Material Handling and Order Release Control in High-Variety Make-To-Order Shops: An Assessment by Simulation

Matthias Thürer* (corresponding author) and Mark Stevenson

Name: Prof. Matthias Thürer (corresponding author)
Institution: Jinan University
Address: School of Intelligent Systems Science and Engineering
Jinan University (Zhuhai Campus)
519070, Zhuhai, PR China
E-mail: matthiasthurer@workloadcontrol.com

Name: Prof. Mark Stevenson
Institution: Lancaster University
Address: Department of Management Science
Lancaster University Management School
Lancaster University
LA1 4YX - U.K.
E-mail: m.stevenson@lancaster.ac.uk

Keywords: *Workload Control; Order Release; Dispatching; Materials Handling; Transportation Task Assignment.*

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Abstract

In many real-life high-variety make-to-order shops, jobs are physically transported from one station to another, and transportation capacity may constrain order progress on the shop floor. Yet, the material handling literature on vehicle assignment rules remains largely inconclusive on which rule to apply, and it neglects order release control. Similarly, and despite the importance of material handling, its impact is widely neglected in the order release literature. In response, this study assesses the combined performance effect of vehicle assignment, order release and dispatching rules. It uses discrete event simulation. Results show that assigning a vehicle to the station with the largest outgoing queue leads to the best performance. This simple vehicle assignment rule has been largely neglected in the literature since the 1980s. In contrast, the two rules that have received the most attention in the literature – the shortest distance and first-come-first-served rules – lead to the worst performance. Meanwhile, order release has a direct detrimental performance effect in pure job shops with material handling constraints. This identifies an important contingency factor so far neglected in the literature that assesses the applicability of order release. More specifically, the use of order release should be restricted to general flow shops with more directed routings since, in these contexts, it can reduce throughput times.

Keywords: *Workload Control; Order Release; Dispatching; Materials Handling; Transportation Task Assignment.*

1. Introduction

The performance of a production system is often not only constrained by the availability of transforming resources, such as people and machines, and by the availability of the resources to be transformed, such as materials, but also by material handling systems for transporting materials or jobs between stations on the shop floor (Gargeya & Deane, 1996; Nabi & Aized, 2020). It has even been argued that omitting the impact of material handling makes the result of planning and scheduling impossible to implement in practice. This is especially so when the movement of jobs on the shop floor relies entirely on the material handling equipment and when transfer times are comparable to production times (Xie & Allen, 2015). A broad literature on material handling systems exists, reflecting the importance of material handling to overall shop performance, for example, the literature on automated guided vehicles (for a review, see e.g. Vis (2005) and Fragapane *et al*. (2021)). But this literature typically focusses on the design of flow path layouts, traffic management, and the determination of pick-up and delivery points. There is a comparatively small body of literature on vehicle management (e.g. Egbelu & Tanchoco, 1984; Srinivasan & Bozer, 1992; Bozer & Yen, 1996; Kim *et al*., 1999; Jeong & Randhawa, 2001; Ho & Chien, 2006; Ho *et al*., 2012; Zamiri Marvizadeh & Choobineh, 2014; Vivaldini *et al*., 2016; Bozer & Eamrungroj, 2018). Moreover, this literature remains largely inconclusive on which rule to apply in order to best choose between a set of transportation tasks when a vehicle becomes available. This is considered a major shortcoming given the importance of transportation task (or vehicle) assignment rules for shops with complex routings, such as high-variety make-to-order shops, a type of shop adopted by many small and medium sized companies in practice.

Another major shortcoming is the wide neglect of production planning and control. Production control in the aforementioned studies is restricted to the use of simple dispatching rules, i.e. the decision concerning which job to process next from a station’s queue. This neglects the impact of other production planning and control functions, such as order release control – a key production planning and control function. When order release is controlled, orders are not directly released onto the shop floor. 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. Hendry *et al*., 2013; Silva *et al*., 2015; Perona *et al*., 2016; Huang, 2017; Sellitto, 2018; Hutter *et al*., 2018) and using simulation (e.g. Portioli-Staudacher & Tantardini, 2011; Thürer *et al*., 2012, 2014, 2021; Fernandes *et al*., 2016, 2021; Gonzalez-R *et al*., 2018; Haeussler & Netzer, 2020).

To the best of our knowledge, the only two studies to date that have considered material handling in a high-variety make-to-order context with order release control are those by Sabuncuoglu & Karapinar (1999 and 2000). First, Sabuncuoglu & Karapinar (1999) considered material handling in their comparison of different order release methods. But the authors did not employ this as an experimental factor, such as by considering different vehicle assignment rules, even though vehicle utilization rates could actually exceed station utilization rates in their simulation, and thus may represent the system constraint. Second, in a follow-up study, Sabuncuoglu & Karapinar (2000) used a similar model, but again no discussion of the actual impact of material handling was presented nor was the interaction between the management of the material handling and production control systems addressed. The neglect of this interaction is considered a shortcoming given that order release has long since been shown to restrict selection possibilities for sequencing rules on the shop floor (Ragatz & Mabert, 1988).

In summary, the literature on transportation task assignment rules remains largely inconclusive on which rule to apply in high-variety make-to-order shops, and this literature neglects higher level planning functions such as order release. Meanwhile, the literature on order release widely neglects material handling constraints. There is consequently a need to further assess the performance of transportation task assignment rules in a high-variety make-to-order order context and to assess the interaction between transportation task assignment rules and order release. In response, this study started by asking two research questions (RQ1 & RQ2):

- *RQ1: What transportation task assignment rule should be used in high-variety make-to-order shops?*
- *RQ2: What is the interaction between order release control, dispatching and the transportation task assignment rule?*

To answer these two questions, we use discrete event simulation to model a high-variety make-to-order system where jobs need to be transported from station to station by a transfer or transport capacity, called a vehicle. Discrete event simulation was chosen since it is a powerful tool for experimenting with different system designs in practice. It is consequently widely applied in the literature concerned with the design of production planning and control and material handling systems (Smith, 2003; Thürer *et al*., 2020).

We assess the interaction between production planning and control, in the form of order release control and dispatching, and the material handling system, in the form of different transportation task (or vehicle) assignment rules. We seek to consolidate the existing literature on station and vehicle-initiated task assignment rules (RQ1) and to explore how production planning and control impacts the performance of these rules and *vice versa* (RQ2). We find that a simple vehicle assignment rule that prioritizes the longest queue performs best, that the ranking of rules is not impacted by production planning and control, and that transportation (or material handling) constraints may result in a detrimental impact of order release for some shop structures.

The literature on vehicle management is briefly reviewed in Section 2. The simulation model used to assess performance and answer our research questions is described in Section 3 before the results are presented and discussed in Section 4. A discussion of our results in the context of the literature is presented in Section 5, before final conclusions are provided in Section 6 together with managerial implications, limitations, and future research directions.

2. Background

Most of the literature on vehicle management considers hierarchical control, applying mixed integer programming models with heuristic algorithms (Fragapane *et al*., 2021). These studies are mostly set in a deterministic context and are consequently not further considered in our study where job characteristics, such as arrival times, routings, and processing times, follow a stochastic process. The literature on vehicle management relevant to our study is concerned with mainly two questions: Which vehicle from a set of idle vehicles should be assigned to a transportation task (the so-called *station-initiated task assignment*)? And, which transportation task from a set of required transportation tasks should be assigned to a vehicle (the so-called *vehicle-initiated task assignment* according to Egbelu & Tanchoco (1984))? If these rules are not based on job characteristics (for example longest queue), or when the vehicle allows for multiple loads, then a third question arises once the vehicle arrived at a station: Which job(s) should be loaded? (Ho *et al*., 2012; Vivaldini *et al*., 2016).

One of the first papers on vehicle management was by Egbelu & Tanchoco (1984). The authors used simulation to assess the performance of five vehicle-initiated task assignment rules, i.e. maximum outgoing queue size, shortest travel time/distance, longest travel time/distance, minimum remaining outgoing queue space, and first-come-first-served; and three station-initiated task assignment rules, i.e. nearest vehicle, farthest vehicle, and longest idle vehicle. The authors argued that vehicle task assignment rules are dominant in periods of high load since it is rare for more than one vehicle to become idle simultaneously during these periods. As a consequence, there are no significant performance differences across station-initiated task assignment rules. Meanwhile, the first-come-first-served rule, where each vehicle checks all stations and collects the oldest load, outperformed all other vehicle-initiated task assignment rules in terms of the unit load throughput. While the shortest distance rule ranked second amongst the rules that were tested it led to unstable workloads at stations, which the authors argued makes it infeasible for use in practice. Srinivasan *et al*. (1994) later used an analytical model to compare the first-come-first-served and shortest distance rules finding that the two rules appear to yield comparable results.

But Bozer & Yen (1996) found that first-come-first-served is not a competitive rule since it is outperformed by the shortest distance rule. Bozer & Yen (1996) presented two new rules. First, a modified shortest distance rule using a distance-based threshold to determine if an empty vehicle should be committed to a transportation task or not. Second, a bidding-based dynamic assignment rule, in which each vehicle places a bid based on its current set of assigned transportation tasks, and the system assigns transportation tasks to the lowest bidder provided that a distance-based threshold is met. Both were shown to outperform the first-come-first served and shortest distance rules.

Kim *et al*. (1999) presented a rule that considers the difference between the workload at the current station and the workload downstream in the routing of a job to avoid blocking if the storage capacity is limited. Meanwhile, Jeong & Rhandawa (2001) used simulation to compare different versions of a multi-attribute rule with single attribute rules, such as those outlined above. Single attribute rules were found to perform better in terms of the main performance measures for which they were originally intended, but multi–attribute rules may lead to better overall performance. This stream of literature was later continued by Ho *et al*. (2012), who presented a method for concurrently solving vehicle assignment and load selection for systems where vehicles can load multiple loads. While the proposed method outperforms a combination of longest queue and identical destination rule identified as best performing in Ho & Liu (2009), it is outperformed by the shortest distance rule in terms of throughput and throughput time. Finally, entropy-based dispatching rules have been introduced by Zamiri Marvizadeh & Choobineh (2014), but authors only show that these rules can outperform other rules in terms of queue waiting time, i.e. the time jobs spent on the shop floor minus total processing times and transfer times.

The above review highlights that a broad set of transportation task assignment rules have been presented in the literature. These rules tend to focus either on distance (or travel time) or ensuring adherence to the shop floor dispatching rule, typically on a first-come-first served basis. The first can be criticized for focusing on vehicle utilization rather than station utilization. The second can be criticized for neglecting the interaction between transportation task assignments and the dispatching rule. First-come-first-served task assignment may lead to different results when an urgency based dispatching rule, such as the operation due date rule, or a load based dispatching rule, such as the shortest processing time rule, is used. In general, existing literature remains inconclusive on which assignment rule to apply. The existing literature can further be criticized for neglecting the impact of higher planning and control functions, such as order release, even though these have long since been shown to impact the performance of dispatching and assignment rules. Material handling is likewise widely neglected in the order release literature, although this may mean that results obtained on the performance impact of order release cannot be replicated in practice. In response, this study uses discrete event simulation to assess the interaction between production planning and control, realized in the form of order release control and priority dispatching, and vehicle management, realized by different station and vehicle-initiated task assignment rules.

3. Methodology

Each high-variety make-to-order shop in practice is different. We therefore use generalized models in order to improve the generalizability of the findings, and to avoid interactions that might inhibit a full understanding of the effects of the experimental factors. To represent high-variety make-to-order shops, we use a discrete event simulation model of a pure job shop and a general flow shop (Oosterman *et al*., 2000). To ensure the applicability of our findings to a broad spectrum of companies in practice, we consider several experimental factors of relevance to material handling. We first describe our two shop types and material handling in Section 3.1. How production planning and control is realized is then described in Section 3.2, before Section 3.3 describes how we implemented vehicle management. Finally, Section 3.4 summarizes our experimental set-up and the main performance measures considered.

3.1 Model Characteristics

3.1.1 Shop and Job Characteristics

Our two simulation models have been implemented in SIMIO©. Both shops contain six stations, where each station is a single, constant capacity resource. There is an incoming queue (i.e. an input buffer) and an outgoing queue (i.e. an output buffer) at each station. Both have infinite capacity to keep our study focused on the interaction between production planning and control and vehicle management. For a recent assessment of the interaction between buffer induced blocking and order release, the reader is referred to Thürer *et al*. (2021).

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. re-entrant flows are prohibited. This leads to the routing vector (i.e. the sequence in which stations are visited) for the pure job shop. For the general flow shop, the routing vector is sorted such that the routing becomes directed and there are typical upstream and downstream stations. The routing characteristics of both shop types are illustrated in Figure 1, which gives an impression of the resulting flows in the pure job shop and the general flow shop, where the thickness of the lines indicates the probability that a job will transition from one station to another.

[Take in Figure 1]

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. The inter-arrival time of jobs to the shop follows an exponential distribution with a mean of 0.648 time units, which deliberately results in a station utilization level of 90%. Due dates are set exogenously by adding a uniformly distributed random allowance factor to the job entry time. This factor was set arbitrarily between 38 and 60 time units to ensure meaningful results for all settings of the experimental factors. The minimum value allows for the maximum number of operations, the maximum processing time, the maximum transportation time and the minimum pool waiting time. The maximum was set such that the percentage tardy is neither too high nor too low. The percentage tardy should not be too high to avoid certain adverse effects, since rules that reduce the variance of lateness across jobs may even lead to an increase in the percentage tardy when due date allowances are too tight on average. The percentage tardy should not be too low to avoid our results being affected by incidental effects, as very few jobs would be responsible for the performance of the shop.

3.1.2 Characteristics of Material Handling

There are six vehicles in the system. We assume that jobs in the order pool (or backlog) are on paper only, meaning there is no transport needed from release to the first station in the routing of a job. To facilitate the implementation of the different assignment rules (described in the following section), we also assume that a different material handling system is responsible for the transportation of finished products to the end customer. Hence, only transportation between stations is needed. The distance between stations is given in Table 1 in time units.

[Take in Table 1]

Two measures for the distance factor k are used, namely 0.43 and 0.33 time units. These values result in approximately a 91% and 70% utilization rate of the vehicles in a pure job shop, where only one job can be loaded at a time and the station-initiated task assignment rule is random. The actually realized vehicle utilization level across scenarios depends on the applied station and vehicle-initiated task assignment rules. Vehicle utilization rates are similar to that used in Sabuncuoglu & Karapinar (1999). In addition to the single load scenario, we also consider the scenario where more than one job can be loaded. For this so-called multiple load scenario (Ho & Chien, 2006), vehicles have a transportation capacity of 10, where the size of jobs follows a uniform integer distribution between 1 and 4. Only jobs that have an identical destination can be loaded into the same vehicle.

We further assume that there is a unidirectional network to avoid network induced blocking. In a bidirectional network, traffic flow takes place in either direction in each aisle; however, vehicles are not allowed to travel in opposite directions at the same time (Vis, 2006), which creates additional uncontrolled vehicle waiting times. As in Sabuncuoglu & Karapinar (2000), a vehicle remains stationary and idle at the station where it has delivered its load if there is no further move request in the system.

3.2 Production Planning & Control

3.2.1 Order Release Control

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. Jobs flow into a pre-shop pool to await release. 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 (e.g. Thürer *et al*. 2012). LUMS COR uses a *periodic* release procedure to keep the workload W_s released to a station s within a pre-established workload limit or norm N_s as follows:

(1) All jobs in the set of jobs J in the pre-shop pool 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 pool and its processing time does not contribute to the station load.

(4) If the set of jobs J in the pool 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 completed, 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). 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 pool sequence with that station as the first in its routing is released irrespective of whether this would exceed the workload norms of any station in a bid to avoid premature station idleness (see, e.g. Land & Gaalman, 1998).

Five settings for the workload norm N_s are considered: 8, 10, 12, 14 and 16 time units. As a baseline measure, experiments without controlled order release have also been executed, i.e. where workload norms are infinite, and 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 10 time units based on preliminary simulation experiments.

3.2.2 Shop Floor Dispatching

Once released, jobs enter the queue of the first station in their routing. The jobs that are waiting in a queue are prioritized according to one of three dispatching rules: Operation Due Dates (ODD), Shortest Processing Times (SPT), and Modified Operation Due Dates (MODD). 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 was set to 10 time units based on preliminary simulation experiments. SPT dispatching prioritizes jobs by p_{ij} . Finally, MODD dispatching (e.g. Baker & Kanet, 1983) prioritizes jobs by $max(\delta_{ij}, t + p_{ij})$, where δ_{ij} is the operation due date of job j at the station corresponding to operation i, and t the simulation time when the dispatching decision is made.This rule shifts the focus from ODD to SPT in periods when many jobs become urgent, i.e. periods of high loads, which leads to superior performance in make-to-order contexts (Land *et al*., 2015).

3.3 Vehicle Management

Once completed at a station, a job flows into the outgoing queue and awaits transportation. Six vehicle-initiated task assignment rules are considered for a vehicle to choose a job (i.e. a transportation task) from the set of jobs that need transportation: (i) First-Come-First-Served (FCFS), (ii) Shortest Distance (SD), (iii) Longest Outgoing Queue (LOQ) at a station, (iv) Largest Load Imbalance (LLI; given by the size of the current outgoing queue minus the size of the incoming queue at the next station in the routing of a job), (v) Operation Due Date (ODD), and (vi) Smallest Physical Size (SPS). The first four are taken from the literature. They provide a comprehensive set of all of the different types of rules that have been presented. The last two are newly introduced in this study. ODD was introduced to provide a better measure of urgency than FCFS, and SPS was introduced to accommodate our multi-load setting. All ties between jobs are resolved by operation due dates using the same operation due dates as for shop floor dispatching. Similarly, for rules that are not based on job characteristics (e.g. LOQ), and for scenarios with multiple loads, operation due dates are used to answer our third question: Which job(s) should be loaded?

Meanwhile, two station-initiated task assignment rules are considered in order to choose a vehicle from the set of free vehicles to transport a job: (i) Random (RND) selection, and based on (ii) the Shortest Distance (SD), i.e. the vehicle that is the closest to the job is selected. Finally, Table 2 summarizes all vehicle and station-initiated task assignment rules used in this study.

[Take in Table 2]

3.4 Experimental Design and Performance Measures

The experimental factors are summarized in Table 3. A full factorial design was used with 1,440 (2x2x2x6x3x2x5) scenarios, where each scenario was replicated 50 times. Results were collected over 10,000 time units following a warm-up period of 3,000 time units.

[Take in Table 3]

Since we focus on a make-to-order shop, our main performance indicator will be delivery performance. Delivery performance will be measured by: the *percentage tardy* – i.e. the percentage of jobs completed after the due date; and, the *mean tardiness,* where $T_j = max(0, L_j)$ indicates the tardiness of job *j*, with L_j being the lateness of job *j* (i.e. the actual delivery date minus the due date of job *j*). We also measure the mean of the *total throughput time* – i.e. the mean of the completion date minus the pool entry date across jobs – and 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.

4. Results

To obtain a first indication of the relative impact of the experimental factors, statistical analysis has been conducted by applying ANOVA. 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 shop type, distance factor, and vehicle loading as blocking factors. This allows the main effects of these factors and the main and interaction effects of our four control related factors – workload norm, shop floor dispatching rule, vehicle-initiated task assignment rule, and station-initiated task assignment rule – to be captured. All main effects and two-way interactions, except between dispatching and the vehicle-initiated task assignment rule in terms of mean tardiness, were shown to be statistically significant at $\alpha = 0.05$. There are some significant three-way interactions, while the four-way interaction is significant for total throughput time and percentage tardy.

Note that we do not present the detailed results for ANOVA here given the space restrictions. We do however present the results from the Scheffé multiple comparison procedure that was applied to obtain a first indication of the direction and size of the performance differences for our vehicle and station-initiated task assignment rules. Table 4 gives the 95% confidence interval. If this interval includes zero, then performance differences are not considered to be statistically significant. We can observe significant performance differences for all pairs for at least one performance measure. Detailed performance results will be presented next in Section 4.1 and Section 4.2 for immediate release and order release control, respectively.

[Take in Table 4]

4.1 Performance Assessment: Immediate Release

Table 5 presents the total throughput time, percentage tardy, mean tardiness and average vehicle utilization rate for the pure job shop with a distance factor of $k = 0.43$ under immediate release.

[Take in Table 5]

The following can be observed from the results:

- *Vehicle-initiated Task Assignment Rules*: The arguably most widely applied rules in the literature, i.e. the FCFS and SD rules, perform the worst. Meanwhile, ODD improves percentage tardy and mean tardiness performance if a single load is used. But the advantage of focusing on the most urgent job vanishes in scenarios with multiple loads, partly due to the higher realized vehicle utilization rate compared to SD. For a single load, the SPS and ODD rules lead to the same performance results since the physical size is equal for all jobs and ODD is used for resolving ties. Meanwhile, LLI improves performance when compared to FCFS, SD, and ODD but is outperformed by LOQ. In general, station load oriented rules (i.e. LLI and LOQ) lead to the best performance, although they do lead to the highest vehicle utilization rate. This highlights the importance of prioritizing operational objectives, such as workload balance, over vehicle-related objectives, such as a low vehicle utilization rate.
- *Station-initiated Task Assignment Rules*: As expected from previous literature, station-initiated task assignment rules have only a limited impact on performance. The main effect is on the vehicle utilization rate, having SD the potential to reduce vehicle utilization.
- *Dispatching Rule*: Also as expected from previous literature, the ODD rule is outperformed by SPT in terms of the percentage tardy but realizes better mean tardiness performance. Meanwhile, MODD leads to the lowest mean tardiness performance and outperforms ODD in terms of the percentage tardy. Moreover, the relative performance of the vehicle and station-initiated task assignment rules is not affected by MODD or ODD dispatching. However, if SPT dispatching is used then the ODD task assignment rule realizes the best performance for a single load and matches the performance of LI and LOQ for a multiple load.

Conclusions similar to the ones obtained when $k = 0.43$ can be obtained when $k = 0.33$. This can be seen from Table 6, which summarizes the performance results for the pure job shop under immediate release with a distance factor of $k = 0.33$. The main difference compared to the results for $k = 0.43$ (see Table 4) is that the positive interaction between SPT dispatching and the ODD vehicle-initiated task assignment rule becomes less pronounced. As expected, a lower distance factor leads to lower vehicle utilization rates and, as a result, performance generally improves.

[Take in Table 6]

Finally, the above conclusions are robust to the shop type applied. The main difference between performance in the pure job shop and general flow shop is that the positive interaction between SPT dispatching and the ODD vehicle-initiated task assignment rule becomes less pronounced in the general flow shop. We therefore only present the results in the general flow shop for MODD dispatching with a distance factor of $k = 0.43$ in Table 7. Note that the general reduction in vehicle utilization is explained by the directed routing. For example, it is less likely that a job completed at station 1 needs to go to station 4 in the general flow shop compared to the pure job shop.

[Take in Table 7]

4.2 Performance Assessment: Order Release Control

Table 8 presents the total throughput time, shop floor throughput time, percentage tardy, mean tardiness, and average vehicle utilization rate obtained when order release control is applied. Only results for a single load, a distance factor of $k = 0.43$, the SD station-initiated assignment rule, and MODD shop floor dispatching are shown since the results were qualitatively similar across these four factors. In general, the conclusions on the performance of the task assignment rules, dispatching rules and their interactions were not affected by the introduction of order release control. However, order release control does appear to have a direct detrimental effect in the pure job shop, while it allows shop floor throughput times to be reduced at similar tardiness performance levels for the general flow shop. Hence, the routing direction has a strong impact on the performance of order release in shops where transportation may be a constraining resource.

[Take in Table 8]

5. Discussion

The majority of studies on vehicle assignment rules focus on urgency or travel distance (i.e. vehicle utilization). In fact, there is a whole stream of literature discussing whether the FCFS or SD rule leads to the best performance (e.g. Egbelu & Tanchoco, 1984; Srinivasan *et al.*, 1994; Bozer & Yen, 1996). This overlooks the suggestion that rules focusing on station loads may actually outperform FCFS and SD. Indeed, we found that LOQ leads to the best performance in our simulation experiments despite being widely neglected in the literature since the 1980s. Not even Kim *et al*. (1999) who presented LLI, which considers the difference between the workload at the current station and the workload at the next downstream station in the routing of a job, considered LOQ. The LLI rule was outperformed by LOQ in our simulation. Moreover, LOQ is simpler to implement than LLI given that it does not require any information from downstream queues in order to make a decision. It is argued here that the neglect of LOQ is due to its poor performance in Egbelu & Tanchoco (1984). The authors found that FCFS and SD lead to the best performance, with LOQ performing poorly. This may have introduced a negative bias towards LOQ in subsequent research. However, Egbelu & Tanchoco (1984) only explain that a vehicle should move to the largest outgoing queue for LOQ, they do not explain which rule is chosen to select a transportation task from this outgoing queue. We posit that it is this latter rule which led to the poor performance. To the best of our knowledge, the next study assessing the performance of the LOQ vehicle assignment rule since Egbelu & Tanchoco (1984) was that by Ho & Chien (2006), who showed that LOQ consistently outperforms SD. Our results confirm Ho & Chien (2006) and extend their study by showing that LOQ also has the potential to outperform all other task assignment rules presented in the literature and newly created in this study.

Our results further highlight that order release has a direct detrimental performance effect in pure job shops with material handling constraints. This confirms Sabuncuoglu & Karapinar (1999). Yet, we also found that the detrimental effect largely disappears in a general flow shop with more directed routings. Meanwhile, Sabuncuoglu & Karapinar (1999) observed a positive performance effect from order release control in a pure job shop with material handling and a limited buffer size. It is argued here that this is explained by the potential of order release control to reduce the blocking of resources, which enhances its performance effect in shops with limited buffer sizes (Thürer *et al*., 2021). In general, our study emphasizes that the need for transportation has a strong impact on the applicability of order release methods, such as Workload Control. This however is not discussed in studies that focus on assessing the applicability of Workload Control, such as those by Henrich *et al*. (2004), Soepenberg *et al*. (2012), and Cransberg *et al*. (2016). Hence, our findings extend the set of contingency factors that need to be considered when determining the applicability of order release control.

6. Conclusions

Transportation can be a major constraint in many real-life high variety make-to-order shops. Yet the literature on vehicle management remains largely inconclusive on which vehicle-initiated task assignment rule to apply in this context. In answer to our first research question (RQ1) – *What transportation task assignment rule should be used in high-variety make-to-order shops?* – we found that the LOQ rule that simply selects the most urgent job from the longest outgoing queue, which has been largely neglected in the literature since 1984, leads to the best performance. In answer to our second research question (RQ2) – *What is the interaction between order release control, dispatching and the transportation task assignment rule?* – we found that the relative performance of vehicle and station-initiated task assignment rules is not affected by the choice of dispatching rule or order release control. However, order release has a direct detrimental performance effect in pure job shops when jobs need to be transported from station to station. Order release control can however reduce throughput times in general flow shops with random yet directed routings without jeopardizing tardiness performance. These findings have important implications for practice and future research.

6.1 Managerial Implications

Our study highlights the importance of the LOQ rule for vehicle-initiated task assignments. While existing studies appear to advise against the use of this rule, our study highlights that the negative findings in Egbelu & Tanchoco (1984) were more than likely due to the way in which jobs were selected from the longest queue. This reemphasizes that findings from the literature need to be contextualized before being transferred to practice, and that the existing literature may not actually focus on the best-performing rules. In fact, while a large literature on vehicle-initiated task assignment rules emerged between 1984 and 2006 (i.e. the publication of Ho & Chien (2006)), this literature mainly focused on the FCFS and SD rules, which both led to worse performance in our study than the LOQ rule. Meanwhile, order release should not be applied in pure job shops where transportation is a constraint.

6.2 Limitations and Future Research

A first main limitation of our study is that we only considered one order release method from the Workload Control literature. This is justified by the need to keep our study focused, while the choice of Workload Control is justified by the shop types under study. Future research could consider other order release methods or approaches that focus on production authorization. A second main limitation of our study is that we did not consider a limited buffer space. Again, this is justified by the need to keep our study reasonably focused and by recent research findings on buffer induced blocking. Future research could however extend this research direction to include buffer induced blocking. Finally, a third limitation is that we also avoided vehicle blocking, which may occur at loading and unloading operations or on the path between stations. Future research could explore the impact of this kind of vehicle blocking on the performance of vehicle assignment rules, including the development of rules that avoid such blocking from occurring. This includes research on traffic management, which represents another level of management that managers may need to consider in addition to production planning and control and transportation task assignment.

References

Bagni, G., Godinho Filho, M., Thürer, M., & Stevenson, M., 2021, Systematic Review and Discussion of Production Control Systems that emerged between 1999 and 2018, *Production Planning & Control*, 32, 7, 511-525.

Baker, K.R. & Kanet., J.J., 1983, Job shop scheduling with modified due dates, *Journal of Operations Management*, 4, 1, 11-22.

Bergamaschi, D., Cigolini, R., Perona, M., & Portioli, A., 1997, Order review and release strategies in a job shop environment: A review and a classification, *International Journal of Production Research*, 35, 2, 399-420.

Bozer, Y.A., & Eamrungroj, C., 2018, Throughput analysis of multi-device trip-based material handling systems operating under the modified-FCFS dispatching rule, *International Journal of Production Research*, 56, 4, 1486-1503.

Bozer, Y.A. & Yen, C.K., 1996, Intelligent dispatching rules for trip-based material handling systems, *Journal of Manufacturing Systems*, 15, 4, 226-239.

Cransberg, V., Land, M., Hicks, C. and Stevenson, M., 2016, Handling the complexities of real-life job shops when implementing workload control: a decision framework and case study, *International Journal of Production Research*, 54, 4, 1094-1109.

Egbelu, P.J. & Tanchoco, J.M., 1984, Characterization of automatic guided vehicle dispatching rules, *International Journal of Production Research*, 22, 3, 359-374.

Fernandes, N.O., Thürer, M., Pinho, T.M., Torres, P., & Carmo-Silva, S., 2020, Workload Control and Optimised Order Release: An Assessment by Simulation, *International Journal of Production Research*, 58, 10, 3180-3193.

Fernandes, N.O., Land, M.J., & Carmo-Silva, S., 2016; Aligning workload control theory and practice: lot splitting and operation overlapping issues, *International Journal of Production Research*, 54, 10, 2965-2975.

Fragapane, G., de Koster, R., Sgarbossa, F. & Strandhagen, J.O., 2021, Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda, *European Journal of Operational Research*, 294, 405-426.

Fredendall, L.D., Ojha, D., & Patterson, J.W., 2010, Concerning the theory of workload control, *European Journal of Operational Research*, 201, 1, 99-111.

Gargeya, V.B. & Deane, R.H., 1996, Scheduling research in multiple resource constrained job shops: a review and critique, *International Journal of Production Research*, 34, 8, 2077-2097.

Gómez Paredes, F., Godinho Filho, M., Thürer, M., Fernandes, N.O., & Jabbour, C.J.C., 2021, Factors for choosing Production Control Systems in Make-To-Order Shops: A Systematic Literature Review, *Journal of Intelligent Manufacturing*, (in print)

Gonzalez-R, P.L., Calle, M., & Andrade-Pineda, J.L., 2018, Job shop management of products under internal lifespan and external due date, *International Journal of Production Research*, 56, 16, 5457-5474.

Haeussler, S. & Netzer, P., 2020, Comparison between rule-and optimization-based workload control concepts: a simulation optimization approach, *International Journal of Production Research*, 58, 12, 3724-3743.

Hendry, L.C., Huang, Y., & Stevenson, M., 2013, Workload control: Successful implementation taking a contingency-based view of production planning & control, *International Journal of Operations & Production Management*, 33, 1, 69-103.

Henrich, P., Land, M. & Gaalman, G., 2004, Exploring applicability of the workload control concept, *International Journal of Production Economics*, 90, 2, 187-198.

Ho, Y.C., Liu, H.C. & Yih, Y., 2012, A multiple-attribute method for concurrently solving the pickup-dispatching problem and the load-selection problem of multiple-load AGVs, *Journal of Manufacturing Systems*, 31, 3, 288-300.

Ho, Y.C. & Liu, H.C., 2009, The performance of load-selection rules and pickup-dispatching rules for multiple-load AGVs, *Journal of Manufacturing Systems*, 28, 1, 1-10.

Ho, Y.C. & Chien, S.H., 2006, A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs, *International Journal of Production Research*, 44, 20, 4193-4222.

Huang, Y., 2017, Information architecture for effective Workload Control: an insight from a successful implementation, *Production Planning & Control*, 28, 5, 351-366

Hutter, T., Haeussler, S., & Missbauer, H., 2018, Successful implementation of an order release mechanism based on workload control: a case study of a make-to-stock manufacturer, *International Journal of Production Research*, 56, 4, 1565-1580.

Jeong, B.H. & Randhawa, S.U., 2001, A multi-attribute dispatching rule for automated guided vehicle systems, *International Journal of Production Research*, 39, 13, 2817-2832.

Kim, C.W., Tanchoco, J.M.A. & Koo, P.H., 1999, AGV dispatching based on workload balancing, *International Journal of Production Research*, 37, 17, 4053-4066.

Land, M.J., Stevenson, M., Thürer, M., & Gaalman, G.J.C., 2015, Job Shop Control: In Search of the Key to Delivery Improvements, *International Journal of Production Economics*, 168, 257-266.

Land, M.J., & Gaalman, G.J.C., 1998, The performance of workload control concepts in job shops: Improving the release method, *International Journal of Production Economics*, 56-57, 347-364.

Nabi, H.Z., & Aized, T., 2020, Performance evaluation of a carousel configured multiple products flexible manufacturing system using Petri net, *Operations Management Research*, 13, 1-2, 109-129.

Oosterman, B., Land, M.J., & Gaalman, G., 2000, The influence of shop characteristics on workload control, *International Journal of Production Economics*, 68, 1, 107-119.

Perona, M., Saccani, N., Bonetti, S., & Bacchetti, A., 2016, Manufacturing lead time shortening and stabilisation by means of workload control: an action research and a new method, *Production Planning & Control*, 27, 7-8, 660-670

Portioli-Staudacher, A., & Tantardini, M., 2011, A lean-based ORR system for non-repetitive manufacturing, *International Journal of Production Research*, 50, 12, 3257-3273.

Ragatz, G. L., & Mabert, V. A., 1988, An evaluation of order release mechanisms in a job shop environment, *Decision Sciences*, 19, 167 – 189.

Sabuncuoglu, I., & Karapinar, H.Y., 2000, A load-based and due-date-oriented approach to order review/release in job shops, *Decision Sciences*, 31, 2, 413–447.

Sabuncuoglu, I. & Karapınar, H.Y., 1999, Analysis of order review/release problems in production systems, *International Journal of Production Economics*, 62, 3, 259-279.

Sellitto, M.A., 2018, Lead-time, inventory, and safety stock calculation in job-shop manufacturing, *Acta Polytechnica*, 58, 6, 395–401.

Silva, C., Stevenson, M., & Thürer, M., 2015, A Case Study of the Successful Implementation of Workload Control: A Practitioner-led Approach, *Journal of Manufacturing Technology Management*, 26, 2, 280-296.

Smith, J.S., 2003, Survey on the use of simulation for manufacturing system design and operation, *Journal of Manufacturing Systems*, 22, 2, 157-171.

Soepenberg, G.D., Land, M.J. and Gaalman, G.J., 2012, Adapting workload control for job shops with high routing complexity*, International Journal of Production Economics*, 140, 2, 681-690.

Srinivasan, M.M., Bozer, Y.A. & Cho, M., 1994, Trip-based material handling systems: throughput capacity analysis, *IIE Transactions*, 26, 1, 70-89.

Srinivasan, M.M., & Bozer Y.A., 1992, Which one is responsible for WIP: the workstations or the material handling system?. *International Journal of Production Research*, 30, 6, 1369-1399.

Thürer, M., Ma, L., & Stevenson, M., 2021, Workload Control Order Release in General and Pure Flow Shops with Limited Buffer Size Induced Blocking: An Assessment by Simulation, *International Journal of Production Research*; 59, 8, 2558-2569.

Thürer, M., Stevenson, M., Aitken, J. & Silva, C., 2020, State-dependent service rates in make-to-order shops: an assessment by simulation, *Operations Management Research*, 13, 1, 70-84.

Thürer, M., Stevenson, M., Silva, C., Land, M.J., Fredendall, L.D., & Melnyk, S.A., 2014, Lean control for make-to-order companies: Integrating customer enquiry management and order release, *Production & Operations Management*, 23, 3, 463-476.

Thürer, M., Stevenson, M., Silva, C., Land, M.J., & Fredendall, L.D., 2012, Workload control (WLC) and order release: A lean solution for make-to-order companies, *Production & Operations Management*, 21, 5, 939-953.

Vis, I.F., 2006, Survey of research in the design and control of automated guided vehicle systems, *European Journal of Operational Research*, 170, 3, 677-709.

Vivaldini, K., Rocha, L.F., Martarelli, N.J., Becker, M. & Moreira, A.P., 2016, Integrated tasks assignment and routing for the estimation of the optimal number of AGVS, *International Journal of Advanced Manufacturing Technology,* 82, 1-4, 719-736.

Wisner, J. D., 1995, A review of the order release policy research, *International Journal of Operations & Production Management*, 15, 6, 25-40.

Xie, C. & Allen, T.T., 2015, Simulation and experimental design methods for job shop scheduling with material handling: a survey, *International Journal of Advanced Manufacturing Technology,* 80, 1-4, 233-243.

Zamiri Marvizadeh, S., & Choobineh, F.F., 2014, Entropy-based dispatching for automatic guided vehicles, *International Journal of Production Research*, 52, 11, 3303-3316.

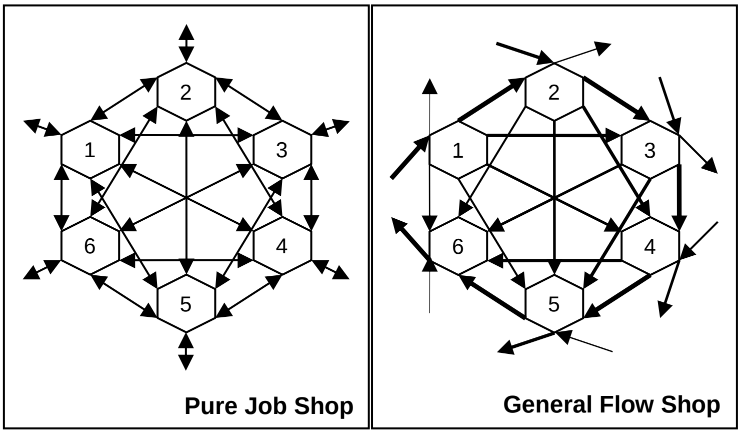

Figure 1: Illustration of The Two Shop Types According to Routing Characteristics (The Probability of Transition between Operations is indicated by the Strength of the Arrows)

Table 1: Travel Distance across Stations 1 to 6

		To Station:					
		Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
From Station:	Station 1	0	1 x *k*	2 x *k*	3 x *k*	2 x *k*	1 x *k*
	Station 2	1 x *k*	0	1 x *k*	2 x *k*	3 x *k*	2 x *k*
	Station 3	2 x *k*	1 x *k*	0	1 x *k*	2 x *k*	3 x *k*
	Station 4	3 x *k*	2 x *k*	1 x *k*	0	1 x *k*	2 x *k*
	Station 5	2 x *k*	3 x *k*	2 x *k*	1 x *k*	0	1 x *k*
	Station 6	1 x *k*	2 x *k*	3 x *k*	2 x *k*	1 x *k*	0

Table 2: Summary of the Station and Vehicle Initiated Task Assignment Rules

Vehicle Initiated Task Assignment	First-Come-First-Served (FCFS); the oldest transportation task across stations is selected
	Shortest Distance (SD); the closest transportation task is selected
	Longest Outgoing Queue (LOQ); the transportation task with the earliest operation due date is selected from the largest outgoing queue
	Largest Load Imbalance (LLI); the transportation task with the largest load imbalance (i.e. size of outgoing minus size of ingoing queue) across stations is selected
	Operation Due Date (ODD); the transportation task with the earliest operation due date across stations is selected
	Smallest Physical Size (SPS); the smallest transportation task across stations is selected
Station Initiated Task Assignment	Random (RND); a vehicle is selected randomly
	Shortest Distance (SD); the vehicle that is closest to the station where the transportation task is located is selected

Table 3: Summary of Experimental Factors

Environmental Factors	Shop Type	Pure Job Shop (random, undirected routing); General Flow Shop (random directed routing
	Distance Factor	*k* = 0.43; *k* = 0.33
	Vehicle Loading	Single load; multiple load (Transporter space units and jobs' random uniform integer between 1 and 4 space units)
Production Planning and Control	Order Release	N_s = 8, 10, 12, 14, and 16 time units; Immediate Release (IMM)
	Shop Floor Dispatching	Operation Due Dates (ODD); Shortest Processing Time (SPT); Modified Operation Due Dates (MODD)
Transporter Management	Vehicle Initiated Task Assignment	First-Come-First-Served (FCFS); Shortest Distance (SD); Longest Outgoing Queue (LOQ); Largest Load Imbalance (LLI); Operation Due Date (ODD); Smallest Physical Size (SPS)
	Station Initiated Task Assignment	Random (RND), Shortest Distance (SD)

Table 4: Results for Scheffé Multiple Comparison Procedure: Vehicle and Station Initiated Task Assignment Rules

	Rule (x)	Rule (y)	TTT		SFTT		%Tardy		Tard.	
			lower1)	upper	lower	upper	lower	upper	lower	upper
Vehicle Initiated	ODD	FCFS	-3.717	-3.199	-2.082	-1.897	-0.068	-0.063	-1.932	-1.497
	SD	FCFS	-3.471	-2.953	-2.215	-2.030	-0.054*	-0.048	-1.079	-0.644
	LOQ	FCFS	-7.547	-7.029	-5.045	-4.859	-0.112	-0.107	-2.400	-1.965
	SPS	FCFS	-3.981	-3.463	-2.301	-2.116	-0.069	-0.064	-1.917	-1.482
	LLI	FCFS	-6.628	-6.110	-4.491	-4.305	-0.100	-0.094	-2.151	-1.716
	SD	ODD	-0.013*	0.505	-0.226	-0.040	0.011	0.017	0.635	1.070
	LOQ	ODD	-4.089	-3.571	-3.055	-2.869	-0.047	-0.041	-0.686	-0.251
	SPS	ODD	-0.523	-0.005	-0.311	-0.126	-0.004*	0.002	-0.202*	0.232
	LLI	ODD	-3.170	-2.652	-2.501	-2.315	-0.034	-0.029	-0.437	-0.002
	LOQ	SD	-4.335	-3.817	-2.922	-2.737	-0.061	-0.056	-1.539	-1.104
	SPS	SD	-0.769	-0.251	-0.179*	0.007	-0.018	-0.012	-1.055	-0.620
	LLI	SD	-3.416	-2.898	-2.368	-2.183	-0.049	-0.043	-1.290	-0.855
	SPS	LOQ	3.307	3.825	2.651	2.836	0.040	0.046	0.266	0.701
	LLI	LOQ	0.660	1.178	0.461	0.647	0.010	0.015	0.031	0.466
	LLI	SPS	-2.906	-2.388	-2.282	-2.097	-0.033	-0.028	-0.452	-0.017
Station Intitiated	SD	RND	-0.820	-0.644	-0.559	-0.496	-0.008	-0.006	-0.220	-0.072

1) 95% confidence interval; * not significant at 0.05

TTT - total throughput time; SFT - shop floor throughput time; %Tardy - percentage tardy; Tard. - mean tardiness

Table 5: Performance Results for Pure Job Shop, k = 0.43 and Immediate Release

Disp. Rule	Vehicle Initiated	Station Initiated	Single Load				Multiple Loading			
			TTT	%Tardy	Tard.	VUtil.	TTT	%Tardy	Tard.	VUtil.
ODD	FCFS	RND	42.6	38.6%	4.0	91.2%	38.6	24.2%	2.0	60.8%
ODD	ODD	RND	38.2	21.9%	1.9	90.9%	35.4	15.6%	1.2	63.5%
ODD	SD	RND	41.3	30.9%	5.4	91.1%	34.4	15.3%	1.3	60.1%
ODD	LOQ	RND	32.4	11.7%	1.8	91.2%	29.6	7.6%	0.5	73.9%
ODD	LLI	RND	33.9	14.7%	2.1	91.4%	30.4	8.6%	0.7	74.1%
ODD	SPS	RND	38.2	21.9%	1.9	90.9%	34.4	14.8%	1.2	64.6%
ODD	FCFS	SD	41.9	36.4%	3.8	90.4%	38.3	23.9%	2.0	58.2%
ODD	ODD	SD	38.3	22.4%	1.9	90.3%	35.4	16.4%	1.4	60.7%
ODD	SD	SD	40.8	29.9%	5.1	90.5%	33.8	13.6%	1.0	57.0%
ODD	LOQ	SD	31.9	10.9%	1.6	90.5%	29.8	8.4%	0.7	72.9%
ODD	LLI	SD	34.1	15.1%	2.3	90.8%	30.5	9.0%	0.7	73.4%
ODD	SPS	SD	38.3	22.4%	1.9	90.3%	33.7	13.7%	1.1	61.6%
SPT	FCFS	RND	31.5	19.4%	4.7	91.0%	27.7	13.0%	3.8	61.4%
SPT	ODD	RND	27.8	8.0%	2.7	90.9%	23.6	6.5%	2.6	64.9%
SPT	SD	RND	29.5	17.6%	5.3	91.1%	23.3	8.1%	3.0	60.9%
SPT	LOQ	RND	23.0	8.1%	3.8	91.4%	19.8	5.6%	2.5	74.2%
SPT	LLI	RND	23.5	9.0%	4.2	91.3%	20.3	6.0%	2.5	74.5%
SPT	SPS	RND	27.8	8.0%	2.7	90.9%	23.1	8.1%	2.8	65.0%
SPT	FCFS	SD	31.2	18.9%	4.7	90.3%	27.0	12.3%	3.5	58.6%
SPT	ODD	SD	27.8	8.0%	2.7	90.3%	23.4	6.6%	2.7	62.0%
SPT	SD	SD	29.1	17.0%	5.1	90.4%	22.9	7.9%	2.9	57.5%
SPT	LOQ	SD	22.9	8.1%	3.7	90.8%	19.3	5.3%	2.2	73.0%
SPT	LLI	SD	23.3	9.0%	4.1	90.8%	20.2	6.0%	2.6	73.7%
SPT	SPS	SD	27.8	8.0%	2.7	90.3%	23.1	8.0%	2.9	62.3%
MODD	FCFS	RND	39.9	25.3%	2.2	91.0%	37.3	13.6%	1.0	61.0%
MODD	ODD	RND	36.9	12.1%	1.0	91.0%	34.3	7.1%	0.6	63.7%
MODD	SD	RND	39.5	22.4%	4.2	90.9%	32.7	6.7%	0.6	60.1%
MODD	LOQ	RND	31.4	6.7%	1.4	91.1%	29.3	3.8%	0.4	74.0%
MODD	LLI	RND	32.7	8.2%	1.7	91.3%	30.1	4.2%	0.4	74.3%
MODD	SPS	RND	36.9	12.1%	1.0	91.0%	33.3	7.2%	0.6	64.6%
MODD	FCFS	SD	39.7	24.4%	2.1	90.3%	36.3	11.8%	0.9	58.0%
MODD	ODD	SD	36.8	12.1%	1.0	90.3%	33.6	6.3%	0.5	60.8%
MODD	SD	SD	39.1	21.5%	4.0	90.6%	32.8	7.0%	0.6	56.9%
MODD	LOQ	SD	31.5	6.9%	1.4	90.7%	28.8	3.0%	0.3	72.9%
MODD	LLI	SD	32.7	7.9%	1.6	90.8%	29.9	4.1%	0.4	73.4%
MODD	SPS	SD	36.8	12.1%	1.0	90.3%	32.3	6.1%	0.5	61.5%

TTT - total throughput time; %Tardy - percentage tardy; Tard. - mean tardiness; VUtil. - vehicle utilization rate

Table 6: Performance Results for Pure Job Shop, k = 0.33 and Immediate Release

Disp. Rule	Vehicle Initiated	Station Initiated	Single Load				Multiple Loading			
			TTT	%Tardy	Tard.	VUtil.	TTT	%Tardy	Tard.	VUtil.
ODD	FCFS	RND	38.4	24.2%	2.0	69.8%	37.3	20.4%	1.7	48.4%
ODD	ODD	RND	34.9	14.5%	1.1	69.7%	34.5	13.9%	1.1	50.1%
ODD	SD	RND	34.7	16.7%	1.6	69.8%	33.1	12.6%	1.0	46.7%
ODD	LOQ	RND	30.2	9.2%	0.8	70.1%	29.5	7.8%	0.6	57.9%
ODD	LLI	RND	31.0	10.0%	0.8	70.1%	30.0	8.6%	0.7	58.4%
ODD	SPS	RND	34.9	14.5%	1.1	69.7%	32.6	11.2%	0.8	50.4%
ODD	FCFS	SD	38.3	23.9%	2.0	68.1%	36.6	18.8%	1.4	45.0%
ODD	ODD	SD	34.5	13.9%	1.1	67.9%	33.8	12.6%	1.0	46.5%
ODD	SD	SD	34.2	15.7%	1.4	68.2%	33.3	13.0%	1.1	43.1%
ODD	LOQ	SD	29.9	8.5%	0.6	68.3%	29.0	7.0%	0.5	56.2%
ODD	LLI	SD	30.9	10.2%	0.8	68.5%	29.8	8.1%	0.7	56.7%
ODD	SPS	SD	34.5	13.9%	1.1	67.9%	32.7	11.3%	0.9	46.8%
SPT	FCFS	RND	27.5	12.6%	3.8	69.8%	26.1	11.1%	3.5	48.9%
SPT	ODD	RND	23.4	6.5%	2.7	69.5%	22.6	6.3%	2.7	50.8%
SPT	SD	RND	23.7	9.2%	3.2	69.9%	22.3	7.5%	2.9	47.3%
SPT	LOQ	RND	19.4	5.5%	2.3	69.9%	18.9	5.3%	2.4	57.9%
SPT	LLI	RND	20.0	6.2%	2.6	69.9%	19.3	5.7%	2.4	58.7%
SPT	SPS	RND	23.4	6.5%	2.7	69.5%	22.3	7.5%	2.9	50.7%
SPT	FCFS	SD	27.0	12.0%	3.6	67.8%	25.9	10.8%	3.5	45.4%
SPT	ODD	SD	23.4	6.4%	2.8	68.0%	22.1	6.2%	2.5	47.1%
SPT	SD	SD	23.3	8.8%	3.1	68.2%	22.1	7.4%	2.9	43.6%
SPT	LOQ	SD	19.5	5.7%	2.5	68.2%	18.8	5.2%	2.4	56.1%
SPT	LLI	SD	19.7	6.1%	2.5	68.1%	19.2	5.6%	2.5	57.0%
SPT	SPS	SD	23.4	6.4%	2.8	68.0%	22.1	7.3%	2.8	47.1%
MODD	FCFS	RND	37.1	13.2%	1.0	69.8%	36.0	10.4%	0.9	48.5%
MODD	ODD	RND	33.7	6.4%	0.5	69.7%	32.9	5.5%	0.5	50.0%
MODD	SD	RND	33.6	9.7%	1.0	70.0%	32.1	5.8%	0.5	46.7%
MODD	LOQ	RND	29.5	4.2%	0.4	70.0%	28.8	3.5%	0.3	58.0%
MODD	LLI	RND	30.1	4.5%	0.4	70.2%	29.1	3.5%	0.3	58.4%
MODD	SPS	RND	33.7	6.4%	0.5	69.7%	32.5	6.3%	0.6	50.5%
MODD	FCFS	SD	36.5	11.9%	0.9	67.9%	35.5	9.6%	0.7	45.0%
MODD	ODD	SD	33.6	6.3%	0.5	68.0%	33.2	6.3%	0.6	46.6%
MODD	SD	SD	33.1	9.0%	0.9	68.1%	32.2	6.3%	0.6	43.1%
MODD	LOQ	SD	29.3	3.8%	0.4	68.2%	28.3	3.2%	0.3	56.1%
MODD	LLI	SD	30.2	4.9%	0.5	68.4%	28.9	3.5%	0.3	56.7%
MODD	SPS	SD	33.6	6.3%	0.5	68.0%	31.7	5.3%	0.5	46.8%

TTT - total throughput time; %Tardy - percentage tardy; Tard. - mean tardiness; VUtil. - vehicle utilization rate

Table 7: Performance Results for General Flow Shop, k = 0.43, Immediate Release and MODD Dispatching

Disp. Rule	Vehicle Initiated	Station Initiated	Single Load				Multiple Loading			
			TTT	%Tardy	Tard.	VUtil.	TTT	%Tardy	Tard.	VUtil.
MODD	FCFS	RND	31.6	5.8%	0.7	78.9%	30.4	4.7%	0.5	58.2%
MODD	ODD	RND	30.2	4.6%	0.5	79.2%	29.2	3.8%	0.4	58.2%
MODD	SD	RND	29.8	5.3%	0.6	79.2%	28.6	3.8%	0.4	57.0%
MODD	LOQ	RND	27.4	3.0%	0.3	79.5%	26.8	2.7%	0.4	63.9%
MODD	LLI	RND	27.9	3.1%	0.4	79.6%	28.1	3.8%	0.5	64.2%
MODD	SPS	RND	30.2	4.6%	0.5	79.2%	29.3	4.1%	0.4	58.2%
MODD	FCFS	SD	30.8	5.1%	0.5	74.9%	30.1	4.4%	0.5	52.1%
MODD	ODD	SD	29.7	4.5%	0.5	74.7%	28.2	3.3%	0.4	51.9%
MODD	SD	SD	29.1	4.8%	0.5	74.9%	27.7	3.2%	0.4	50.7%
MODD	LOQ	SD	27.0	2.7%	0.3	74.7%	26.7	2.8%	0.3	60.0%
MODD	LLI	SD	27.5	3.1%	0.3	74.7%	27.2	2.8%	0.3	60.1%
MODD	SPS	SD	29.7	4.5%	0.5	74.7%	28.4	3.4%	0.4	51.7%

TTT - total throughput time; %Tardy - percentage tardy; Tard. - mean tardiness; VUtil. - vehicle utilization rate

Table 8: Performance Results for Single Load, k = 0.43, SD Station Initiated Assignment Rule and MODD Dispatching

Norm Level	Vehicle Initiated	Pure Job Shop					General Flow Shop				
		TTT	SFTT	%Tardy	Tard.	VUtil.	TTT	SFTT	%Tardy	Tard.	VUtil.
16	FCFS	42.3	37.6	30.6%	3.2	90.4%	31.6	28.8	5.6%	0.5	74.8%
	ODD	38.7	34.8	16.8%	1.3	90.2%	30.5	27.7	4.9%	0.5	74.7%
	SD	41.3	37.0	25.6%	4.4	90.4%	30.1	27.4	5.6%	0.6	75.0%
	LOQ	33.5	30.3	8.8%	1.5	90.6%	28.1	25.4	3.7%	0.3	74.8%
	LLI	35.0	31.3	10.8%	1.8	90.8%	28.8	25.8	4.4%	0.5	75.0%
	SPS	38.7	34.8	16.8%	1.3	90.2%	30.5	27.7	4.9%	0.5	74.7%
14	FCFS	42.3	36.4	31.2%	3.2	90.2%	31.6	28.2	6.1%	0.6	74.7%
	ODD	39.4	34.1	18.6%	1.5	90.5%	29.9	26.8	4.5%	0.4	74.6%
	SD	41.7	36.2	26.5%	4.7	90.6%	29.9	26.7	5.3%	0.5	74.8%
	LOQ	34.2	30.0	9.8%	1.7	90.8%	27.5	24.5	3.5%	0.3	74.5%
	LLI	34.5	30.1	10.5%	1.7	90.5%	28.7	25.5	4.1%	0.4	75.1%
	SPS	39.4	34.1	18.6%	1.5	90.5%	29.9	26.8	4.5%	0.4	74.6%
12	FCFS	43.5	34.9	33.7%	4.3	90.3%	31.8	27.3	6.8%	0.8	74.7%
	ODD	39.9	32.5	20.7%	1.9	90.4%	30.1	26.2	4.7%	0.5	74.7%
	SD	43.0	34.5	29.3%	5.7	90.7%	30.6	26.1	6.3%	0.8	75.1%
	LOQ	34.1	28.6	10.5%	1.7	90.6%	28.3	24.3	4.0%	0.5	74.9%
	LLI	36.3	29.4	14.1%	2.5	90.8%	28.1	24.1	3.7%	0.5	74.8%
	SPS	39.9	32.5	20.7%	1.9	90.4%	30.1	26.2	4.7%	0.5	74.7%
10	FCFS	47.1	32.6	40.6%	7.5	90.5%	31.7	25.8	6.4%	0.9	74.7%
	ODD	41.8	30.3	26.3%	3.2	90.5%	30.2	24.7	5.4%	0.7	74.6%
	SD	45.1	31.8	33.7%	7.4	90.4%	30.1	24.7	5.8%	0.9	75.0%
	LOQ	34.9	26.9	12.8%	2.1	90.7%	27.8	22.8	3.4%	0.5	74.8%
	LLI	37.1	27.3	16.6%	2.9	90.6%	28.4	23.1	4.0%	0.7	74.9%
	SPS	41.8	30.3	26.3%	3.2	90.5%	30.2	24.7	5.4%	0.7	74.6%
8	FCFS	62.7	28.8	57.4%	21.6	90.3%	32.7	23.6	8.3%	1.9	74.9%
	ODD	47.8	26.8	40.2%	7.8	90.3%	31.1	22.9	6.5%	1.5	75.0%
	SD	57.9	28.0	49.3%	18.4	90.2%	30.8	22.6	6.9%	1.6	75.1%
	LOQ	36.2	24.0	16.8%	3.0	90.4%	28.0	20.9	4.6%	1.1	74.7%
	LLI	41.2	24.4	25.4%	5.7	90.8%	28.3	21.2	4.5%	0.9	75.0%
	SPS	47.8	26.8	40.2%	7.8	90.3%	31.1	22.9	6.5%	1.5	75.0%

TTT - total throughput time; SFT - shop floor throughput time; %Tardy - percentage tardy; Tard. - mean tardiness; VUtil. - vehicle utilization rate