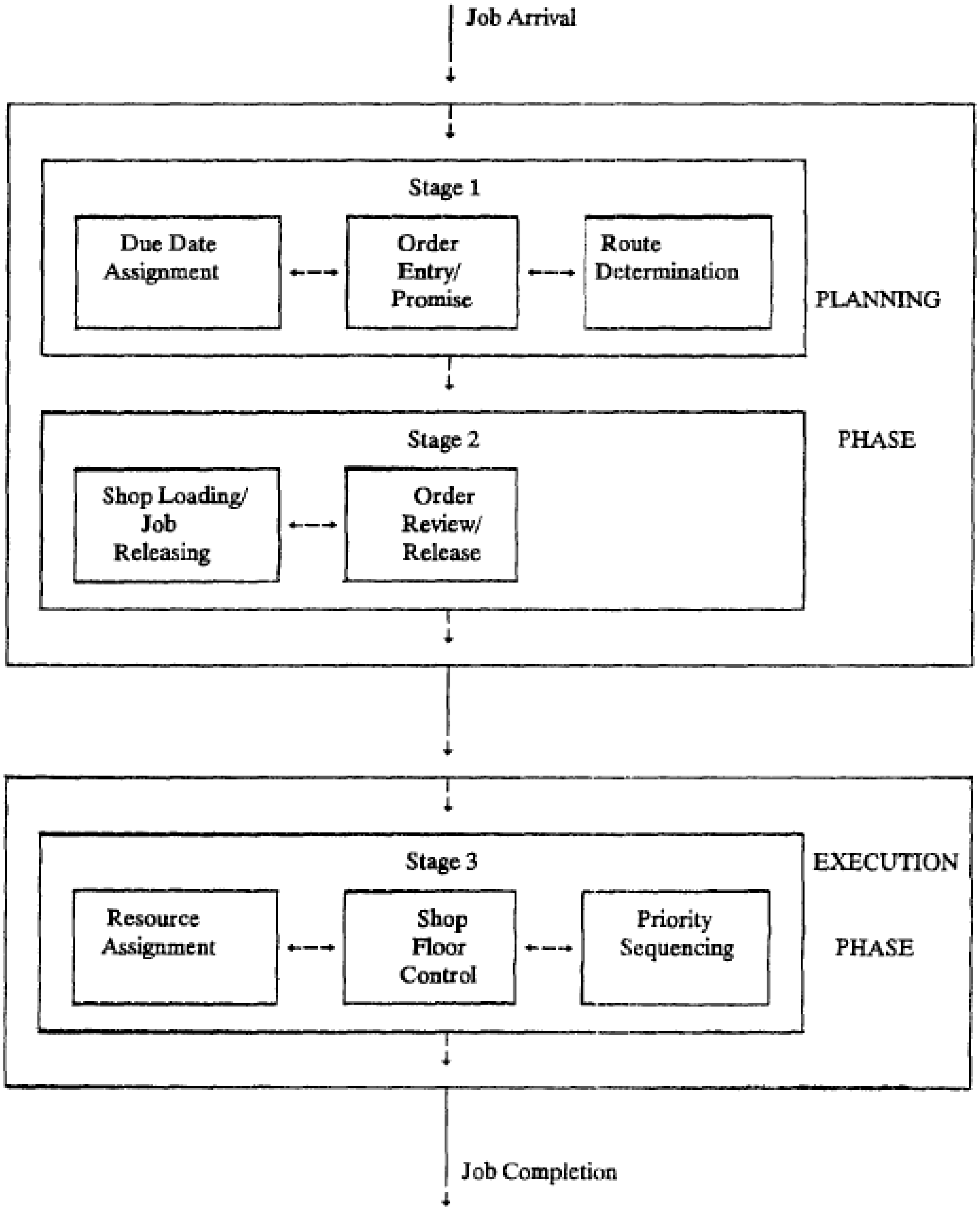
(4) Machine-only constrained job shop: a job shop in which machines are the only constraints. There are no constraints on labour and auxiliary resources.

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 a labour constrained job shop. In general, auxiliary resource constrained 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 queue). However, auxiliary resources, and in particular tools, have a heterogeneous characteristic. Orders in queue at a work centre do not simply require one type of tooling or auxiliary resource; they require a specific tool or a set of tools. In other words, the need for a particular type of labour is only machine dependent, while the need for a particular type of tool is both machine and job dependent.

The production control system for a job shop can be viewed as a three stage process as shown in Fig. 1 (Baker 1984, and Ragatz and Mabert 1988). Treleven (1989) provides an extensive review of the design and operating (planning and execution) decisions in labour constrained system research. This paper is directed towards a review and critique on only scheduling research, but is applicable to the broader scope of multiple resource constrained job shops. Hence, the primary focus of this paper is on the execution phase of the job shop production control system. In the next section, the interaction effects of resource constraints on shop performance are presented. In §§ 3, 4, and 5, the scheduling research in labour constrained, auxiliary resource constrained, and more than two resources constrained job shops is presented. Also, in § 4, scheduling research conducted in auxiliary resource constrained job shops is compared with that carried out in labour constrained job shops. In the concluding section, a brief agenda for future research in multiple resource constrained job shops is outlined.

2. Interaction effect of resources in the job shop

The job shop production system can be categorized in terms of the extent to which resource constraints are present in the production process. More specifically, the number and type of constraining resources in the shop provide an important framework for analysing the production shop. A shop with constraints only on auxiliary resources, or labour (with no constraints on machines) in the long run is probably unrealistic. In the short run however, a shop may be constrained by auxiliary resources or labour only. This may primarily occur due to the type of job mix that may exist at a particular period of time. For a better understanding of multiple resource constrained job shops, it is essential to study the importance of the interaction effects of resources in job shops with more than one resource.



In a dynamic machine-only constrained shop, machines are sometimes idled due to the stochastic nature of the shop. In a dual constrained job shop (labour constrained job shop, or auxiliary resource constrained job shop), the machine can also be idle due to the non-availability of the second resource. Figure 2 illustrates the effective utilization of a machine in a dual constrained shop.

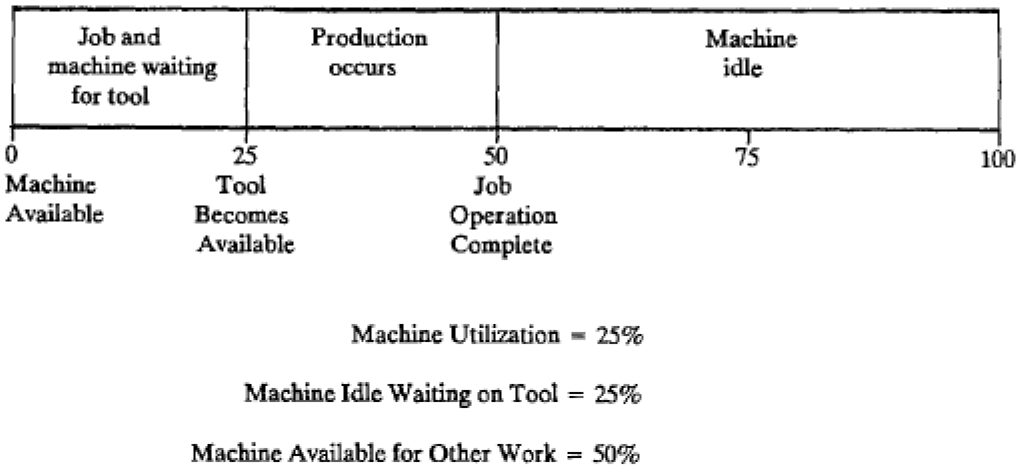


Figure 2. Breakdown of machine utilization in a dual resource constrained job shop.

In dual resource constrained job shops, the average job flow time is not only impacted by the degree of constraint imposed by each resource, but also by the interaction effect of the resource constraints. Figure 2, conceptually, shows the impact of introducing a second resource constraint on average job flow time. As the degree of auxiliary resource constraint is reduced relative to the machine constraint, Curve I and Curve II in Fig. 3 move closer together. Curve II in Fig. 3 is based on the same level of utilization for the two resources. Figure 4 is a three-dimensional surface graph which more completely depicts the interaction effect of machine and second resource utilization levels on average job flow time for a typical dynamic shop. Figure 4 was developed based on a computer simulation of a 6 machine, 4 tool randomly routed job shop. From the three dimensional surface in Fig. 4, it is evident that as the average machine utilization increases, the average job flow time also increases. Also, as the tool utilization level increases, the average job flow time increases. At a given level of machine utilization, the rate of change in average job flow time is greater at higher levels of tool utilization. Also, at a given level of tool utilization, the rate of change in average job flow time is greater at higher levels of machine utilization. At higher levels of both machine and tooling constraints, average job flow time increases dramatically. Each additional constraint does not have a simple 'additive' impact on flow time but rather a 'compounding' or synergistic effect.

3. Labour constrained job shops

The single constraint shop presumes that other resources may be present in the shop, but they do not significantly restrict output. In a machine-only constrained shop, only machines are 'active' constraints in the shop. Traditionally, a shop has been considered to be machine constrained if there are ever one or more jobs waiting to be served by a machine. For example, Nelson (1966) defined a labour constrained production system as one in which there are L labourers and M machine centres (each having *ma* identical machines), and

$$\sum_{a=1}^{M} m_a > L \qquad (1)$$

Such a definition assumes that a labourer is required during the entire time a job is being processed at a machine. Furthermore. Nelson's definition is inadequate to define a labour constrained shop where significant labour is required for setups. In spite of this shortcoming, Nelson's definition has been an often-quoted standard in defining shops with more than one resource type.

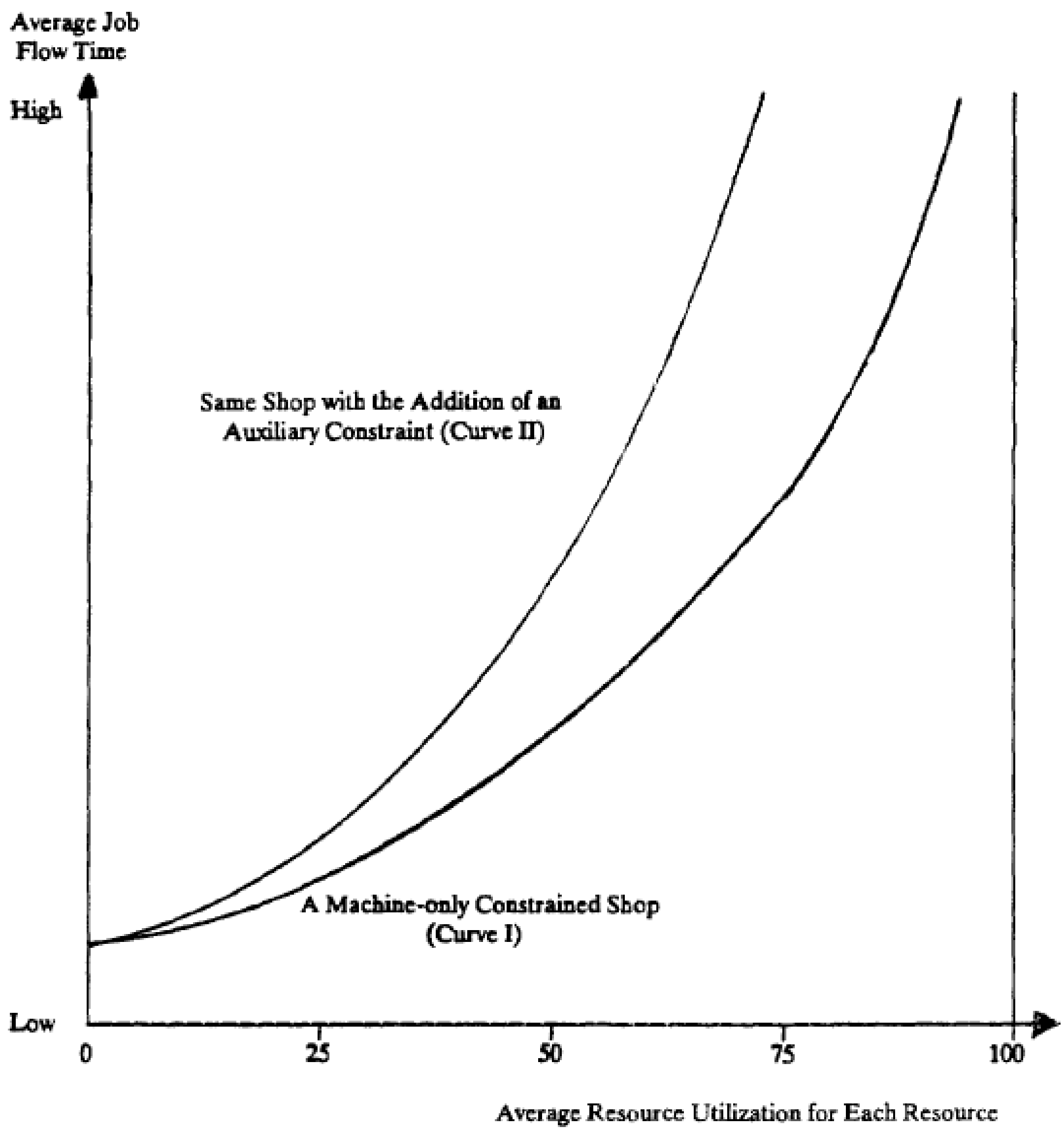


Figure 3. Impact of the second resource constraint on average job flow time.

Most of the job shop scheduling literature has been written on the assumption that machines are the only shop constraints; labour and auxiliary resources are always available for processing an order at any work centre. This assumption generally does not fit the 'real' world. The more realistic situation is that not all machines are manned simultaneously; labour is used as a flexible resource assigned to operate different machines at different times depending on the needs of the different orders (Park 1987).

Treleven and Elvers (1985) stated that:

> 'A dual-constrained job shop is one in which shop capacity may be constrained by machine and labour capacity or both. This situation exists in shops that have equipment that is not fully staffed and machine operators who are capable of operating more than one piece of equipment. These operators may be transferred from one work centre to another (subject to skills restrictions) as the demand dictates. When a work centre is fully staffed, transfer of additional operators to that centre will not increase capacity. In this situation, the centre is said to be machine [only] limited. A labour [only] limited situation exists when a work centre is not fully staffed. Addition of more, identical equipment will not increase capacity; addition of more operators will. In a dual [machine and labour] constrained job shop, some or all of the work centres have the potential to alternate between being machine [only] and labour [only] limited (p. 51).

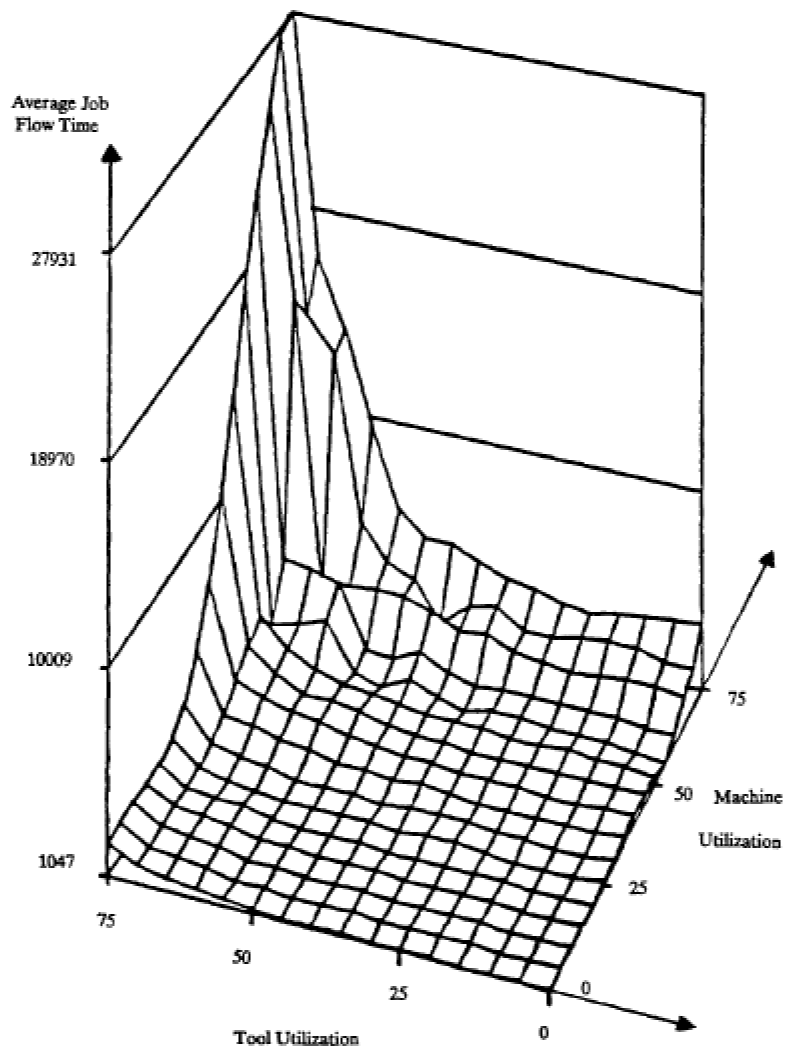


Figure 4. Impact of resource constraints on average job flow time.

The definition given by Treleven and Elvers) 1985) does not specifically consider the degree of constraint imposed by each resource. As shown in Fig. 4, the constraint level of both resources impacts total shop performance. Treleven and Elvers also state that labour constrained shops have equipment that is not fully staffed. This observation may not be relevant when labour is required only for equipment setup. Once a machine is set up, labourers may be free to move to other machines. Ne1ther the Treleven and Elvers (1985) study nor other studies (Nelson, 1967, 1968 and 1970, Goodman 1972, Holstein and Berry 1972, Fryer. 1974 and 1975, Gunther 1979 and 1981) distinguished between production and setup requirements of labour. In previous research on labour constrained job shops, labour is assumed to be required for the entire duration of the operation on a machine and not for setup.

In most of these labour constrained job shop studies, while the labour utilization was maintained at high levels (80- 90%), the machine utilization varied from 45% to 90% (wherever reported). In labour constrained job shop studies where the machine and labour utilization were 90%, the machines were always manned $(L = \sum_{a=1}^{M} m_a)$. As such, in these shops labour was not constraining the system even though machines and labour were 'used' in the shop. In most studies where the shop was truly labour constrained, the machine utilization (when reported) was typically not more than 75%. This is in line with Fig. 4. It should he noted that high labour utilization levels restrict flexibility (Nelson 1967, Hogg *et al.* 1975b. Rochette and Sadowski, 1976) and low labour utilization levels limit the job shop's ability to use its capital resources efficiently (Nelson 1968, Rochette and Sadowski. 1976). Further, Nelson (1967), Hogg *et al.* (1975b), Rochette and Sadowski (1976), and Treleven and Elvers (1985) have pointed out that labour constrained job shops operate most efficiently at machine staffing levels ranging from 50% to 75%.

In the last couple of decades, researchers have addressed the dual (machine and labour) constrained job shop problem using heuristic (Rowe 1960, Allen 1963, Nelson 1967, 1968, and 1970, Goodman 1972, Holstein and Berry 1972, Fryer 1973, 1974 and 1975, Weeks and Fryer 1976 and 1977, Weeks l':J79, Gunther 1979 and 1981, Treleven and Elvers 1985) and mathematical approaches (Avi-Itzhak *et al.* 1965, Nelson 1966, Takács 1968, and Sykes 1970). Park (1987) observed that there is no indication that sophisticated mathematical approaches hold a distinct advantage over heuristic approaches in solving problems in more complex systems.

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. Thus, the level of complexity of shop floor control in the execution phase is greater in a dual constrained shop as compared to machine only constrained shop. Examples of labour assignment rules for assigning labour to the work centre include (Treleven 1982):

(I) Job in queue with the earliest entry into the system;
(2) Earliest average entry into the system of all jobs in its queue;
(3) Job in queue with the shortest imminent operation time;

(4) Shortest average imminent operation time of all jobs in its queue;
(5) Job in queue with the earliest due date;
(6) Earliest average due date of all jobs in its queue;
(7) Job in queue with the lowest critical ratio;
(8) Lowest average critical ratio of all jobs in its queue;
(9) Job in queue with the least slack per remaining number of operations;
(10) Lowest average slack per remaining number of operations of all jobs in its queue; and
(11) Longest queue.

Labour constrained systems not only have a second set of scheduling execution rules (labour assignment rules in addition to dispatching rules), but also have a second set of performance measures (e.g., number of labour changes, cost of labour transfers, etc.) in addition to conventional job shop performance measures such as average work-in-process, average job tardiness, number of jobs tardy, etc. Similar to the machine-only constrained job shop literature, a large portion of the labour constrained job shop research has been focused on the execution phase of shop operations. Rowe (1960), Allen (1963), and Elvers and Treleven (1985) addressed the issues relating to job priority, sequencing, and dispatching in the job shop constrained by machines and labour. A considerable number of studies have been conducted on the labour assignment and transfer problem (Nelson 1966, 1967, 1968, and 1970, Goodman 1972, Holstein and Berry 1972, Fryer 1973, 1974, and 1975, Gunther 1979 and 1981, Tre1even 1982, and Elvers and Treleven 1985).

Nelson (1967, 1968, and 1970) developed a small general model (two work centres, each consisting of identical machines) for studying labour constrained systems. Nelson (1967) varied the number of workers (L) from one through four. When L = 4, there was a worker for each machine in the system, resulting in only a machine constraint. He showed that the assignment of idle labour to the work centre with the most jobs in queue in conjunction with the shortest operation time dispatching rule for jobs at machines is the most effective combination to reduce the mean flow time for jobs. The assignment of idle labour to the work centre with the most jobs in queue in conjunction with the first-in-system-first-served dispatching rule for jobs at machines is the most effective combination to reduce the variance of the flow time. In a later study, Nelson (1970) concentrated on two specific factors of system control: labour efficiency and the degree of centralized labour assignment control. He tested the performance of a labour constrained job shop by varying the labour efficiency and the degree of centralized control of labour. The results indicate that the degree of centralized control of labour assignment is progressively more important to system performance as the labour efficiency for each work centre decreases.

Recognizing the high costs of labour transfers in a typical manufacturing environment, Holstein and Berry (1972) identified a specific work flow labour assignment rule which sought the advantage of moving workers among machines without incurring unduly large control costs (i.e. costs of transferring workers and supervisory costs involved in making and following up on decisions). The principal objective of the Holstein and Berry (1972) work flow labour assignment rule was to provide capacity through labour assignments so that work moved smoothly and rapidly along the main paths (i.e., those routes which have the heaviest work load). This specific study addressed the problem of determining labour assignments at or near the time of actual production, when assignments made at the planning level are adjusted to respond to actual shop conditions, e.g., pressures for the completion of specific orders, equipment breakdowns, or the existence of long queues caused by statistical variations in the movement of work through the shop. 'Work flow structure' information was used to determine labour assignments. Work flow structure information describes the way jobs flow through the shop. With the application of the work flow labour assignment rule, priority is given to jobs on the main work flow path. Once there, the rule makes it difficult for labour to be reassigned. The net effect of the application of the work flow labour assignment rule is a significant reduction of job flow times along 1 he main paths of work flow and a significant reduction of the incidence of labour transfers without great increases in the overall flow time statistics.

Goodman (1972) considered both machine and worker flexibility in evaluating machine and worker assignment rules in a job shop consisting of five machines and five workers. Machine flexibility was defined as a machine's capability to perform another machine's operation, and worker flexibility was defined as a worker's ability to operate more than one machine. Each machine and worker is designed to have a specified (i.e., fixed and known level of) proficiency (efficiency, using Nelson's terminology). The more proficient a resource (machine or worker) is in performing an operation, the higher the rate of production and reliability of performance for that operation. Three levels each of machine and labour flexibility were used in the study.
As flexibility increased, machines could perform more types of operations and workers could operate more machines (of course not all machines at the same level of proficiency). The machine and worker assignment rules that were tested ranged from assigning work to workers and machines with the highest proficiency to assigning work at random to workers and machine's (independent of the degree of proficiency). As the degree of proficiency oriental ion in the worker assignment rules was increased, the shop showed improvement in the mean values of flow time and lateness criteria.

Gunther (1979) evaluated a number of labour assignment procedures in a labour constrained job shop in which labour transfer involves a deterministic time delay. The study showed that when workers are eligible for transfer whey they are idle and there are no jobs in queue, the shop performed well in terms of mean flow time, and Gunther (1979) recommended such a transfer policy for situations in which delays on account of labour transfer were considered. (Gunther 1981) extended his 1979 research to include information access delays as well labour transfer delays. He suggested that at a labour constrained work centre. jobs can be delayed not only because all workers are unavailable processing jobs at other work centres, hut can also be delayed when workers are being transferred between work centres and when workers are accessing information needed in order to transfer. The results (assuming information access delays and labour transfer delays indicate that if the first-come first- serve sequencing rule is applied and labour transfer and assignment is delayed at a work centre until all jobs at that work centre are completed, both the mean ;.md the variance and job flow time are reduced. Both the studies carried out by Gunther involved only one worker and two machines.

Treleven (1982) and Treleven and Elvers (1985) examined eleven different labour assignment rules in conjunction with five dispatching rules in a job shop with 18 machines and 12 machine operators (giving a machine staffing level of 67%). A secondary experiment was also conducted with 18 machines and 9 machine operators (for a machine staffing level of 50%). In each of the experiments, the machine and labour resources were divided equally among three divisions.

Divisions represent segments of the production facility among which the operators cannot he transferred. This is due to the great differences in the skill levels required. The jobs, however, flow from one division to another as required by the routeings. Within each division there are three work centres, each containing two identical machines fed by a common queue. The operators in each division (four in the primary, three in the secondary experiment) may be transferred within the division from one centre to another subject to a limitation of one operator per machine. The results of the study showed that none of the labour assignment rules has an impact on shop performance measures (with the exception of the number of labour transfers) that is significantly different from the others. Such a finding appears to be counter-intuitive, for one might expect that particular labour assignment rules paired with dispatching rules would perform better than other pairings. The lack of a significant performance differentiation among the labour assignment rules for five performance criteria (mean queue time, queue time variance, mean lateness, lateness variance, and percentage of late jobs) suggests that the choice of labour assignment rules should be based on the performance measure relating to the number of labour transfers or performance criteria other than those used in the study. The lack of significant differences among the labour assignment rules based on mean job flow time is contrary to the findings of Gunther (1979 and 1981). Such a difference in results could possibly be explained by the assumption of information access and labour transfer delays made by Gunther. In an extension study, Elvers and Treleven (1985) concluded that there was no significant difference between impacts of job shop and flow shop routeing patterns on the relative effectiveness of various job dispatching rules.

Recognizing that the timing of labour transfers is important in a labour constrained job shop (based on the work of Weeks and Fryer 1976), Treleven (1987) studied two 'push' rules and three 'pull' rules. A push labour assignment decision means that labour cannot be transferred until it is in excess at a work centre. A pull labour assignment decision initiates labour transfers whenever labour needs are deemed to be critical (by using whatever indicators) at a particular work centre. In other words, 'push' rules involve labour transfers initiated back on lack of need, and 'pull' rules involve labour transfers initiated by labour need. Treleven presented arguments for using 'pull' rules and 'push' rules depending on the specific environment in which the shops operate, but did not comment on which rules ('pull' or 'push') are better.

Fryer (1975), Hogg *et al.* (1975b), Hogg *et al.* (1977), and Weeks (1979) concluded that dual resource constrained job shops with a smaller number of resources are more sensitive to changes in dispatching and resource assignment rules than job shops with a larger number of resources. However, their studies indicated that the rankings of the decision rules were not significantly affected by shop size.

Miller and Berry (1974) conducted an experimental comparison of labour-loading and labour-saved heuristics in assigning manpower in a closed job shop. The labour-loading heuristic builds up a solution, piece by piece, until a complete labour assignment plan is developed which includes all the labourers and machines. The labour-saved heuristic starts with a complete labour assignment plan and modifies it until no further reductions in idle labour and machine time can be obtained. Through their study, Miller and Berry concluded that the labour-loading heuristic provides a simple manual procedure for determining labour assignments which is of practical use in many operating situations. However, they argued, that important gains in labour and machine productivity can be obtained, at the expense of added computational requirements, by applying the labour-saving heuristic.

Park (1987) proposed and tested several mechanisms (immediate release, maximum shop load, forward finite loading, and backward infinite loading) for controlling the release of jobs to the shop floor in a labour constrained job shop. The results of the study showed that not only does the job releasing function have a significant impact on the performance of the labour constrained system, but the effective release mechanisms should consider the job information and current status such that the changes in the due date tightness, labour flexibility and cost structure can be considered. In addition, Park (1987) demonstrated that system performance improves significantly when minimum labour flexibility is introduced into the system: continuing increases in labour flexibility show a diminishing return in shop performance.

4. Auxiliary resource constrained job shop

Auxiliary resources in the job shop have traditionally been considered as unconstrained, or as part of machine capacity. Practitioners have long recognized that constraints in the form of machine capacity, manpower availability, and reduced safety stock levels result in lowered production capability. 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 now realize that the planning and control of auxiliary resources is as important as the management of machines and manpower (Melnyk *et al.* 1989).

Emphasizing the importance of auxiliary resources, and particularly tooling in a production environment, Mason (1986) offered the following statistics:

(1) Typically, 16'i'o of scheduled production cannot he met because tooling is not available.

(2) In most cases, 40- 80% of a foreman's time is spent looking for and expediting materials and tools.

(3) In some plants, operators spend up to 20% of their time searching for cutting tools.

(4) *30*- 60% of a shop's tooling inventory is somewhere on the shop floor, lost and expensed, much of it stored away in personal tool boxes.

(5) Typically, a metalworking firm's annual budget for tooling, jigs, fixtures, consumable supplies, and spare parts is 7 12 times larger than its entire capital-equipment budget.

Strycula (l987) pointed out that jobs spend as long as 7% of their total time in the shop, waiting for tools. In addition, there are some less obvious, and sometimes non-quantifiable costs associated with tooling. Some of these costs are: (1) value of excess tool inventory required because of hoarding and needless duplication, (2) value of obsolete tool inventory, (3) annual tool inventory loss/shrinkage, (4) excess charges for emergency purchases because of the lack of necessary tooling inventory, (5) wasted expensed on the purchase of incorrect tools, and (6) market losses due to shipments missed because of missed tools. The panacea for all these problems, as suggested by Wassweiler (1982), Devaney (1984), Green (1984), Kupferberg (1986), Mason (1986), and Strycula (1987), is efficient and effective tool management systems and efficient and effective utilization of tooling and auxiliary resources. There is little reported research with regard to auxiliary or tooling constraints, and the impact of such constraints on the operation and scheduling, in a job shop environment. It is essential that future research should include the development of a more general and complete definition such as Nelson's for auxiliary resource constrained shops.

Only in the last couple of decades have auxiliary resource management issues been addressed in the literature. For improving shop floor productivity, Broom (1967), Deis (1983), and Mason (1986) suggested tool tracking and monitoring, and Gayman (1986), and Mason (1986) recommended toolroom automation (which includes proper handling of tools and tooling data enabling faster location and issue of tools). Wassweiler (1982) emphasized the need for integrating tool planning with Material Requirements Planning. In addition, he points out that tooling is most frequently a concern of companies that are involved in heavy fabrication (e.g. stamping, hobbing, grinding, etc.), and those firms that use: (l) long lead time replacement tools, (2) high-cost tools, (3) a large number of duplicate tools, and (4) non-company owned tools. However, the suggestions presented by Broom (1967), Wassweiler (1982), Deis (1983), Gayman (1986) and Mason (1986) are not based on any 'empirical' studies.

Brown *et al.* (1981) were the first to empirically study the impact of limited tooling in production planning and execution. Their paper addresses multi-period production and sales planning in a seasonal industry with a single dominant production operation for which auxiliary resources (in the form of dies, moulds, etc.) can be shared among parts and is limited in availability. The problem is modelled as a mixed linear integer program. Lagrangean relaxation is applied so as to exploit the availability of highly efficient techniques for minimum cost network flow problems and for single-item dynamic lot-sizing type problems. Though addressing tooling issues in the production system, Brown *et al.* (1981) did not deal with the execution stage of the job shop production control system.

As compared to the substantial amount of research that has been reported with regard to the execution stage of shops constrained by machines and labour, there has been very little research addressing the role of auxiliary resources at the shop floor control stage. However the scant research that has been carried out in auxiliary constrained shops has primarily related to the execution stage (i.e. job sequencing and scheduling at work centres). As in labour constrained job shops, auxiliary resource constrained job shops (i.e., job shops which 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) stated 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.* (1989) does not focus on the issue of how tooling will be assigned to the various machine centres.

Melnyk *et al.* (1989) simulated a simple job shop based on one type of operation, one machine, and one type of tool for all jobs. They simulated a job shop with a single work centre operating and the remainder of the shop in aggregate. Despite the latter being included to provide competition for four different auxiliary resources (in the form of tools) available in the shop, the auxiliary resource assignment rules were not operationalized by Melnyk *et al.* (1989) in the same manner as was done by Treleven (1982). It should also be noted that Treleven's (1989) scheduling research in dual (labour) constrained job shops had the number of machines varying from 2 to 1000 and the number of workers from 1 to 500, which is very different from the model built by Melnyk *et al.* (1989). Their study was made under the following restrictive assumptions: (1) no penalty for tool changes; (2) tooling has infinite life; (3) only production tooling has been considered; and (4) simple dispatching rules were used.

In their study. Melnyk *et al*, (1989) reported that both machines and tools had the same level of utilization (85%). Such a high effective utilization however is in conflict with Fig. 4 that shows explosive queues under scenarios with such high utilization of both resources. Once again, the answer to this dilemma may be in the fact that a one machine shop (in the Melnyk *et al.* 1989 study) is unrealistic. They also evaluated the interaction between tooling assignment rules. Job priority rules, and the level of tooling available. The four tooling assignment rules were:

(1) *Job priority.* This is the most simple of tool assignment rules. When the machine becomes idle, the job at the head or the queue is selected. If the tool for the job is available, the job is processed immediately. However, if the tool is not available, then the job waits (along with the machine) until the required tool is free. As a result, the work centre is idle while waiting for the tool.

(2) *Job priority subject to tool availability.* Under this tooling assignment logic, when the machine completes a job, the highest priority job for which the tool is available is chosen for processing. This rule seems to be more of a dispatching rule than a tool assignment rule.

(3) *Avoid tool change.* Under this rule, once a tool is assigned to the machine, it is not released until all of the jobs in the queue needing that tool are processed. The order in which the jobs using the tool are processed is determined by the priority rule. This could be viewed as a two-queue system. The high priority queue consists of all jobs not requiring a tool change while the low priority queue consists of jobs requiring a tool change.

(4) *Modified avoid tool change.* Of the four tooling assignment rules, this is the most complex. This is a four-queue system. Jobs are categorized by whether they require a tool change (as in the ·avoid tool change' rule) and also by their criticality. The criticality of each job is determined by its ·float'. Float is defined as the slack time minus a safety factor. A safety factor of 1·50 is used in the study. Jobs with a negative float value are considered critical. When the machine completes a job, the next job to be processed is chosen by examining the four queues in the following order: (1) critical job with no tool change, (2) critical job with tool change, (3) non-critical job with no tool change, and (4) non-critical job with tool change. Within each queue, jobs are ordered by the priority rule.

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 had used labour assignment rules in determining which machine would be first served by an idle worker, Melnyk *et al.* (1989) used tool assignment rules somewhat interchangeably with job dispatching rules (for prioritizing jobs at machines) based on a availability of tools. The 'avoid tool change' rule is the only tool assignment rule (used by Melnyk *et al.* (1989) 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.* (1989) 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.* (1989) considered only one machine centre with four tools. With only one machine centre, 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 Treleven (1982), and Melnyk *et al.* (1989), it is essential to adopt a common definition of dispatching rules and resource assignment rules. In this paper, it is suggested that the definitions of dispatching rules and auxiliary resource assignment rules are identical in principle to the dispatching rules and labour assignment rules used by Treleven (1982). Consequently, 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.

Melnyk *et al.* (1989) did show that the level of tool availability has a significant impact on shop floor performance in terms of mean flow time, mean tardiness, number of jobs tardy and number of tool changes. Their study showed that the proper choice of tool assignment rules appears to be more critical than choice of priority (dispatching) rules in a tool constrained environment. In a subsequent study, Ghosh *et al.* (1992), using the same model as the one used by Melnyk *et al.* (1989), reported that as the level of sequence dependence increases and the availability of tooling decreases, the performance of the shop is greatly influenced by the tool assignment rule used to manage the flow of tooling to and from the work centres. These findings, by implication, shows a possible difference between labour constrained scheduling research and auxiliary resource constrained scheduling research. However, once again, a point to note is that Melnyk *et al.* (1989) treated tool assignment rules as a form of dispatching rules.

Nelson (1967) and Melnyk *et al.* (1989) have been the pioneers in conducting empirical research in the area of scheduling resources in labour constrained job shops and auxiliary resource constrained job shops respectively. However, accurate comparisons between the two studies cannot be made because of different assumptions made in the studies by Melnyk *et al.* (1989) and Nelson (1967). The following paragraphs illustrate differences in the two models. Nelson's model included two work centres (each consisting of two identical machines) and varying number of workers (L varying from 1 to 4 to build in the degree of constraint). Nelson used average job flow time and number of jobs in the system (i.e. average work-in-process) as performance measures. Nelson used three dispatching rules (shortest processing time, first-come-first-serve, and first-in-system-first-serve), and five labour assignment rules (random assignment, first-come-first-serve, shortest processing time, first-in-system-first-serve, and most jobs in queue). The labour assignment rules used by Nelson are identical in principle to the ones used by Treleven (1982).

The model developed by Melnyk *et al.* (1989) had one work centre (consisting of one machine) and the remainder of the shop in aggregate to provide competition for four different auxiliary resources available in the shop. While Nelson used average job flow time and average work-in-process as performance measures, Melnyk *et al.* (1989) used average number of tool changes, average number of tardy jobs, and average tardiness in addition to average flow time. Melnyk *et al.* (1989) used two dispatching rules (shortest processing time, and minimum slack), and four tool assignment rules (job priority, avoid tool change, modified avoid tool change, and job priority subject to tool availability). However, as stated earlier, the tool assignment rules used by Melnyk *et al.* (1989) are not compatible with the labour assignment rules developed by Nelson (1967), and Treleven (1982).

Over the last few years, there has been considerable research on the scheduling of automated guided vehicles (AGVs) and materials handling systems (MHSs) in job shop environments. Egbelu and Tanchoo (1984) presented heuristic rules for dispatching AGVs in a job shop environment. Their study focused only on constraints in the form of one resource (i.e. AGVs). The paper written by Hutchinson *eta/.* (1991) briefly mentioned material handling, in-system storage, tool magazines, and pallets and fixtures; however, these resources did not pose any constraints on the system they studied. Sabuncuog1u and Hommertzheim (1992) proposed an on-line dispatching algorithm for scheduling jobs on a machine or an AGV. However, their study does not involve a simultaneous requirement of the AGV and the machine. Srinivasan and Bozer (1992) simulated a manufacturing system that consists of two components: workstations (termed machines in the current paper) and a trip-based material handling system. Their study related resources to the generation of work-in-process (WJP). Their study showed that machines are largely responsible for the WIP even if the utilization of the machines is approximately equal to the utilization of the devices in the trip-based material handling system.

5. Job shops with more than two resource constraints

The work done by Hogg *et al.* (1975a) was the first paper to describe a job shop (in the form of an aircraft engine overhaul facility) with more than two types of resource constraints. However, that research did not take into account the simultaneous requirement of more than one type of resource. None of the previous research on scheduling has addressed the job shop constrained by more than two resources (i.e. machines. labour, and auxiliary resources) at one point in time. The extent to which shops are constrained by machines, labour, and auxiliary resources is dependent on the job mix. Goldratt and Fox (1984 and 1986) have suggested the use of optimized production technology (OPT) to improve performance of multiple resource constrained job shops. Goldratt and Fox (1986) offered the following definitions:

(1) Capacity----the available time for production

(2) Bottleneck -any resource whose capacity is less than the demand placed upon in.

(3) Non-bottleneck -any resource whose capacity is greater than the demand placed on it.

(4) Capacity constrained resource (CCR) - any resource whose utilization is very nearly equal to capacity and could be a bottleneck if it were not scheduled carefully.

There are several 'OPT principles'. They are summarized as follows:

(1) Balance flow, not capacity.

(2) The level of utilization of a non-bottleneck is determined not by its own potential, but by some other constraint in the system.

(3) Utilization and activation of a resource are not synonymous.

(4) An hour lost at a bottleneck is an hour lost for the total.

(5) An hour saved at a non-bottleneck is just a mirage.

(6) Bottlenecks govern both throughput and inventory in the system.

(7) The transfer batch (between machine centres) may not, and many times should not, be equal to the process batch.

(8) The process batch should be variable, not fixed.

(9) Schedules should be established by looking at all of the constraints simultaneously. Lead times are the result of a schedule and cannot be predetermined.

Further, Dilworth (1993) notes that 'some of the OPT ideas appear to be very useful when the product mix and level of demand change considerably' (p. 363). However, there is no reported empirical evidence to prove that scheduling based on constrained resources does produce better shop performance in a dynamic product mix environment. More importantly, the OPT methodology, being proprietary, has not been completely described in the open literature in the level of detail needed for independent empirical testing and evaluation.

6. Conclusions

A review of the literature indicates that while a substantial amount of research has been undertaken in machine and labour constrained job shops, there is a dearth of research involving auxiliary resources in the job shop. The following paragraphs illustrate briefly the future multiple resource constrained job shop scheduling research agenda that needs to be undertaken.

McKay *et al.* (1988) point out, and rightly so, that scheduling research in job shops has not been well grounded in practice. Very little scheduling research has been based on data obtained from existing job shops. While Allen (1963), Gere (1963), Harris (1965), Jain (1975), Randolph (1976), Green and Appel (1981), Melnyk *eta/.* (1986), McKay *et al.* (1988), McCahon (1991), Wisner and Siferd (1995) did survey based empirical studies that have focused primarily on single (machine-only) constrained job shops. LeGrande (1963), Bulkin *et al.* (1966). Maggard *et al.* (1974), and Rochette and Sadowski (1976) focused on job shops with more than one resource constraint. It should be noted that only five of the fourteen studies have been carried out after 1980 and only one study (Wisner and Siferd 1995) has a sample size of more than 50 job shops. It was during the 1980s that job shops have attempted to reform themselves through the acquisition of advanced manufacturing technologies (in computer aided design, flexible manufacturing systems, etc.) and the application of better shop floor control mechanisms (such as just-in-time production). Hence, it is all the more important for researchers to focus their efforts on current practices, rather than developing 'solutions in search of problems'. This has been echoed by Treleven (1989), who re-iterated that empirical survey research on scheduling should be carried out to identify the decision and problem areas in job shops constrained by more than one resource. A few research questions that need to be immediately addressed through survey-based research on multiple constrained job shops could include: (1) What is the number of times in a given time period that job shops are constrained by machines, labour, auxiliary resources, any combination of two resources out of the three, or all three resources simultaneously? (2) What are the dispatching and resource assignment rules that are regularly used in job shops? (3) Do shop floor control managers use sophisticated techniques of shop loading based on resource constraints (i.e. bottlenecks)? and (4) Do shop floor managers use performance measures (such as average flow time, mean queue time, percentage of jobs late, etc.) that have been used in scheduling research on a frequent basis? It should be, however, noted that this does not represent an exhaustive list of the issues.

Industry observations have shown that there are only a few bottlenecks (resources that constrain the system) 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. Goldratt and Fox (1986) have suggested that to enhance job shop performance, jobs should be scheduled based on the bottleneck resource. Hence to achieve that end, 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-bottlenecks machine since it can produce more than is needed to supply critical bottleneck resources. Since job shops may be actively constrained by both primary (machines) and secondary resources, it would appear that shop scheduling should consider both types of constraints. As a precondition to the development and application of appropriate, scheduling rules, shop managers must be able to measure the degree to which each resource is constraining the system. A few issues that need to be clarified as a part of future research would include: (I) What are the measures by which a shop can be categorized as being constrained by a particular resource? (2) At what level of resource utilization is the job shop truly constrained by that resource? (3) Does the absolute level of resource utilization alone indicate the degree to which the shop is constrained by that resource or does the relative utilization level of other resources also play a role in deciding the degree to which the shop is constrained? and (4) Does the frequency of a job at a work centre waiting for a resource indicate that the shop is constrained by that resource? Recent research efforts by Gargeya (1994) and Lawrence and Buss (1994) have attempted to study these issues closely.

Figure 3 indicates that the inherent variability in a machine-only constrained job shop restricts the maximum resource utilization of the shop to about 95%. Figure 4 (based on a simulation study) indicates that the maximum resource utilization of a dual constrained job shop may not exceed 75%. It is probable that with better shop floor control mechanisms the utilization of resources could be enhanced. Future research needs to be undertaken to isolate the type of dispatching and resource assignment rules that could enhance the dual constrained job shop. Also, similar studies need to be carried out for shops with more than two constraining resources.

Melnyk *et al.* (1986) have described as static (those that do not change the priority of an order as conditions change in the shop) and as dynamic (those that change the priority of orders as conditions change in the shop) dispatching rules, and as local (those that take into account information relating to a job in a queue) and as global (those that consider information from other sources within the shop) dispatching rules. These types of rules have been researched in machine-only and labour constrained job shops but have not been tested in auxiliary resource constrained shops as well as in job shops having more than two constraints. In recent years shop loading algorithms have been applied to labour constrained shops (Miller and Berry 1974 and 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 future research needs on this front should 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? (2) Can shop loading algorithms, similar to the ones developed by Miller and Berry (1974) and Park (1987) in labour constrained job shops, be effectively used in auxiliary resource constrained job shops? In a recent paper, Gargeya and Deane (1992) have described a shop loading algorithm in an auxiliary resource constrained job shop.

This paper has extended the review work of Treleven (1989) to include scheduling research in auxiliary resource constrained job shops as well as in job shops constrained by more than two resources. This article has offered a comparative analysis of the scheduling research in labour and auxiliary resource-constrained job shops. Also, future avenues for scheduling research in multiple resource constrained job shops have been described. With a bibliography of more than 90 articles and books, this paper provides a good set of references for researchers in the area of multiple resource constrained job shop scheduling.

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