Order Release, Dispatching and Resource Assignment in Multiple Resource Constrained Job Shops: An Assessment by Simulation

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Keywords: *Theory of Constraints; Order Release; Dispatching; Resource Allocation; Workload Control.*

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Abstract

In manufacturing shops in practice, machine capacity is often constrained by more than one type of resource. Yet research mainly focusses on the effects of only one type of resource that constrains machine capacity, e.g. labor, tooling or auxiliary constraints. In response, we use simulation to assess the impact of order release, dispatching and resource assignment rules in make-to-order job shops with multiple resource constraints. The capacity wasted while a machine stands idle waiting for other resources increases with the number of constraints, and all three production planning and control functions have little impact on this waiting time. Effective production planning and control can however improve operational performance in terms of time and tardiness related measures. In general, combining order release control with a dispatching rule that prioritizes jobs for which all resources are available at dispatching and a longest queue resource assignment rule leads to the best performance. Most importantly, and rather counterintuitively, prioritizing orders with the fewest missing resources worsens the performance of both the dispatching and resource assignment rule since it reduces resource utilization during periods of high load. Results from dual resource constrained shops are consequently not directly transferable to more complex resource constrained shops.

Keywords: *Theory of Constraints; Order Release; Dispatching; Resource Allocation; Workload Control.*

1. Introduction

This study assesses the performance of three different production planning and control functions – order release control, dispatching and the resource assignment rule – in multiple resource constrained job shops, i.e. job shops in which two or more types of resources constrain machine capacity and thus the throughput of the shop (Gargeya & Dean, 1996). It is argued here that multiple resource constraints are commonly encountered in practice, specifically in high variety make-to-order shops where resource requirements can differ greatly between jobs. Yet, to the best of our knowledge, no study to date has assessed the impact of multiple resource constraints in this context. Rather, research focusses on only one type of resource that constrains machine capacity. This has left managers unsupported in their decision concerning how best to accommodate multiple resource constraints as part of production planning and control. The findings from of our simulation experiments begin to address this shortcoming by identifying six important implications for managers of high variety make-to-order shops with multiple resource constraints.

A broad literature has emerged on so-called Dual Resource Constrained (DRC) shops (e.g. Bobrowski & Park, 1989; Felan *et al.*, 1993; Malhotra & Kher, 1994; Fredendall *et al.*, 1996; Bokhorst *et al.*, 2004; Bokhorst & Gaalman, 2009; Salum & Araz, 2009; Sammarco *et al.*, 2014; Thürer *et al.*, 2019). But the term "DRC shop" typically refers to shops where machine capacity is constrained by only one type of constraint – labor (Thürer *et al.*, 2020). Melnyk *et al.* (1989) however argued that additional tooling constraints, different from machine constraints, result in a more complex resource matching problem than DRC, since jobs in a queue at a station do not simply require any type of tooling but rather a specific tool or set of tools. The same argument was put forward by Gargeya & Dean (1999) for the inclusion of auxiliary resources. Melnyk *et al.* (1989) found that a rule that gives the highest priority to a job for which the tool is available will perform consistently well. This finding was later confirmed by Gosh *et al.* (1992) who considered a similar simulation model to Melnyk *et al.* (1989) but added sequence dependent setup times for tools. Similarly, Gargeya & Dean (1999) found that a rule which considers the total number of resources required and the number of units of resources available can outperform the alternative rules available from the literature. Still, in all three studies, orders only required one type of tool and consequently the throughput of shops was subjected to only dual resource constraints, i.e. only a tooling/auxiliary resource and machine resource constraints were considered.

A simulation study that considers multiple types of tools (and thus resource constraints) was presented by Amoako-Gyampah *et al.* (1992), but the authors considered machines with robotic material handling units used for: (i) tool changing from a tool magazine with limited size, and (ii) the loading and unloading of jobs. The main focus was consequently on the assessment of different strategies for tool allocation, i.e. the decision concerning which tools to store in which tool magazine. Amoako-Gyampah *et al*. (1992) also only considered static demand, i.e. a fixed quantity of jobs that arrive at the system within a given production period. This makes it similar to the wider literature on job shop scheduling with tooling constraints. For example, Hertz & Widmer (1996) presented a heuristic method for solving the m-machine, n-job shop scheduling problem with tooling constraints, where parts require different tools and tools can be loaded into a station tool magazine (of limited size). A similar problem for identical parallel machines was later addressed by Beezão *et al*. (2017). Meanwhile, Cakici & Mason (2007) presented two different heuristic solution approaches for the scheduling of photolithography machines in semiconductor manufacturing where reticle requirements are the auxiliary resource constraints.

Summarizing the above, while a broad literature on scheduling with multiple resource constraints exists, this literature typically focusses on a deterministic context and on the tool allocation decision, while the literature on stochastic contexts only considers dual resource constraints, i.e. machine capacity being constrained by only one additional labor, tooling or auxiliary resource. While these studies provide a first indication on how to control production in job shops with multiple resource constraints, it remains largely unknown whether their results also hold in job shops where more than two resources are required to realize machine capacity and complete an operation. In response, this study uses discrete event simulation to assess for the first time the performance of order release, dispatching and resource assignment rules in a make-to-order job shop with multiple resource constraints. We did not consider capacity adjustments since this would have required us to consider capacity increases for each of the resources and the machine resource. To keep our study focused we therefore decided to focus on control policies (input control and sequencing decisions) that do not affect resource capacity. Simulation was chosen since it provides a powerful tool for experimenting with different system designs (Mourtzis, 2020).

The simulation model used to assess performance is described next in Section 2. This includes using relevant literature to provide a description of how we realized production planning and control and how we modelled resource constraints. The results from the simulations are then presented in Section 3, before a discussion together with six important managerial implications is presented in Section 4. Final conclusions are provided in Section 5 together with the limitations and future research directions.

2. Simulation

This study started by asking:

What is the impact of order release, dispatching and resource assignment rule in make-to-order job shops with multiple resource constraints?

To answer this question, we use a simulation model of a Pure Job Shop, i.e. a shop in which both the number of stations that need to be visited by a job (its operations) and their sequence follow a random variable (Melnyk & Ragatz, 1989; Oosterman *et al*., 2000). We follow Dolgui *et al*. (2020) in that the term '*operation*' refers to a set of interrelated processing steps that is considered as an indivisible action executed at one position (station). There are no multi operations and no reentrant loops to avoid unnecessary complexities and in order to keep our study focused. Meanwhile, a stylized standard model is used to avoid interactions that may otherwise interfere with our understanding of the main experimental factors. While any individual shop in practice will differ in many aspects from our stylized environment, the model used in this study captures the job and shop characteristics of high variety make-to-order shops, i.e. high routing variability, high processing time variability, and high arrival time variability. We first describe the production planning and control mechanism applied in Section 2.1. How our shop and resource constraints were modeled is then described in Section 2.2 before Section 2.3 summarizes our experimental setup and the main performance measures that are considered.

2.1 Production Planning and Control

2.1.1 Order Release Control

Order release is a key production planning and control function. When order release is controlled, orders are not directly released onto the shop floor upon arrival. Rather, they are retained in a backlog from where they are released to meet certain performance metrics, such as to limit work-in-process and adhere to due dates. Given its importance, a broad literature exists on the performance of order release methods, such as Workload Control, both in practice (e.g. Wiendahl, 1992; Bechte 1994; Hendry *et al*., 2013; Silva *et al*., 2015; Perona *et al*., 2016; Huang, 2017; Hutter *et al*., 2018) and using simulation (e.g. Land & Gaalman, 1998; Perona & Portioli, 1998; Cigolini, & Portioli-Staudacher, 2002; Portioli-Staudacher & Tantardini, 2011; Thürer *et al*., 2012, 2014; Fernandes *et al*., 2016, 2020; Gonzalez-R *et al*., 2018; Haeussler & Netzer, 2020).

Given its importance, there are many order release methods in the literature; for examples, see the reviews by Wisner (1995), Land & Gaalman (1996), Bergamaschi *et al*. (1997), Fredendall *et al*. (2010), Bagni *et al*. (2021) and Gomez Paredes *et al*. (2021). In this paper, the LUMS COR (Lancaster University Management School Corrected Order Release) method is used given its good performance in high variety shops compared to other release methods (e.g. Thürer *et al*. 2012). Meanwhile, only one release method was chosen to keep our study focused.

LUMS COR combines a periodic and continuous release element. It uses a *periodic* release procedure to keep the workload W_s released to a station s within a preestablished workload norm as follows:

(1) All jobs in the set of jobs J in the backlog are sorted according to planned release dates.

(2) The job $j \in J$ with the highest priority is considered for release first.

(3) Take R_j to be the ordered set of operations in the routing of job j. If job j's processing time p_{ij} at the i^{th} operation in its routing – corrected for station position i – together with the workload W_s released to station s (corresponding to operation i) and yet to be completed fits within the workload norm N_s at this station, that is $\frac{p_{ij}}{i} + W_s \leq N_s \ \ \forall i \in R_j$, then the job is selected for release. That means it is removed from J and its load contribution is included, i.e. $W_s := W_s + \frac{p_{ij}}{i} \ \ \forall i \in R_j$. Otherwise, the job remains in the backlog and its processing time does not contribute to the station load.

(4) If the set of jobs J in the backlog contains any jobs that have not yet been considered for release, then return to Step 2 and consider the job with the next highest priority. Otherwise, the release procedure is complete and the selected jobs are released to the shop floor.

Since a released job contributes to W_s until its operation at this station is complete, the load contribution to a station in LUMS COR is calculated by dividing the processing time of the operation at a station by the station's position in a job's routing (Oosterman *et al*., 2000).

Finally, in addition to the above periodic release mechanism, LUMS COR incorporates a *continuous* workload trigger. If the load of any station falls to zero, the next job in the backlog sequence with that station as the first in its routing is released irrespective of whether this would exceed the workload norms of any station. The intention behind this mechanism is to avoid premature station idleness (see, e.g. Land & Gaalman, 1998).

As in previous simulation studies on order release control (e.g., Land & Gaalman, 1998; Fredendall *et al*., 2010; Thürer *et al*., 2012), it is assumed that all jobs are accepted, materials are available, and all necessary information regarding shop floor routings, processing times, etc. is known. Six workload norms – 4, 6, 8, 10, 12 and 14 time units – are considered. As a baseline measure, experiments without controlled order release have also been executed, i.e.

where jobs are released onto the shop floor immediately upon arrival. The periodic release interval is set to 4 time units. Finally, the planned release date of a job is given by its due date minus an allowance for the operation throughput time for each operation in its routing. The allowance for the operation throughput time at each station is set to 8 time units, a setting that best represents the shop floor throughput time results across the different scenarios obtained in preliminary simulation experiments. We used the full experimental setting for these preliminary simulations but only replicated scenarios 10 times.

2.1.2 Dispatching Rules

Once released, orders enter the queue at the first station in their routing, where they are subjected to a dispatching rule that decides which job to process next. In this study we use one dispatching rule as a baseline that does not consider resource availability and three rules that consider resource availability. These three rules were identified as best performing in Melnyk *et al.* (1989) and Gargeya & Dean (1999). Four different dispatching rules will consequently be considered in this study as follows:

- *The Operation Due Date (ODD) Rule*: The most urgent job is processed first. This rule was chosen since it performs well in job shops (e.g. Kanet & Hayya, 1982). The operation due date for the last operation in the routing of a job is equal to the due date while the operation due date of each preceding operation is determined by successively subtracting an allowance for the operation throughput time from the operation due date of the next operation. In this study, the allowance for the operation throughput time at each station is set to 8 time units based on preliminary simulation experiments.
- *The All (Resources) Available Rule*: Orders for which all resources are available are processed first, with any ties resolved by the ODD rule. This is the Job Priority Subject to Tool Availability rule from Melnyk *et al.* (1989). The rule was chosen since it performed consistently well in Melnyk *et al.* (1989).
- *The Least (Resources) Missing Rule*: Prioritizes orders according to the number of missing resources, i.e., the number of required resources that are not available. All ties are resolved by the ODD rule. If there are four resources, then this rule will create five classes (i.e. None, 1, 2, 3 and 4 resources missing) that are considered in sequence. In contrast, the All Available rule always creates only two classes.
- *The (Resource) Criticality Factor Rule*: Prioritizes orders according to the criticality factor, which is given by the ratio of the total number of resources required and the number of

resources available. If no resources are available, then the factor is set to five. All ties are resolved by the ODD rule. This rule was introduced by Gargeya & Dean (1999).

2.1.3 Resource Assignment Rules

Once selected for processing by the dispatching rule, a job requests the resources needed for the specific operations in its routing. All resources need to be available to be seized. Meanwhile, when more than one job simultaneously requests a resource and a resource becomes available, a decision must be made on which job should seize the resource. The four different rules considered for this resource assignment decision are based on Gargeya & Deane (1999):

- *The Operation Due Date (ODD) Rule*: The most urgent job, according to the ODD, receives the resource.
- *The Shortest Processing Time (SPT) Rule*: The smallest job receives the resources, with the objective being to free the resource again as fast as possible.
- *The Longest Queue Rule*: The job at the station with the longest queue (in terms of the number of jobs) receives the resource, with the objective being to control the queue length.
- *The Least (Resources) Missing Rule*: Prioritizes orders according to the number of missing resources. All ties are resolved by the ODD rule.

2.2 Overview of Modeled Shop and Job Characteristics

A simulation model of a Pure Job Shop (Melnyk & Ragatz, 1989; Oosterman *et al*., 2000) has been implemented in SIMIO$^{©}$. The model can be obtained from the corresponding author upon request. The shop contains six stations. Each station is a single and unique capacity resource. We model a balanced shop to avoid distracting our focus away to unbalanced shops and fixed bottlenecks. As in previous research on resource constraints (e.g., Melnyk *et al*., 1989; Gargeya & Deane, 1999; Thürer *et al*., 2019), we consider machine capacity to be constant. Resource availability constrains realized machine capacity. These resources may be labor, tooling or auxiliary resources. All the resources required for an operation need to be seized by a station to realize capacity and process the orders. Resources are freed once an operation is complete – they can then be seized by other jobs. We consider two levels of resource constraint: three different types of resources and four different types of resources. There exists four units of each type of resource. The number of type of resources needed for an operation is uniformly distributed between 1 and 3 for the scenarios with three resources and between 2 and 4 for the scenarios with four resources. Resources are drawn without replacement.

As in recent studies on DRC shops (e.g. Thürer *et al*., 2020), we adjust the interarrival time to ensure comparable resource utilization. The interarrival time of assembly orders follows an exponential distribution. The mean is set to 0.73 time units for the scenarios with three resources and to 0.82 time units for the scenario with 4 resources, such that on average resources are occupied 80% of the time. We use the resource occupation to define parameters since it is independent from the control strategy applied. The station utilization is dependent on the control strategy given that a station is blocked if a job is loaded and a resource is missing. Meanwhile, the routing length of jobs varies uniformly from one to six operations. The routing length is first determined before the routing sequence is generated randomly without replacement, i.e. reentrant flows are prohibited. Operation processing times at stations follow a truncated 2-Erlang distribution with a mean of 1 time unit after truncation and a maximum of 4 time units. Finally, due dates are set exogenously by adding a uniformly distributed random allowance factor to the job entry time. This factor was set arbitrarily between 45 and 65 time units.

2.3 Experimental Design and Performance Measures

The experimental factors are: (i) the two levels for the number of resources (three and four resources), (ii) the seven levels of the workload norm (4, 6, 8, 10, 12, 14 and immediate release), (iii) the four dispatching rules (ODD, All Available, Least Missing, and Criticality Factor) and (iv) the four resource assignment rules (ODD, SPT, Longest Queue, and Least Missing). A full factorial design was used with 224 (2x7x4x4) scenarios, where each scenario was replicated 100 times. Results were collected over 10,000 time units following a warm up period of 3,000 time units. The number of replications and the run length were based on results for the halfwidth of the 95% confidence interval for the total throughput time, while the warmup period was based on the results in Land (2004). As in Melnyk *et al*. (1989) and Amoako-Gyampah *et al*. (1992), we consider three performance measures: the *total throughput time* – i.e. the mean of the completion date minus the backlog entry date across jobs; the *percentage tardy* – i.e. the percentage of jobs completed after the due date; and, the *mean tardiness,* that is $T_j = \max(0, L_j)$, with L_j being the lateness of job j (i.e. the actual delivery date minus the due date of job j). In addition, and since we consider order release control, we also measure the mean of the *shop floor throughput time*. While the total throughput time includes the time that an order waits before being released, the shop floor throughput time only measures the time after an order has been released to the shop floor.

3. Results

To give a first indication of the performance impact of our experimental factors, statistical analysis of our results was conducted using an ANOVA (Analysis of Variance). ANOVA is here based on a block design, which is typically used to account for known sources of variation in an experiment. In our ANOVA, we treat the number of resources as the blocking factor. This allows the main effect of this environmental factor and the main and interaction effects of our three control related factors – order release, the dispatching rule and the resource assignment rule – to be captured. The results are presented in Table 1. All main effects and all two way interactions except the interaction between the norm and resource assignment rule in terms of the total throughput time and percentage tardy were found to be statistically significant at a level of 0.05. There were no significant three way interactions.

[Take in Table 1]

The Scheffé multiple comparison procedure was also applied to obtain a first indication of the direction and size of the performance differences. Table 2 and Table 3 give the 95% confidence interval for the different dispatching and resource assignment rules, respectively. If this interval includes zero, performance differences are not considered to be statistically significant. We can observe significant performance differences for all pairs for at least one performance measure. This will be explored further in Section 3.1, where we focus on the performance of the dispatching and resource assignment rules, and in Section 3.2, where we assess the impact of order release control.

[Take in Table 2 & Table 3]

3.1 Performance of the Dispatching and Resource Assignment Rules with Immediate Release

Table 4 summarizes the results for immediate release. In addition to our main performance measures – total throughput time (TTT), percentage tardy and mean tardiness – we also provide results for the realized station utilization rate. Note that the shop floor throughput time is not presented since it is equivalent to the total throughput time for immediate release as there is no release delay.

[Take in Table 4]

Station utilization in our simulations is determined by two factors: the time the station is processing, and the time the station is waiting for a resource (i.e., blocked). Theoretically, the station utilization rate without a constraint is 80% for an interarrival time of 0.73 time units (used for the three resource scenario) and 71% for an interarrival time of 0.82 time units (used for the four resource scenario). This means that although the station utilization rate that is realized for the three resource scenarios is higher than for the four resource scenarios, the negative impact caused by the station waiting for a resource is larger for the four resource scenarios (as expected). In other words, resource constraints have a significant impact on the realized utilization rate, and this impact increases with the number of resources. For a scenario where four resources are used, an 80% resource utilization rate leads to an increase in machine utilization of almost 20% (from 71% to approximately 91%). Thus, for 20% of the time the machine is standing idle waiting for resources.

Note that the number of resources does not impact the relative performance of our dispatching and resource assignment rules. Overall, the following can be observed from our results:

- *The Dispatching Rule*: As somewhat expected, ODD dispatching, which neglects resource availability, leads to the highest station utilization rate. Yet the ODD rule still performs well in terms of the mean tardiness, only being outperformed on this measure by the All Available rule. The All Available rule, which prioritizes the orders in the queue for which all required resources are available, leads to the best overall performance. Note that a resource may also be missing for the 'all resources available' dispatching rule, since a job for which a resource is missing is selected whenever there is no job in the queue for which all resources are available. The Least Missing and the Criticality Factor rules lead to the lowest station utilization rate and the best performance in terms of the percentage tardy; but this is achieved at the expense of a significant increase in mean tardiness. Jobs that require a large number of resources are delayed since they are more likely to have a large number of resources that are not available (and thus missing). For example, a job that requires four resources, of which only two are available, is delayed over a job that requires only one resource that is not available. This situation does not occur for the All Available rule where either neither of the two jobs would be chosen if there is a job in the queue that has all resources available or else the most urgent of the two jobs would be chosen.
- *The Resource Assignment Rule*: The Longest Queue assignment rule leads to the best performance followed by the ODD rule. As expected, SPT releases resources faster, which leads to a lower station utilization rate. However, this is at the expense of poor performance in terms of all other performance measures. The ODD rule is a time equivalent of the

Longest Queue Rule, i.e. the longer the queue the more likely it is that the ODD is violated. This explains why the performance of the two rules is very similar. SPT neglects the queue state while at the same time SPT effects (as for the dispatching rule) do not take place since the resource selection is made by looking across the various station queues. This leads to a worsening of the performance. Meanwhile, the Least Missing resource assignment rule leads to the worst overall performance. Since resources are seized simultaneously, the job with the least resource requirements is prioritized. This leads to the counterintuitive situation that fewer resources are used in periods of high load since it is more likely that a job with fewer resource requirements is available. This in turn leads to stronger resource constraints in periods when the workload starts to reduce. This effect can be observed from Figure 1, which gives the results for the number of jobs in the system and the number of resources allocated for the ODD and Least Missing resource assignment rules. For example, for Least Missing resource assignment, fewer resources are allocated around 5,250 time units and more around 5,350 time units compared to under ODD resource assignment.

- *The Dispatching and Resource Assignment Rules*: Performance differences across resource assignment rules are not impacted by the dispatching rule and vice versa. In general, the dispatching rule has a stronger impact on performance than the resource assignment rule.

[Take in Figure 1]

3.2 Performance with Order Release Control

Introducing an order release control mechanism in the form of LUMS COR does not impact the main conclusions from above on the performance of the dispatching and resource assignment rules. This can be observed from Table 5, which gives the results for the different dispatching and resource assignment rules with a norm level of six time units. This norm level was chosen since it led to the best overall performance.

[Take in Table 5]

Order release cuts shop floor throughput times by approximately 50% for the scenarios with three resources and by about 40% for the scenarios with four resources. At the same time, mean tardiness is reduced for all settings of the dispatching and resource assignment rules. However, the percentage of tardy jobs is only reduced for the ODD and All Available dispatching rules. In contrast, for the Least Missing and Criticality Factor dispatching rules, percentage tardy increases.

To assess the impact of the norm level, Table 6 gives the results for each level for the All Available dispatching rule and the ODD and Longest Queue resource assignment rules. We observe that the positive impact of order release is stronger for the Longest Queue resource assignment rule, leading to this rule being the best performing rule when order release control is exercised.

[Take in Table 6]

4. Discussion and Managerial Implications

Our study highlights the negative impact on performance of multiple resource constraints. A resource utilization rate of 80% increased the station utilization rate by approximately 20% in our simulation environment. This increase represents waiting waste, i.e. machine capacity that is not being utilized because an auxiliary resource is missing. This negative impact would become even more pronounced if jobs were allowed to seize resources one by one. This is an option that is not permitted in our study given the sheer size of the negative impact. Stations quickly become blocked for too long and cannot handle the input of work anymore. At the same time, locking situations may occur in which one jobs holds Resource A and needs Resource B and one job holds Resource B and needs Resource A. To realize stable simulations, i.e., stations can handle the incoming workload, we needed to ensure that jobs seize all resources simultaneously. Thus, the first of six important managerial implications is that:

> *In high variety make-to-order shops with multiple resource constraints, resources should be seized simultaneously, not one by one.*

Multiple resources pose challenges since the probability that one resource becomes a constraint increases with the number of resources. Given that in make-to-order job shops job properties and therefore resource requirements are variable, there may be periods when there are more than enough resources and resource utilization is low and other periods when there are not enough resources and resource utilization exceeds 100%. In other words, resource utilization rates will fluctuate. The periods when the resource requirements exceed 100% do not overlap for the different type of resources. As a consequence, the more resources that are required, the more likely it is that one or more resources will experience a shortage period. Our results showed that production planning and control has little impact on the realized station utilization rate. Thus, machine utilization can only be reduced at the higher planning levels above the shop floor. Previous research has demonstrated how considering machine capacity during customer enquiry management, where order acceptance, due date and pricing decisions are made, can improve performance (Thürer *et al*., 2014). Therefore, as a second managerial implication it is argued that:

> *Managers in high variety make-to-order shops with multiple resource constraints should consider all potential resource constraints already at the customer enquiry stage*.

Although production planning and control has only a limited impact on realized station utilization rate (and thus waiting waste), it significantly impacts throughput time and tardiness performance. Our findings partly confirm the results from Melnyk *et al*. (1989), in that overall performance can be improved by prioritizing orders that have all of the necessary resources available at the shop floor dispatching stage. Yet, we question the use of a dispatching rule that prioritizes jobs according to the number of resources available, as was suggested for example in Gargeya & Dean (1999). Results from dual resource constrained shops can be partly confirmed in the former case, but not in the latter. This leads to a third and fourth managerial implication:

> *Managers in high variety make-to-order shops with multiple resource constraints should be aware that prior results from dual resource constrained shops may not be directly transferable to shops with more constraints.*
>
> *Rather counterintuitively, in high-variety make-to-order shops with multiple resource constraints the dispatching and resource assignment rules should not consider the number of resources that are missing.*

The resource assignment rule that decides which job an available resource should choose when more than one job is requesting it was found to have less of an impact on performance than the dispatching rule, which precedes the resource assignment rule and decides which job should be processed next. In general, we found that resource assignment rules that consider the station state outperform the alternative rules that are identifiable from the literature. Therefore, a fifth implication is that:

> *Managers in high variety make-to-order shops with multiple resource constraints should choose a resource assignment rule that considers the current queue state, such as the ODD or Longest Queue assignment rule*.

Finally, order release control was shown to have a positive impact on performance. For the best-performing combination of dispatching and resource assignment rule (i.e. the All Available and Longest Queue rules), a reduction in shop floor throughput times of approximately 40%, a percentage tardy decrease of about 30% and a mean tardiness reduction of about 10% can be observed if the norm level is set appropriately. Therefore, as a final managerial implication, we posit that:

> *Managers in high variety make-to-order shops with multiple resource constraints should introduce a backlog from which orders are introduced onto the shop floor in accordance with a suitable order release control mechanism, such as LUMS COR.*

5. Conclusions

Machine utilization in many make-to-order shops in practice is constrained by other resources. While a broad literature exists on constrained job shops, this literature typically assumes the presence of only one additional resource, e.g. labor, tooling or auxiliary resources. To the best of our knowledge, no prior study has provided an assessment of the performance of different production planning and control functions in job shops that have more than one resource constraining machine capacity. This is an important shortcoming since we have shown that the results from shops with dual resource constraints are not directly transferable to a multiple constraint context. We started by asking: *What is the impact of order release, dispatching and resource assignment rule in make-to-order job shops with multiple resource constraints?* Using simulation, it was found that all three production planning and control functions have little impact on station utilization, i.e. the time that a machine stands idle waiting for other resources, but they have a significant impact on the operational performance of orders in terms of time and tardiness related performance measures. In general, combining order release control with a dispatching rule that prioritizes jobs for which all resources are available at dispatching together with a longest queue resource assignment rule leads to the best performance in our simulation experiments. Most importantly, and rather counterintuitively, prioritizing orders with the least resources missing leads to the worst performance for both the dispatching and resource assignment rules. Prioritizing orders with the least resources missing will lead to an artificially low resource utilization in periods of high load and an increase in resource utilization when the high load period has subsided.

A first main limitation of our study is that we neglected the impact of capacity adjustments. To keep our study focused we only considered order release, dispatching and the resource assignment rule. Future research could explore how best to adjust capacity across resource and machine capacities. A second main limitation of our study is its focus on a manufacturing setting with a classical shop floor layout. While multiple resource constraints often occur in this context, they are even more prevalent in other contexts, such as fixed position layouts and healthcare. In this context, one could also consider different types of resources that are controlled by different control strategies. For example, medical equipment can be stored in inventory while nurses and doctors follow assignment rules. Meanwhile, our findings are based on stylized simulation models. Whilst this allows for more in depth insights and a high degree of generalizability, future research should seek to contextualize our findings to real life job shops, thereby continuing the practice-theory research cycle.

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Table 1: ANOVA Results

	Source of Variance	Sum of Squares	Degrees of freedom	Mean Squares	F-Ratio	p-Value
Total Throughput Time	Number of Resources	294140.32	1	294140.32	1561.02	0.00
	Norm (N)	227701.53	6	37950.26	201.40	0.00
	Dispatching (D)	159360.23	3	53120.08	281.91	0.00
	Resource Assignment (R)	245584.31	3	81861.44	434.44	0.00
	N x D	10325.31	18	573.63	3.04	0.00
	N x R	2691.16	18	149.51	0.79	0.71
	D x R	9762.45	9	1084.72	5.76	0.00
	N x D x R	1510.73	54	27.98	0.15	1.00
	Error	4199512.80	22287	188.43		
Shop Floor Throughput Time	Number of Resources	250772.73	1	250772.73	4661.25	0.00
	Norm (N)	1423722.30	6	237287.04	4410.59	0.00
	Dispatching (D)	37735.58	3	12578.53	233.80	0.00
	Resource Assignment (R)	35793.42	3	11931.14	221.77	0.00
	N x D	17840.92	18	991.16	18.42	0.00
	N x R	24459.05	18	1358.84	25.26	0.00
	D x R	1790.64	9	198.96	3.70	0.00
	N x D x R	2751.53	54	50.95	0.95	0.59
	Error	1199028.10	22287	53.80		
Percentage Tardy	Number of Resources	38.50	1	38.50	2031.19	0.00
	Norm (N)	21.90	6	3.65	192.57	0.00
	Dispatching (D)	18.15	3	6.05	319.24	0.00
	Resource Assignment (R)	19.19	3	6.40	337.57	0.00
	N x D	8.41	18	0.47	24.66	0.00
	N x R	0.36	18	0.02	1.05	0.40
	D x R	2.21	9	0.25	12.93	0.00
	N x D x R	0.53	54	0.01	0.52	1.00
	Error	422.43	22287	0.02		
Mean Tardiness	Number of Resources	48266.89	1	48266.89	595.08	0.00
	Norm (N)	86410.62	6	14401.77	177.56	0.00
	Dispatching (D)	119126.45	3	39708.82	489.57	0.00
	Resource Assignment (R)	109368.48	3	36456.16	449.47	0.00
	N x D	43463.23	18	2414.62	29.77	0.00
	N x R	2459.73	18	136.65	1.68	0.03
	D x R	8169.54	9	907.73	11.19	0.00
	N x D x R	2099.46	54	38.88	0.48	1.00
	Error	1807688.80	22287	81.11		

Table 2: Results for the Scheffé Multiple Comparison Procedure: Dispatching Rule

Rule (x)	Rule (y)	TTT[2]		SFT[3]		Percent Tardy		Mean Tardiness	
		lower[1]	upper	lower	upper	lower	upper	lower	upper
All Available	ODD	-7.541	-6.091	-3.437	-2.662	-0.069	-0.054	-3.376	-2.424
Least Missing	ODD	-6.452	-5.001	-3.497	-2.722	-0.083	-0.068	2.163	3.115
Criticality Factor	ODD	-6.387	-4.937	-3.184	-2.409	-0.057	-0.043	2.246	3.198
Least Missing	All Available	0.364	1.815	-0.448*	0.328	-0.022	-0.007	5.064	6.015
Criticality Factor	All Available	0.429	1.879	-0.135*	0.640	0.004	0.019	5.147	6.098
Criticality Factor	Least Missing	-0.661*	0.790	-0.075*	0.700	0.018	0.033	-0.393*	0.559

[1] 95% confidence interval; [2] Total Throughput Time; [3] Shopfloor Throughput Time
* not significant at 0.05

Table 3: Results for the Scheffé Multiple Comparison Procedure: Resource Assignment Rule

Rule (x)	Rule (y)	TTT[2]		SFT[3]		Percent Tardy		Mean Tardiness	
		lower[1]	upper	lower	upper	lower	upper	lower	upper
SPT	ODD	0.319	1.769	-0.133*	0.642	0.003	0.018	0.623	1.575
Longest Queue	ODD	-3.097	-1.647	-1.241	-0.466	-0.024	-0.009	-2.351	-1.399
Least Missing	ODD	5.925	7.375	2.174	2.949	0.054	0.069	3.739	4.690
Longest Queue	SPT	-4.141	-2.691	-1.496	-0.721	-0.035	-0.020	-3.450	-2.498
Least Missing	SPT	4.880	6.331	1.919	2.694	0.044	0.058	2.640	3.591
Least Missing	Longest Queue	8.296	9.747	3.028	3.803	0.071	0.086	5.614	6.565

[1] 95% confidence interval; [2] Total Throughput Time; [3] Shopfloor Throughput Time
* not significant at 0.05

Table 4: Results for Immediate Release

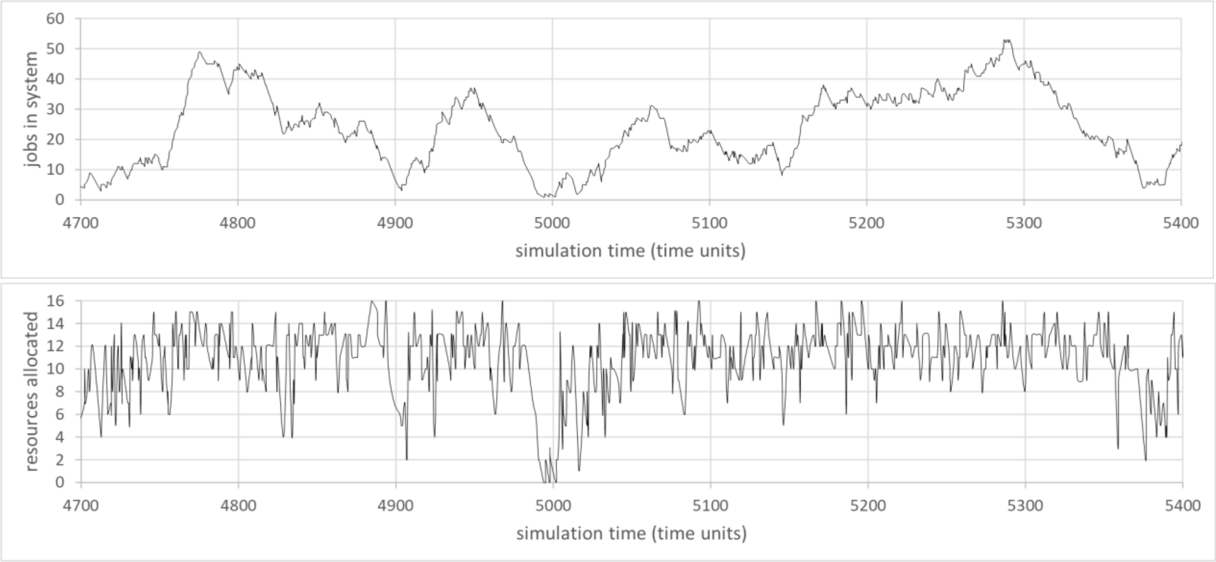
		Three Resources				Four Resources			
Dispatching	Resource Assignment	TTT	Percentage Tardy	Mean Tardiness	Station Util.	TTT	Percentage Tardy	Mean Tardiness	Station Util.
ODD	ODD	49.79	36.9%	9.27	96.2%	37.47	20.3%	4.37	92.9%
	SPT	55.87	43.6%	13.98	95.2%	39.85	24.0%	6.42	90.7%
	Longest Queue	48.77	35.2%	8.79	96.4%	37.53	20.2%	4.57	93.3%
	Least Missing	59.98	48.3%	16.32	96.7%	46.78	33.0%	9.39	94.1%
All Available	ODD	40.45	27.5%	6.45	94.3%	31.93	14.1%	2.51	91.2%
	SPT	43.94	31.3%	9.30	93.8%	35.03	19.4%	4.77	89.7%
	Longest Queue	38.55	24.5%	5.17	94.7%	32.12	14.3%	2.56	91.9%
	Least Missing	46.19	34.5%	9.84	95.0%	38.64	23.1%	5.43	92.6%
Least Missing	ODD	44.73	17.8%	19.18	94.2%	34.99	14.1%	12.25	90.2%
	SPT	45.57	18.2%	19.68	93.8%	35.22	14.7%	12.33	89.4%
	Longest Queue	40.19	17.3%	14.68	94.8%	33.98	13.0%	11.03	92.0%
	Least Missing	51.57	19.8%	24.93	94.9%	42.89	17.3%	18.41	91.6%
Criticality Factor	ODD	49.29	26.3%	22.27	94.2%	36.45	15.3%	14.19	90.0%
	SPT	47.38	25.6%	20.63	93.7%	35.16	15.0%	13.10	89.1%
	Longest Queue	40.92	24.7%	14.22	94.6%	32.89	15.1%	10.55	91.3%
	Least Missing	55.60	28.8%	27.62	94.7%	43.07	17.8%	19.51	91.0%

Table 5: Results for a Norm Level of Six Time Units

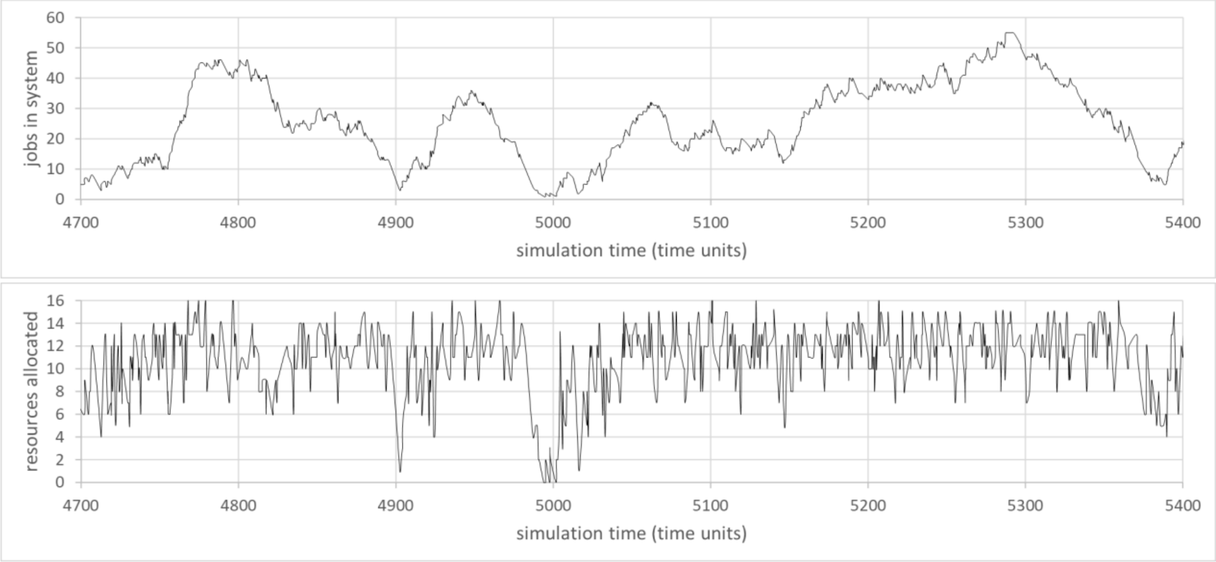
	Dispatching	Resource Assignment	TTT	SFT	Percentage Tardy	Mean Tardiness	Station Util.
Three Resources	ODD	ODD	46.89	20.29	25.9%	10.73	95.9%
		SPT	48.71	20.26	26.3%	12.69	95.1%
		Longest Queue	43.39	19.96	23.7%	8.24	96.1%
		Least Missing	54.94	21.08	33.2%	16.29	96.4%
	All Available	ODD	39.04	18.77	20.6%	6.93	94.6%
		SPT	41.04	18.85	22.0%	8.81	94.1%
		Longest Queue	36.86	18.47	18.5%	5.46	95.0%
		Least Missing	44.48	19.41	25.9%	10.35	95.2%
	Least Missing	ODD	40.84	17.98	23.5%	10.78	94.6%
		SPT	41.49	17.96	23.4%	11.66	94.0%
		Longest Queue	37.28	17.59	20.9%	8.02	95.0%
		Least Missing	46.49	18.51	27.4%	14.89	95.2%
	Criticality Factor	ODD	41.08	18.25	25.7%	10.68	94.5%
		SPT	40.76	18.02	24.8%	10.94	93.9%
		Longest Queue	35.84	17.51	21.1%	6.89	94.6%
		Least Missing	46.44	18.78	29.8%	14.52	95.0%
Four Resources	ODD	ODD	33.87	19.22	13.8%	4.19	92.3%
		SPT	34.43	19.03	13.8%	5.38	90.5%
		Longest Queue	33.06	18.98	13.1%	3.86	92.8%
		Least Missing	41.44	20.55	21.5%	8.38	93.3%
	All Available	ODD	30.50	18.24	10.9%	3.11	91.1%
		SPT	31.51	18.18	11.8%	4.31	89.6%
		Longest Queue	29.65	18.03	10.2%	2.66	91.7%
		Least Missing	36.34	19.48	17.0%	5.91	92.3%
	Least Missing	ODD	30.97	17.58	15.0%	6.03	90.5%
		SPT	31.17	17.36	14.8%	6.54	89.4%
		Longest Queue	29.58	17.21	13.9%	4.60	91.6%
		Least Missing	36.96	18.62	20.0%	9.60	91.7%
	Criticality Factor	ODD	31.04	17.50	16.0%	6.29	90.3%
		SPT	30.65	17.17	15.2%	6.50	89.2%
		Longest Queue	28.10	16.81	13.4%	4.07	91.0%
		Least Missing	36.41	18.47	20.3%	9.56	91.3%

Table 6: Performance Impact of the Workload Norm for All Available Dispatching

	Resource Assignment	Norm	TTT	SFT	Percentage Tardy	Mean Tardiness	Station Util.
Three Resources	ODD	IMM	40.45	40.45	27.5%	6.45	94.3%
		14	40.60	31.85	27.8%	6.01	94.5%
		12	39.99	29.63	26.3%	5.64	94.6%
		10	39.85	27.00	24.9%	5.73	94.6%
		8	39.42	23.42	22.7%	6.06	94.6%
		6	39.04	18.77	20.6%	6.93	94.6%
		4	41.66	12.96	22.5%	10.78	94.7%
	Longest Queue	IMM	38.55	38.55	24.5%	5.17	94.7%
		14	38.43	30.83	24.4%	4.68	94.8%
		12	38.26	28.92	23.4%	4.63	94.8%
		10	37.56	26.30	21.4%	4.38	94.8%
		8	37.16	22.98	19.7%	4.61	94.9%
		6	36.86	18.47	18.5%	5.46	95.0%
		4	38.69	12.68	20.6%	8.58	94.9%
Four Resources	ODD	IMM	31.93	31.93	14.1%	2.51	91.2%
		14	32.00	27.34	14.5%	2.41	91.2%
		12	31.69	26.03	13.8%	2.32	91.2%
		10	31.55	24.41	13.0%	2.31	91.2%
		8	31.07	21.92	11.6%	2.46	91.2%
		6	30.50	18.24	10.9%	3.11	91.1%
		4	30.27	13.08	12.3%	4.59	90.8%
	Longest Queue	IMM	32.12	32.12	14.3%	2.56	91.9%
		14	32.27	27.47	14.9%	2.55	91.9%
		12	31.95	26.14	13.9%	2.45	91.9%
		10	31.50	24.37	13.0%	2.29	91.9%
		8	30.98	21.84	11.7%	2.46	91.9%
		6	29.65	18.03	10.2%	2.66	91.7%
		4	29.27	12.79	11.8%	4.02	91.3%



(a) ODD Dispatching and ODD Resource Assignment



(b) ODD Dispatching and Least Missing Resource Assignment

Figure 1: Overtime Analysis (for four Resources)