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# Scheduling dynamic job shop manufacturing cells with family setup times: a simulation study

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**Abstract** Heuristics based on dispatching rules are still widely used in practice as methods for effective scheduling systems. Despite the successful development of various novel dispatching rules for traditional job shop scheduling environments, nearly none of these has been applied to cellular manufacturing within the last decade. In this paper, we close this gap by implementing novel dispatching rules into two-stage heuristics in order to solve group scheduling problems in a job shop manufacturing cell. By a comprehensive simulation study these heuristics are evaluated and compared to established effective dispatching rules. It is shown that in some scenarios new heuristics are capable of leading to superior results compared to previous heuristics with respect to mean flow time, mean tardiness and the proportion of tardy jobs. Besides, several influencing factors for the performance of heuristics are analyzed and statistically evaluated.

**Keywords** group scheduling · job shop · cellular manufacture · production logistics · heuristics · dispatching rules · simulation

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## 1 Introduction

For decades shorter product life cycles, foreign competition and growing product diversity have been forcing manufacturing industry to continually ensure an increasing productivity while, at the same time, providing a high level of flexibility. Group technology and cellular manufacturing have evolved as successful possibilities to meet these requirements [19]. In the context of manufacturing, *group technology* is defined as concept of grouping heterogeneous parts to part families in order to establish efficient production processes [39]. The assignment of parts to part families is usually conducted according to similarities concerning the parts' geometry as well as required processes, machines and tools. As similar parts are processed together, particularly setup times can be reduced significantly [39]. Especially the integration of group technology into the concept of lean manufacturing gave impetus for a widespread application in practice [5].

Based on group technology, *cellular manufacturing* defines the grouping of resources and machines to autonomous manufacturing cells on the shop floor [8]. The objective is to form independent cells that are capable of processing all necessary operations for a set of part families. Hence, intercellular material flow is avoided [39]. Besides the minimization of setup times, the main advantages of cellular manufacturing are lower throughput times, decreasing inventory, higher quality and fewer transport processes. With this, cellular manufacturing can constitute a basis for the successful implementation of just-in-time production [43]. Practical applications of cellular manufacturing have been reported in several areas of industry, such as automotive production [33], electronics manufacturing [14] and semiconductor industry [7].

In cellular manufacturing systems an effective scheduling system is crucial to gain these advantages. While manufacturing cells often constitute a job shop or a flow shop environment, the existence of part families leads to a scheduling task on two levels, usually referred to as group scheduling. On the one hand, a sequence of parts within each part or tooling family assigned to a certain cell has to be determined. On the other hand, a preferably optimal order of processing families has to be found. While minor setup times within a part family can be integrated into processing times, for every changeover of jobs from different part families either sequence-independent (SIST) or sequence-dependent setup times (SDST) have to be taken into account. As an extension of classical scheduling, static group scheduling problems with sequence-dependent setup times are known to be NP-hard already even for single machine environments [25]. Thus, the development and application of heuristics is necessary. An effective scheduling system is characterized by its ability to reflect real production environments and especially its dynamic nature. Accordingly, it should be robust concerning diverse changes of shop conditions [24]. Simple heuristics based on dispatching rules are able to meet these requirements particularly since they are easy to implement in real-world manufacturing systems. Thus, they are of high relevance for practical applications and considered in this study.

In this paper, the center of attention are two-stage heuristics that are characterized by three distinct major dispatching decisions [32]: First, the transition between two part families has to be defined. Exhaustive rules assume that all jobs of a family have to be processed before a job from a different family is taken into account. In contrast, non-exhaustive rules allow switching of families even though parts of the current family are still queuing [21]. As exhaustive rules have shown superior performance compared to non-exhaustive rules for group scheduling problems [13], this study is limited to exhaustive rules. Second, a decision has to be made about which part family is processed. This *family rule* also determines the occurring setup times. Finally, a *job rule* determines the sequence of jobs within the current part family.

Even though many manufacturing cells are organized as job shops, only few publications focus on this type of layout [11]. Meta-heuristic approaches have been proposed for scheduling static and deterministic job shop cells recently [40, 11, 38] and static flowshop manufacturing cells still receive various attention [4, 18]. However, to the best of our knowledge dynamic environments have not been considered since the last simulation study by Reddy and Narendran [30] and van der Zee et al. [42]. At the same time, several novel dispatching rules and recommendations for the design of rules have been proven to be efficient in job shop manufacturing systems without part families [36, 28]. Still, these rules have never been applied to group scheduling problems. Especially for sequencing part families no combined dispatching rules have been applied and tested so far. Furthermore, the influence of a cell's configuration has not been discussed in detail. In this paper we attempt to close this gap, pursuing a threefold objective: First, an detailed overview of existing simulation studies in group scheduling environments is given. For the first time important results in this area are summarized in a comprehensive way. This analysis forms the basis for the following identification of existing effective group scheduling dispatching rules as well as novel rules that have not been taken into account for group scheduling so far. Secondly, these rules are compared to each other in a dynamic manufacturing environment. By this, the most effective scheduling rules concerning the objectives of flow time and tardiness can be identified. Finally, influencing factors that have not been considered explicitly in literature so far, such as cell configuration and type of setup times, are examined in order to give insights on significant parameters of a group scheduling production system. To achieve the last two objectives a comprehensive simulation study is conducted since simulation is known as suitable method for analyzing complex problems with large amounts of data [29]. Two different configurations of cells are used. Besides a manufacturing cell with five machines, that has been widely used in literature, a smaller cell with three machines is considered. With this, the proposed study can give helpful insights for effective scheduling systems in practical cellular manufacturing environments.

The remainder of this work is organized as follows: Section 2 gives a detailed overview of previous simulation studies on group scheduling problems. Prior results and the significance of various influencing factors are summarized.
Based on this, open questions are identified and the studied simulation model is described in Section 3. A well-founded selection of exhaustive two-stage heuristics and the chosen parameters are presented. Section 4 details the results of the conducted simulation study regarding the performance of the tested heuristics as well as influencing factors. Finally, in Section 5 essential findings are summarized and aims for future research are pointed out.

## 2 Literature review

Since the first study in 1960 [2] until today [36], dispatching rules have been widely investigated in literature and are still of high relevance for research as well as for practice. While in the beginning basic dispatching rules had been tested only since the 1990s the capability of developing powerful heuristics by combining rules was exploited [1]. Moreover, various influencing factors for shop performance have been analyzed. Other research pointed out the significance of an integrated process planning and scheduling [34]. Siemiatkowski and Przybylski [37] modeled and investigated process alternatives in cellular manufacturing systems by a simulation study.

For group scheduling problems several two-stage heuristics were applied and tested in simulation studies since the 1980s [27, 29]. An overview of popular and effective heuristics is given in Table 1. Since different shop types showed very similar results, all simulation studies on job shop, flow shop and single machine manufacturing cells are considered in the following. As the setup of a simulation study has a significant impact on the performance of certain rules, basic characteristics and effective dispatching rules are listed for each study, too. Fundamental insights and the influencing factors identified in these studies are summarized in the following.

*Two-stage heuristics versus single-stage dispatching rules* Mosier, Elvers and Kelly [27] were the first to prove the dominance of two-stage heuristics over single-stage dispatching rules concerning production-flow-oriented criteria in job shop cells. In their simulation study several variations of utilization and setup to processing time ratios were tested. Only for due-date-based criteria, the use of single-stage rules could partly lead to superior results. However, no due-date-oriented family rule was considered [31]. This gap was closed by Mahmoodi, Dooley and Starr [23] who studied several due-date-based family rules. Still, two-stage heuristics outperformed single-stage heuristics for all criteria. These results were also confirmed for flow shop manufacturing cells by Wemmerlöv and Vakharia [45]. Besides, two-stage heuristics showed a significantly lower variance compared to single-stage dispatching rules, whose performance is greatly determined by system parameters [27, 31]. This justifies a wide-ranging applicability of dispatching rules within two-stage heuristics.

*Exhaustive versus non-exhaustive heuristics* Mahmoodi and Dooley [21] observed that exhaustive family rules generally outperform non-exhaustive rules regarding production-flow-oriented criteria. Only for mean tardiness non-exhaustive rules could improve cell performance in cells with low utilization and loose due dates. Non-exhaustive rules show two contrary effects: a splitting of part families allows more jobs to be on time while, at the same time, this results in additional setup operations and, hence, increasing total flow time. Furthermore, exhaustive heuristics were proven to be more robust regarding changes of influencing system parameters, in particular concerning the setting of due dates. The superiority of exhaustive rules was also confirmed by Frazier [13]. Moreover, they are readily understandable and easy to implement in practice.

*Number and size of part families* Simulation studies conducted by Wemmerlöv [43] and Wirth, Mahmoodi and Mosier [46] showed that the advantage of two-stage heuristics compared to single-stage dispatching rules decreases with an increasing number of part families. This becomes reasonable by considering an extreme example with each family consisting of a single job only. Understandably, in this case a family rule does not enhance the performance of a job rule. Frazier [13] confirms these results in his study for flow shop cells. Furthermore, he states that the number of part families does not impact the advantageousness of different two-stage heuristics compared to each other.

A dominating part family with a significant higher number of jobs generally leads to lower mean flow times as fewer setup operations are necessary [43]. As a result, jobs belonging to this part family are less likely to be tardy. However, jobs from smaller part families tend toward a late date of completion as the machines are rarely set up for processing these part families. Particularly under mean tardiness criterion and a high cell utilization two-stage heuristics are often less robust, i. e. their performance differs widely dependent on variations of family size [31]. Hence, especially the variation of family size represents a significant influencing factor for the selection of dispatching rules.

*Due date setting procedures* Russel and Philipoom [32] investigated the effect of different types of due date setting procedures. They showed that a heuristic's performance can be influenced by due date setting procedures significantly, especially if mean tardiness is minimized. Nevertheless, superior two-stage heuristics remain favorable regardless of the chosen strategy. Mean flow time criterion was generally less influenced by due date setting procedures. Besides, Mahmoodi and Dooley [21] report a case in that a non-exhaustive rule is superior compared to an exhaustive rule: in a setting with loose due dates the non-exhaustive *dynamic due-date-based heuristic* (*DK*) rule led to slightly lower mean tardiness, while with tight due dates *DK* and *earliest due date* (*EDD*) performed similarly.

*Setup times* Wemmerlöv [43] showed that increasing setup times lead to larger flow times for both, priority rules and two-stage heuristics. The latter are less influenced by changes of setup times. In addition, a dominating part family as well as increasing setup times lead to a broader spread of the performance of heuristics concerning mean flow time. Wirth, Mahmoodi and Mosier [46] come to the conclusion that the size of setup times has no significant impact on the performance of a cell but on the ranking of heuristics.

*Cell utilization* Furthermore, Wirth, Mahmoodi and Mosier [46] proved that cell utilization is crucial for its performance. Cells with a low workload generally result in low flow times and less tardy jobs. However, the effectiveness of two-stage heuristics is less influenced by a varying cell utilization [31].

*Cell configuration* Mahmoodi, Tierney and Mosier [26] disclosed that generally flow shop cells lead to a similar ranking of heuristics compared to job shop cells as presented by Mahmoodi, Dooley and Starr [23]. Besides, only few dispatching rules have been tested in single machine cells as well as job shop cells. Thus, a profound analysis of cell

Table 1: Literature overview of simulation studies on group scheduling

| # | author | year | shop | superior rules | | | # tested heuristics | #families | #operations/job | #routes | #machines | setup |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | mean flow time | mean tardiness | % tardy | | | | | | |
| 1 | WEMMERLÖV [43] | 1992 | Single | SPT/SPT | | | 3 | 4,8, 16,32 | 1 | 1 | 1 | SIST |
| 2 | MAHMOODI/MARTIN [25] | 1997 | Single | MS/SPT | FCFS/FCFS | | 6 | 3 | 1 | 1 | 1 | SDST |
| 3 | RUSSELL/PHILIPOOM [32] | 1991 | Flow Shop | APT/SPT | EDD/EDD,FCFS/EDD, FCFS/SL,FCFS/EDD | | 22 | 5 | 5 | 1 | 5 | SIST |
| 4 | WEMMERLÖV/VAKHARIA [45] | 1991 | Flow Shop | FCFS/FCFS | | FCFS/FCFS | 4 | 3,6 | 5 | 1 | 5 | SIST |
| 5 | MAHMOODI/TIERNEY/ MOSIER [26] | 1992 | Flow Shop | MS/SPT | EDD/TSPT | EDD/TSPT | 4 | 3 | 5 | 1 | 5 | SDST |
| 6 | FRAZIER [13] | 1996 | Flow Shop | MJ/SPT | EDD/TSPT | MJ/SPT,SPT/SPT | 11 | 4,8 | 6 | 1 | 6 | SDST |
| 7 | REDDY/NARANDRAN [30] | 2003 | Flow Shop | MJ/EDD,PH/SPT | MJ/SPT,PH/SPT | MJ/SPT,MJ/EDD PH/SPT | 9 | 3 | 5 | 1 | 5 | SIST |
| 8 | VAN DER ZEE/GAALMAN/ NOMDEN [42] | 2011 | Flexible Flow Shop | MASP_AD/SPT | | | 5 | 4,8 | 2 | 1 | 2,5 | SIST |
| 9 | MOSIER/ELVERS/ KELLY [27] | 1984 | Job Shop | MW/SPT | MW/SL | SL/SL | 15 | 3 | 2-4 | 6 | 4 | SIST |
| 10 | FLYNN [12] | 1987 | Job Shop | FCFS/FCFS | | | 2 | 3 | 19,9 | 10 | 39 | SDST |
| 11 | MAHMOODI/DOOLEY/ STARR [23] | 1990a | Job Shop | MS/SPT | EDD/TSPT,EDD/SPT | MS/SPT | 9 | 3 | 4-5 | 12 | 5 | SDST |
| 12 | MAHMOODI/DOOLEY/ STARR [22] | 1990b | Job Shop | MS/SPT | EDD/TSPT | MS/SPT,MS/FCFS | 6 | 3 | 4-5 | 12 | 5 | SDST |
| 13 | MAHMOODI/DOOLEY [21] | 1991 | Job Shop | MS/SPT | DK/TSPT | MS/SPT | 12 | 3 | 4-5 | 12 | 5 | SDST |
| 14 | RUBEN/MOSIER/ MAHMOODI [31] | 1993 | Job Shop | MS/SPT | EDD/TSPT,FCFS/FCFS | MS/SPT | 5 | 3 | 3-5 | 12 | 5 | SDST |
| 15 | WIRTH/MAHMOODI MOSIER [46] | 1993 | Job Shop | MS/SPT | MS/SPT | MS/SPT | 5 | 3 | 4-5 | 12 | 5 | SDST |
| 16 | KANNAN/LYMAN [17] | 1994 | Job Shop | SL/SPT,SL/SL | MW/SL,SL/SL | | 12 | 3 | 3-5 | 16 | 5 | SIST |
| 17 | PONNAMBALAM/ARAVINDAN/ REDDY [29] | 1999 | Job Shop | DK/EDD,DK/SPT DK/FCFS | DK/EDD,DK/FCFS | DK/EDD,DK/FCFS | 6 | 3 | 5-7 | 54 | 7 | SDST |

APT = average processing time, DK = dynamic due-date-based heuristic, EDD = earliest due date, FCFS = first come first serve, MASP_AD = minimum weighted work load considering batch size, MJ = most jobs, MS = minimum setup time, MW = most work in queue, PH = predictive heuristic, SL = slack, SPT = shortest processing time, TSPT = two class truncated SPT configurations with a single machine is not possible. Nevertheless, concerning the influencing factors mentioned above similar conclusion were drawn in single machine environments [43]. Hence, a limited impact of the cell configuration on the selection of heuristics can be expected. The influence of cell size has not be discussed in detail so far.

*Distribution of inter-arrival and processing times* The greatest impact on shop performance concerning mean flow time was ascertained by the distribution of inter-arrival and processing times. For an exponential distribution of the arrival of jobs Mahmoodi, Tierney and Mosier [26] detected strong differences in heuristics' performance. However, this effect is stronger for single-stage heuristics compared to two-stage group scheduling heuristics. For uniformly distributed inter-arrival and processing times the differences between heuristics decrease [43].

## 3 Model description

### 3.1 Manufacturing environment

The assumed model of a job shop manufacturing cell by Mahmoodi and Dooley [21] has been applied in several publications already [17,46]. Since it is our goal to analyze the influence of several factors on shop performance, the use of this model allows a direct comparison of the results to previous studies and eliminates the impact of a novel cell configuration on the performance of heuristics. Furthermore, based on various empirical studies the considered cell represents a typical size and configuration of real-life manufacturing cells [31,42,44]. Nowadays, however, an increasing number of reconfigurable machines and a concentration of operations instead of diversification often lead to smaller manufacturing cells and lower numbers of operations become more relevant. Thus, a second cell with less machines was considered additionally. This cell model is also motivated by a mid-sized injection molding enterprise, that produces composite thermosetting plastic elements and uses a similar production system. Besides a closer representation of manufacturing practice, this allows an analysis of the influence of cell size on a manufacturing cell's performance.

In the simulation model a set of jobs $j \in N$ has to be processed on one or several machines $i \in M$ of a manufacturing cell. Each job is assigned to a distinct part family $f \in F$. It has to be noted that a job is not further specified and may, dependent on the respective production system, also be interpreted as lot consisting of several identical products. Figure 1 displays both considered types of cells consisting of five and three machines, representing limited resources. As a job arrives in the system all relevant parameters are set and it is assigned to one of three part families as well as a certain route. In the first configuration, referred to as *5M*, all

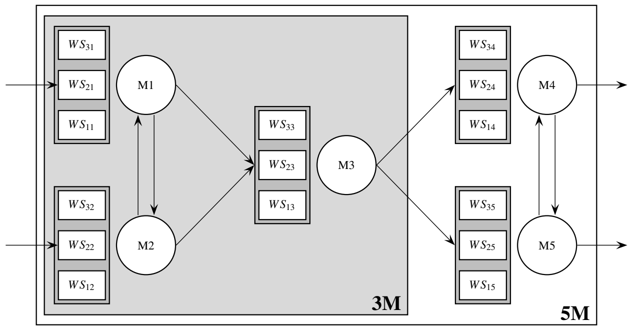


Fig. 1: Considered model of a job shop manufacturing cell

jobs consist of four to five operations with predetermined machines. Each route starts with an operation either on Machine 1 or Machine 2 and exits on Machine 4 or 5. Furthermore, Machine 3 is considered by all available routes. Hence, Machine 3 constitutes a bottleneck that can be used as a measure for the utilization of the manufacturing cell [27]. Reentrant material flows are not considered. Every machine is able to treat one operation at a time and started jobs are not allowed to be disrupted. Moreover, time for transportation is neglected and there are unlimited buffers. The second cell configuration considered equally consists of the first three machines, but Machines 4 and 5 are not taken into account anymore. This smaller cell is referred to as *3M*. In front of every machine three queues are established, one for each part family. With this, for a cell with 5 machines there are 12 different routes per part family. For the smaller cell with 3 machines 4 different routes per part family exist.

As described above, several job characteristics that influence the performance of heuristics have been investigated very well already and, hence, can provide a practical orientation. In this study, parameters were chosen similarly to previous studies in order to secure comparability of results.

*Job arrivals* All jobs are released immediately after arrival in the system. Inter-arrival times are exponentially distributed. This guarantees independence of arrivals of two succeeding jobs and is known to model real-world job arrivals realistically [3,41]. The mean value of inter-arrival times was determined by a pilot study using the basic two-stage heuristic FCFS/FCFS. With an average inter-arrival time of 70 minutes a medium utilization at Machine 3 of 85% could be ensured [21], with utilization being defined as proportion of occupancy time and available time of Machine 3.

*Processing times* Due to varying material quality and inconstant speed of operation through operation personnel, in reality processing times are often subject to considerable variation. Thus, similar to [31] a third-order Erlang distribution with a mean value of 60 minutes was chosen, i.e. processing times$\sim \text{Erl}_{k=3}(\lambda = 60)$.

*Setup times* Minor setup times for a changeover between two parts of the same family are assumed to be part of the processing times [21]. In contrast, major family setup times have to be taken into account as soon as the part family is switched. Since the variation of setup times is usually higher compared to processing times, a second-order Erlang distribution is used for generating these [25]. Until now, the influence of different setup to processing time ratios has been analyzed for either sequence-independent setups [32] or sequence-dependent setups [46] only. However, the impact of the type of setup time on the performance of heuristic algorithms has not been studied, yet. Hence, we analyze the considered manufacturing cell with sequence-dependent as well as sequence-independent setup times.

- For the case of sequence-independent family setups, a mean value of 30 minutes was considered.
- Sequence-dependent setup times were determined according to the mean values for every changeover from a family $f$ to $e$ shown in Table 2.

Table 2: Sequence-dependent setup times

| [min] | | Family $e$ | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Family $f$ | 1 | 0.00 | 15.00 | 30.00 |
| | 2 | 15.00 | 0.00 | 45.00 |
| | 3 | 30.00 | 45.00 | 0.00 |

With this, for SIST the mean value of setup to processing time ratio is 0.5, which is in accordance with previous studies that chose values between 0.1 [43] and 1.27 [25]. It has to be noted, that for SDST setup to processing time ratio may differ slightly from 0.5 since the number of setups to a certain family may be dependent on the proportion of jobs that are assigned to each family.

*Due date* Due dates $d_j$ for each jobs are determined by Total Work Content (TWK) technique [45]. A constant parameter $K$ is multiplied with the sum of processing times $t_{ji}$ of a job $j$ on all machines $i$. This value is added to the time of arrival $T_j$ of job $j$ in the cell:

$$d_j = T_j + K \cdot \sum_{i=1}^{m} t_{ji} \qquad (1)$$

In general, if the value of $K$ is low, due dates become tight and tardiness of jobs increases. In contrast, a high value of $K$ leads to loose due dates and ultimately results in no tardiness at all. Due-date-based job and family rules are appropriate to consider this effect. On the basis of the FCFS/FCFS heuristic, several values for $K$ have been tested. $K = 4.57$ and $K = 4.11$ considering configuration 3M and respectively 5M using sequence-independent setup times with no dominating part families lead to an average tardiness of about 35%, which was chosen for our simulation study.

*Family dominance* An influencing factor, that is analyzed in our study, is the dominance of a part family regarding its size. In nearly all previous publications arriving jobs are assigned to each part family with an identical probability. Nevertheless, as mentioned before, especially two-stage heuristics are affected by a family's dominance significantly. Hence, besides a uniform distribution of jobs to part families, a strong dominance of one part family is investigated. The latter is accomplished by assigning new jobs with a probability of 80% to the first part family, while 10% of the arriving jobs are assigned to each of the other families [31].

## 3.2 Group scheduling heuristics

Based on the literature review in Section 2 as well as the results of recent studies on dispatching rules in classical job shop environments, promising novel combinations of family and job rules are proposed. All tested combinations are exhaustive heuristics, due to their superior performance. Thus, all jobs of a queue have to be processed before a job of another family is taken into account. The tested heuristics are as follows:

(1) **FCFS/FCFS:** This simple heuristic selects the part family that contains the job that arrived first at the current machine (first come first serve). All jobs from this part family are processed according to their arrival at the queue [22]. As one of the first group scheduling heuristics that has widely been used in previous simulation studies, FCFS/FCFS provides a basis for evaluating other rules.

(2) **MS/SPT:** First, the part family requiring minimum setup time (MS) is selected. The jobs of this family are sequenced according to shortest processing time dispatching rule (SPT). MS/SPT is known as one of the best rules for minimizing mean flow time as well as the proportion of tardy jobs in group scheduling environments.

(3) **$\frac{\text{MS}}{\text{MJ}}$/SPT:** Even though recent studies point out the effectiveness of combined dispatching rules [36], these have not been applied for scheduling part families, so far. The family rule $\frac{\text{MS}}{\text{MJ}}$ is a promising combination. A families $e$ priority index $P_e$ is determined by the quotient of setup time $s_{fei}$ for a changeover from the currently processed family $f$ to $e$ on machine $i$ and the number of jobs $n_{ei}$ waiting in the queue of family $e$ at machine $i$. With this, the family with a minimum priority index is chosen, cal-

culating $P_e$ by

$$P_e = \frac{s_{fei}}{n_{ei}} \qquad \forall e, f \in F, e \neq f. \qquad (2)$$

Hence, the minimum setup time per job in a queue decides which family is processed first. The performance of this dispatching rule is investigated together with SPT for sequencing jobs within each family.

(4) **$\frac{\text{MS}}{\text{MJ}}$/SPT+RPT:** An additive combination of SPT rule and the remaining processing time (RPT, also referred to as *shortest remaining processing time* rule SRPT) also led to good results for job shop scheduling [36]. The job rule chooses a job $j$ that has the lowest sum of processing times of the current operation $u$ and the processing times from the current operation $u$ up to the operation on the last subsequent machine $m$. Hence the priority index $P_j$ for each job $j$ is determined by

$$P_j = t_{ju} + \sum_{i=u}^{m} t_{ji} \qquad \forall j \in N. \qquad (3)$$

Compared with $\frac{\text{MS}}{\text{MJ}}$/SPT this newly combined heuristic serves as a basis for assessing the impact of the job rule on the performance of a heuristic.

(5) **EDD/TSPT:** The family rule EDD first dispatches the family that contains the job with earliest due date. All jobs of this family are sequenced according to TSPT rule (two class truncated SPT). In contrast to the conventional slack rule (SL), jobs with negative or no slack are considered first and are assigned to a priority queue. With $CT$ being the current time and $t_{ju}$ the processing time of the current operation $u$, a job's $j$ slack $SL_j$ is defined by

$$SL_j = d_j - \sum_{i=u}^{m} t_{ji} - CT \qquad \forall j \in N. \qquad (4)$$

All jobs in the priority queue with $SL_j \leq 0$ are ordered according to SPT [23]. Each job with $SL_j > 0$ belongs to a non-priority queue, which is considered only if no job with negative or no slack exists. For these jobs, again, SPT rule is used. This rule is known to show a high performance concerning the minimization of average tardiness and serves as a benchmark for novel heuristics.

(6) **$\bar{\text{SL}}$/TSPT:** The total slack of a family has been considered several times in a variety of ways, but always as non-exhaustive rule [21]. Since exhaustive rules generally showed superior results, here $\bar{\text{SL}}$ is used in an exhaustive manner. The family priority index $P_e$ at the respective machine $i$ is determined by the total slack of all jobs assigned to a certain family divided by the number of jobs

$$P_e = \frac{\sum_{j=0}^{n} (d_j - \sum_{i=u}^{m} t_{ji} - CT)}{n_{ei}} \qquad \forall e \in F. \qquad (5)$$

Again, part families are sequenced in ascending order of $P_e$, while all jobs are sequenced concerning the TSPT rule. This heuristic serves for evaluating the novel family rule $\bar{\text{SL}}$ especially.

(7) **$\bar{\text{SL}}$/SL:** The SL rule for sequencing jobs within each part family is considered, which is promising for due-date-based criteria. With Equation 4 the priority index for a job $j$ is given by

$$P_j = SL_j \qquad \forall j \in N. \qquad (6)$$

It is combined with the new exhaustive family slack rule $\bar{\text{SL}}$.

(8) **$\bar{\text{SL}}$/$\frac{\text{SL}}{\text{RPT}}$:** Likewise, the novel combined $\frac{\text{SL}}{\text{RPT}}$ job rule, that can be seen as slack per unit of remaining processing time, is used for sequencing the jobs within each part family. The idea behind this rule is that for jobs with a high number of remaining operations (and therewith processing time) the probability of waiting times on subsequent machines might be higher compared to jobs with less work remaining. Hence, jobs with little slack and a high number of following machines are prioritized by processing jobs with a minimum priority index $P_j$ at the current machine $u$ first.

$$P_j = \frac{SL_j}{\sum_{i=u}^{m} t_{ji}} \qquad \forall j \in N. \qquad (7)$$

(9) **$\frac{\text{MS}}{\text{MJ}}$/SL:** A combination of a due-date-oriented job rule with a family rule that takes setup time related information into account may provide good results for minimizing tardiness related criteria. Hence, the combined $\frac{\text{MS}}{\text{MJ}}$ rule is used for sequencing families, while SL is applied for jobs.

Summing up, heuristics (3), (4), (6), (7), (8) and (9) have not been tested in the past and are considered for the first time.

### 3.3 Experimental setup

The described production environment was implemented using *simcron MODELLER*. This discrete event simulator has been developed for modeling production processes specifically. In the beginning of every simulation run, the production system is empty and undergoes a warm-up period [15]. Similar to previous studies, the length of the warm-up period was predefined with 2,000 hours. Dependent variables were not recorded during this timespan. After the warm-up period for each run, 8,000 hours of the manufacturing process were simulated [21,22]. Since reliable results can be realized by a long duration of a run rather than by frequent reiterations, this procedure conforms the recommended setup for simulation studies [20].

The variation of the examined influencing factors setup type and part family dominance leads to four scenarios for both configurations 3M and 5M:

**Scenario I**: sequence-dependent setup times with no dominating part family
**Scenario II**: sequence-independent setup times with no dominating part family
**Scenario III**: sequence-dependent setup times with dominance of one part family
**Scenario IV**: sequence-independent setup times with dominance of one part family

In order to achieve statistically precise results 40 runs were performed for each configuration. Hence, the number of simulation runs in total is determined by

$$2\,\text{configurations} \cdot 4\,\text{scenarios} \cdot 9\,\text{heuristics} \cdot 40\,\text{runs} = 2,880\,\text{simulation runs}. \quad (8)$$

Statistical tests are necessary to prove the significance of different rules or experimental factors. In order to evaluate ascertained results for differences in heuristic performance, a two-sample t-test was performed for a confidence interval of 0.95. Also, a two-way Analysis of Variance (ANOVA) as well as a one-way ANOVA for specific rules were conducted to examine possible effects of experimental factors.

### 3.4 Performance measures

In order to evaluate the performance of heuristics and the impact of influencing factors a production-flow-oriented as well as two due-date-based measures are monitored. Production-flow-oriented performance measures are used to minimize the total work in process (WIP) and, therewith, inventory as well as capital commitment costs [6, 16]. In contrast, due-date-oriented performance measures aspire a punctual completion of jobs in order to minimize contractual penalties and customer discontent [35].

1. The minimization of **mean flow time** $\bar{F}$ represents the first objective and equals a job's time in the system. Flow time is a common performance measure in job shop environments. It is defined as the sum of completion times $C_j$ less the release times $r_j$ concerning all jobs $j$ divided by the total number of jobs $n$ [10]:

$$\bar{F} := \frac{1}{n}\sum_{j=1}^{n} F_j = \frac{1}{n}\sum_{j=1}^{n}(C_j - r_j). \quad (9)$$

2. In this study, we consider **mean tardiness** $\bar{T}$ as first due-date-based performance measure. It is defined as the average difference between the completion time $C_j$ and due date $d_j$ of all jobs $j$ [9]:

$$\bar{T} := \frac{1}{n}\sum_{j=1}^{n}(max\{C_j - d_j; 0\}). \quad (10)$$

3. Since contractual penalties are not necessarily proportional to tardiness but can be incurred as fixed penalties per tardy job, besides mean tardiness the *proportion of tardy jobs* is considered as second due date related performance measure. It is defined as number of tardy jobs divided by the total number of jobs:

$$T_{\#} := \frac{1}{n}\sum_{j=1}^{n} U_j, \quad \text{with} \begin{cases} U_j = 1, \text{ if } C_j > d_j \\ U_j = 0, \text{ if } C_j \leq d_j. \end{cases} \quad (11)$$

## 4 Results and discussion

### 4.1 Mean flow time

*General results* Table 3 summarizes the average values over all studied scenarios and ranks all investigated heuristics regarding mean flow time. A line between heuristics indicates differences that are not statistically significant according to two-sample t-test. It can be seen that considerable divergences arise subject to the selected heuristic. However, Figure 2 shows, that the relative performance of all heuristics comparing 3M and 5M in all scenarios is very similar. Furthermore, data confirms the results of previous studies that the application of dispatching rules that are calculated similarly to the considered optimization criteria are usually promising. Due-date-based dispatching rules generally lead to higher flow times compared to production-flow-oriented rules.

*Results with respect to scenarios* All four scenarios lead to similar results concerning the ranking of heuristics, showing statistically insignificant differences only. Overall, either MS/SPT or the novel $\frac{\text{MS}}{\text{MJ}}$/SPT heuristic perform best, followed by the $\frac{\text{MS}}{\text{MJ}}$/SPT+RPT heuristic. The novel $\bar{\text{SL}}/\frac{\text{SL}}{\text{RPT}}$ heuristic performed as poor as FCFS/FCFS and even showed the weakest effectiveness considering family dominance (cf. Table 3).

*Influence of job and family rules* However, novel combined job rules cannot lead to an improvement of mean flow time in general. Out of all production-flow-based rules SPT+RPT shows the weakest results compared to single dispatching rules. Using $\frac{\text{MS}}{\text{MJ}}$ family rule, SPT job rule leads to between 0.3% (Scenario II - 541.52 vs. 543.27) and 1.4% (Scenario III - 418.2 vs. 421.62) better results compared to the combined SPT+RPT in the case of 3M. Considering 5M this difference is even between 2.0% (Scenarios III and IV) and

Table 3: Ranking of heuristics: Mean flow time

| 3M Ranking | No dominating family/SDST Scenario I [min] | | No dominating family/SIST Scenario II [min] | | Family dominance/SDST Scenario III [min] | | Family dominance/SIST Scenario IV [min] | |
|---|---|---|---|---|---|---|---|---|
| 1 | 538.85 | $\frac{MS}{MJ}$/SPT | 541.52 | $\frac{MS}{MJ}$/SPT | 391.97 | MS/SPT | 418.20 | $\frac{MS}{MJ}$/SPT |
| 2 | 539.15 | MS/SPT | 542.38 | MS/SPT | 394.62 | $\frac{MS}{MJ}$/SPT | 418.58 | MS/SPT |
| 3 | 541.37 | $\frac{MS}{MJ}$/SPT+RPT | 543.27 | $\frac{MS}{MJ}$/SPT+RPT | 400.40 | $\frac{MS}{MJ}$/SPT+RPT | 421.62 | $\frac{MS}{MJ}$/SPT+RPT |
| 4 | 553.71 | $\frac{MS}{MJ}$/SL | 562.90 | $\frac{MS}{MJ}$/SL | 405.32 | EDD/TSPT | 426.35 | EDD/TSPT |
| 5 | 589.55 | $\overline{SL}$/TSPT | 580.38 | EDD/TSPT | 408.05 | $\overline{SL}$/TSPT | 427.57 | $\overline{SL}$/TSPT |
| 6 | 591.95 | EDD/TSPT | 585.70 | $\overline{SL}$/TSPT | 412.13 | $\frac{MS}{MJ}$/SL | 441.12 | $\frac{MS}{MJ}$/SL |
| 7 | 622.12 | $\overline{SL}$/SL | 604.73 | $\overline{SL}$/SL | 430.58 | $\overline{SL}$/SL | 450.97 | $\overline{SL}$/SL |
| 8 | 647.18 | FCFS/FCFS | 629.22 | FCFS/FCFS | 456.32 | FCFS/FCFS | 477.53 | FCFS/FCFS |
| 9 | 648.80 | $\overline{SL}$/$\frac{SL}{RPT}$ | 634.62 | $\overline{SL}$/$\frac{SL}{RPT}$ | 481.62 | $\overline{SL}$/$\frac{SL}{RPT}$ | 501.95 | $\overline{SL}$/$\frac{SL}{RPT}$ |

| 5M Ranking | No dominating family/SDST Scenario I [min] | | No dominating family/SIST Scenario II [min] | | Family dominance/SDST Scenario III [min] | | Family dominance/SIST Scenario IV [min] | |
|---|---|---|---|---|---|---|---|---|
| 1 | 801.23 | $\frac{MS}{MJ}$/SPT | 808.45 | MS/SPT | 608.82 | $\frac{MS}{MJ}$/SPT | 640.83 | MS/SPT |
| 2 | 804.98 | MS/SPT | 809.12 | $\frac{MS}{MJ}$/SPT | 610.17 | MS/SPT | 643.15 | $\frac{MS}{MJ}$/SPT |
| 3 | 823.52 | $\frac{MS}{MJ}$/SPT+RPT | 831.15 | $\frac{MS}{MJ}$/SPT+RPT | 621.40 | $\frac{MS}{MJ}$/SPT+RPT | 651.70 | EDD/TSPT |
| 4 | 846.51 | $\frac{MS}{MJ}$/SL | 852.60 | EDD/TSPT | 627.07 | EDD/TSPT | 654.63 | $\overline{SL}$/TSPT |
| 5 | 872.87 | $\overline{SL}$/TSPT | 853.41 | $\frac{MS}{MJ}$/SL | 627.47 | $\overline{SL}$/TSPT | 656.72 | $\frac{MS}{MJ}$/SPT+RPT |
| 6 | 875.97 | EDD/TSPT | 856.40 | $\overline{SL}$/TSPT | 647.03 | $\frac{MS}{MJ}$/SL | 682.81 | $\frac{MS}{MJ}$/SL |
| 7 | 923.93 | $\overline{SL}$/SL | 908.22 | $\overline{SL}$/SL | 672.97 | $\overline{SL}$/SL | 698.90 | $\overline{SL}$/SL |
| 8 | 938.83 | FCFS/FCFS | 923.48 | FCFS/FCFS | 698.67 | FCFS/FCFS | 732.92 | FCFS/FCFS |
| 9 | 939.83 | $\overline{SL}$/$\frac{SL}{RPT}$ | 926.40 | $\overline{SL}$/$\frac{SL}{RPT}$ | 722.13 | $\overline{SL}$/$\frac{SL}{RPT}$ | 743.20 | $\overline{SL}$/$\frac{SL}{RPT}$ |

| ... performance differences are not statistically significant

2.7% (Scenario I). Among due-date-based job rules $\frac{SL}{RPT}$ offers the least performance. It is outperformed even by the simple FCFS/FCFS heuristic. Moreover, TSPT outperforms $\frac{SL}{RPT}$ by 7.1% (5M, Scenario I) to 15.3% (3M, Scenario III), both tested with $\overline{SL}$ family rule. This dispatching rule prioritizes jobs with larger remaining work if slack is equal. Thus, it prefers jobs with longest processing time while jobs with smaller processing times have to wait and, consequently, mean flow time is increasing. Apparently, this negative effect dominates the original idea of anticipating possible setup operations as described in Section 3.2. An overall improvement of up to 15.3% depending on the chosen job rule indicates a strong impact of the job rule on a heuristic's performance.

In scenarios of equal sized families, except Scenario II in 5M configuration, the novel combined $\frac{MS}{MJ}$/SL heuristic outperform due-date-oriented heuristics. In Scenarios III and IV, EDD/TSPT and $\overline{SL}$/TSPT generally show superior results. This, again, suggests a strong influence on the performance caused by the job selection rule. If a dominating part family queue is chosen TSPT prioritizes according to SPT, within priority and non-priority queue. This helps to process efficient the jobs of this part family until a time consuming setup is required. In case of equal sized families, there are more setups which can be better managed by the $\frac{MS}{MJ}$ family rule and the impact of the job rule decreases.

## 4.2 Mean tardiness

*General results* Concerning all scenarios applied to 5M configuration, comparisons of the best and worst heuristics show differences between 30.7% (Scenario II) and 38.4% (Scenario I). Considering scenarios with families of the same size and 3M configuration, this difference is very similar. A dominating family leads to performance differences of even up to 49.4% (3M, Scenario III). With $\frac{MS}{MJ}$ family rule and replacing the SPT+RPT job rule by SPT, small improvements of 1.0% (Scenario II) to 3.8% (Scenario IV) can be aspired im 3M configuration. But regarding 5M, much more improvement of up to 9.2% (Scenario I) can be achieved.

*Results with respect to scenarios* In comparison to results with flow time objective, for mean tardiness the ranking of heuristics varies considerably dependent on the regarded scenario (see Table 4). This implies a significant impact of the studied influencing factors. Due-date-based dispatching rules are not advantageous in all scenarios. Instead, for sequence-dependent setup times and part families of the same size (Scenario I) the novel $\frac{MS}{MJ}$/SPT heuristic leads to the lowest average tardiness in 5M configuration. MS/SPT, which is also an production-flow-oriented rule, follows even with a statistically significant difference considering 5M configuration. Regarding 3M all heuristics using the $\frac{MS}{MJ}$ family rule show superior results. Concerning the family rules, $\overline{SL}$ outperformed EDD significantly. In general, in Scenario I all analyzed optimization criteria lead to a similar ranking of heuristics regarding both configurations.

No clear statement can be made about the advantageousness of production flow or due-date-based rules for Scenario II in 5M configuration. Thus, the proposed $\frac{MS}{MJ}$/SPT and $\bar{S}$L/TSPT heuristics are as efficient as the well known MS/SPT and EDD/TSPT heuristics. On the contrary, production-flow-based family rules significantly outperform due-date-based family rules in the same scenario considering 3M. This also applies to both configurations with respect to Scenario I shown in Table 4.

Both scenarios with family dominance result in a similar ranking in both configurations. Due-date-based family heuristics like $\bar{S}$L/TSPT and EDD/TSPT significantly performed best, followed by $\bar{S}$L/SL, MS/SPT and $\frac{MS}{MJ}$/SPT respectively. Similar to mean flow time criterion, $\frac{MS}{MJ}$/SL is outperformed by due-date-oriented heuristics in all scenarios of family dominance as well as Scenario II using the 5M configuration. Remaining scenarios show an opposite ranking. Thus, family rules benefit from the consideration of setup information in scenarios of equal sized families. This is reasonable since setups occur more often in this case. Finally, the novel $\bar{S}$L/TSPT shows superior results for scenarios of family dominance and $\frac{MS}{MJ}$/SPT for scenarios of equal sized families.

*Influence of job and family rules* Applying SL as job rule instead of $\frac{SL}{RPT}$ results in a decrease of average mean tardiness between 12.2% (Scenario II) and 30.4% (Scenario IV) considering the 5M and even between 18.0% (Scenario I) and 45.6% (Scenario III) using 3M configuration if, at the same time, families are sequenced by $\bar{S}$L.

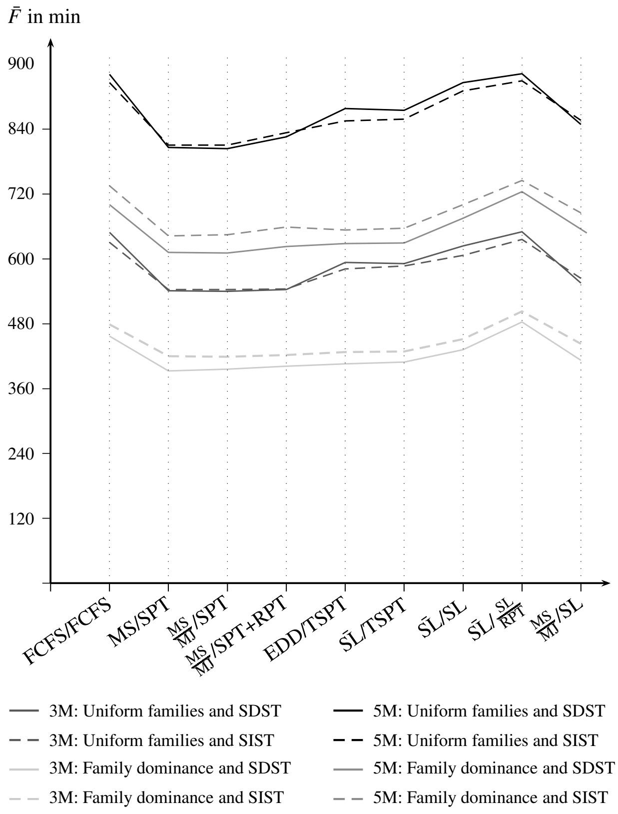


Fig. 2: Results: mean flow time

## 4.3 Proportion of tardy jobs

*General results* Table 5 shows the simulation results and the ranking of heuristics considering the proportion of tardy jobs. A comparison of charts displayed in Figure 3 and Figure 4 shows that the rankings of heuristics are generally similar to those gained considering mean tardiness. Furthermore, both configurations are similar and even comparable to the ranking with mean flow time criterion in the case of equal sized families (cf. Table 3). Thus, flow-time-oriented heuristics like $\frac{MS}{MJ}$/SPT and MS/SPT show best results.

*Results with respect to scenarios* Scenario II with 5M configuration shows that novel $\frac{MS}{MJ}$/SPT outperforms all other heuristics significantly. Considering all four scenarios and both configurations, in seven out of eight cases the novel $\frac{MS}{MJ}$/SPT performed superior in respect of the proportion of tardy jobs. In contrast, due-date-oriented heuristics performed poorly and the novel combination of a flow-time-oriented family rule and due-date-oriented job rule, $\frac{MS}{MJ}$/SL, is middle-ranking. Furthermore, Figure 4 shows, that the novel $\bar{S}$L/ TSPT rule performs more robust than EDD/ TSPT. In Scenario I and Scenario III considering 3M EDD/ TSPT performs very poor while in all other scenarios the performance of these two heuristics is similar. The novel combined job rules SPT+RPT and $\frac{SL}{RPT}$ are outperformed by the simple SPT and respectively SL rule in all scenarios. FCFS/FCFS and $\bar{S}$L/$\frac{SL}{RPT}$ perform worst. The results show, that the criterion of proportion of tardy jobs is very robust regarding both sets of family sizes and setup times. Furthermore, they indicate that a fast production flow is particularly successful to achieve less tardy jobs.

## 4.4 Multi-criteria evaluation

In order to evaluate whether certain heuristics are dominated by other, the heuristics' performance considering several performance measures is investigated in this section by the use of selected scatter plots with Pareto-fronts, one for each Scenario.Considering mean flow time and proportion of tardy jobs the rankings of heuristics resemble over all scenarios. In case of differences usually one superior rule evolves, which is mostly the novel $\frac{MS}{MJ}$/SPT. Exemplarily,

Table 4: Ranking of heuristics: Mean tardiness

| 3M Ranking | No dominating family/SDST Scenario I [min] | | No dominating family/SIST Scenario II [min] | | Family dominance/SDST Scenario III [min] | | Family dominance/SIST Scenario IV [min] | |
|---|---|---|---|---|---|---|---|---|
| 1 | 67.17 | $\frac{MS}{MJ}$/SL | 68.35 | $\frac{MS}{MJ}$/SPT | 32.43 | EDD/TSPT | 36.52 | $\bar{SL}$/TSPT |
| 2 | 67.88 | $\frac{MS}{MJ}$/SPT | 69.02 | $\frac{MS}{MJ}$/SPT+RPT | 33.17 | $\bar{SL}$/TSPT | 37.65 | EDD/TSPT |
| 3 | 68.03 | MS/SPT | 69.82 | MS/SPT | 33.68 | MS/SPT | 39.00 | MS/SPT |
| 4 | 68.72 | $\frac{MS}{MJ}$/SPT+RPT | 71.75 | $\frac{MS}{MJ}$/SL | 34.82 | $\bar{SL}$/SL | 39.15 | $\bar{SL}$/SL |
| 5 | 79.53 | SL/TSPT | 75.78 | SL/TSPT | 35.85 | $\frac{MS}{MJ}$/SPT | 40.38 | $\frac{MS}{MJ}$/SPT |
| 6 | 83.92 | EDD/TSPT | 76.07 | EDD/TSPT | 36.85 | $\frac{MS}{MJ}$/SL | 41.45 | $\frac{MS}{MJ}$/SPT+RPT |
| 7 | 87.58 | $\bar{SL}$/SL | 77.47 | $\bar{SL}$/SL | 37.27 | $\frac{MS}{MJ}$/SPT+RPT | 43.58 | $\frac{MS}{MJ}$/SL |
| 8 | 106.87 | $\bar{SL}/\frac{SL}{RPT}$ | 96.68 | FCFS/FCFS | 41.47 | FCFS/FCFS | 46.85 | FCFS/FCFS |
| 9 | 106.95 | FCFS/FCFS | 99.37 | $\bar{SL}/\frac{SL}{RPT}$ | 64.05 | $\bar{SL}/\frac{SL}{RPT}$ | 67.72 | $\bar{SL}/\frac{SL}{RPT}$ |

| 5M Ranking | No dominating family/SDST Scenario I [min] | | No dominating family/SIST Scenario II [min] | | Family dominance/SDST Scenario III [min] | | Family dominance/SIST Scenario IV [min] | |
|---|---|---|---|---|---|---|---|---|
| 1 | 66.08 | $\frac{MS}{MJ}$/SPT | 68.87 | $\bar{SL}$/TSPT | 32.98 | $\bar{SL}$/TSPT | 37.17 | EDD/TSPT |
| 2 | 68.78 | MS/SPT | 69.05 | MS/SPT | 33.70 | EDD/TSPT | 37.68 | $\bar{SL}$/TSPT |
| 3 | 72.28 | $\frac{MS}{MJ}$/SL | 70.38 | $\frac{MS}{MJ}$/SPT | 36.68 | $\bar{SL}$/SL | 40.85 | $\bar{SL}$/SL |
| 4 | 72.80 | $\frac{MS}{MJ}$/SPT+RPT | 71.62 | EDD/TSPT | 37.33 | $\frac{MS}{MJ}$/SPT | 42.68 | MS/SPT |
| 5 | 75.25 | SL/TSPT | 74.22 | $\frac{MS}{MJ}$/SL | 37.40 | MS/SPT | 43.67 | $\frac{MS}{MJ}$/SPT |
| 6 | 82.18 | EDD/TSPT | 76.00 | $\frac{MS}{MJ}$/SPT+RPT | 40.78 | $\frac{MS}{MJ}$/SPT+RPT | 46.56 | $\frac{MS}{MJ}$/SL |
| 7 | 86.47 | $\bar{SL}$/SL | 79.80 | SL/SL | 42.00 | FCFS/FCFS | 47.60 | $\frac{MS}{MJ}$/SPT+RPT |
| 8 | 99.02 | $\bar{SL}/\frac{SL}{RPT}$ | 90.85 | $\bar{SL}/\frac{SL}{RPT}$ | 42.32 | $\frac{MS}{MJ}$/SL | 49.65 | FCFS/FCFS |
| 9 | 107.22 | FCFS/FCFS | 99.32 | FCFS/FCFS | 51.80 | $\bar{SL}/\frac{SL}{RPT}$ | 58.68 | $\bar{SL}/\frac{SL}{RPT}$ |

| ... performance differences are not statistically significant

this is illustrated in Figure 5. A similar Pareto frontier is gained in Scenario I and Scenario II considering mean tardiness and proportion of tardy jobs (see Figure 6). $\frac{MS}{MJ}$/SPT dominates most often all other heuristics.

The decision for an superior heuristic is crucial in the case of mean tardiness and proportion of tardy jobs, particularly in Scenario III and Scenario IV. Considering Scenario III EDD/TSPT and $\bar{SL}$/TSPT perform well to minimize mean tardiness, whereas $\frac{MS}{MJ}$/SPT and MS/SPT showed superior performance considering the proportion of tardy jobs. Thus, depending on the priority of criteria the respective rules should be preferred (see Figure 7). Furthermore, $\frac{MS}{MJ}$/SPT tends to be superior considering the proportion of tardy jobs and MS/SPT is more suitable to minimize mean tardiness, as shown for example in Figure 8.

## 4.5 Cell size

Table 3 indicates less flow time in all scenarios considering the three machine configuration. This is reasonable, since there are less machines requiring a processing of operations. Considering the criterion of mean tardiness and proportion of tardy jobs the data of 5M configuration resemble those of 3M configuration. This also can be explained by the adjustment of due dates according to Total Work Content technique (TWK) to achieve a similar proportion of tardy jobs in both configurations.

As it is shown in Figure 2, Figure 3 and Figure 4, graphs of both configurations have a similar shape with respect to the regarded scenarios. Thus, each scenario influences both configurations in a very similar manner. The only remarkable difference concerning the minimization of mean tardiness effects the ranking of EDD/TSPT and $\frac{MS}{MJ}$/SPT+RPT in Scenario II.

Depending on the respective scenario the best performing heuristic compared to worst heuristics leads to between 12.7% (Scenario II) and 15.7% (Scenario III) lower mean flow time in case of five machines and between 14.7% (Scenario II) and 18.6% (Scenario III) in case of 3 machines. Considering all scenarios the difference between the best and worst heuristic is always at least 2% greater in the 3M configuration compared to 5M. This indicates that in small cells the selection of a good heuristic is more crucial. In larger cells with a higher number of operations these differences may be alleviated by subsequent stages. At the same time, however, statistically significant differences in the ranking of heuristics appear less frequent in the three machine configuration compared to 5M (cf. Table 3, 4 and 5). Thus, differences between the well performing heuristics are less considering small cells.

Table 5: Ranking of heuristics: Proportion of tardy jobs

| 3M Ranking | No dominating family/SDST Scenario I [%] | | No dominating family/SIST Scenario II [%] | | Family dominance/SDST Scenario III [%] | | Family dominance/SIST Scenario IV [%] | |
|---|---|---|---|---|---|---|---|---|
| 1 | 23.88 | $\frac{MS}{MJ}$/SPT | 24.41 | $\frac{MS}{MJ}$/SPT | 8.69 | $\frac{MS}{MJ}$/SPT | 10.26 | $\frac{MS}{MJ}$/SPT |
| 2 | 24.22 | $\frac{MS}{MJ}$/SPT+RPT | 24.67 | MS/SPT | 8.80 | MS/SPT | 10.43 | MS/SPT |
| 3 | 24.25 | MS/SPT | 25.24 | $\frac{MS}{MJ}$/SPT+RPT | 8.91 | $\frac{MS}{MJ}$/SPT+RPT | 10.51 | $\frac{MS}{MJ}$/SL |
| 4 | 25.21 | $\frac{MS}{MJ}$/SL | 25.70 | $\frac{MS}{MJ}$/SL | 8.91 | $\frac{MS}{MJ}$/SL | 10.56 | $\frac{MS}{MJ}$/SPT+RPT |
| 5 | 30.42 | $\bar{SL}$/TSPT | 29.07 | EDD/TSPT | 10.10 | $\bar{SL}$/TSPT | 11.30 | EDD/TSPT |
| 6 | 32.01 | $\bar{SL}$/SL | 29.58 | $\bar{SL}$/TSPT | 10.82 | $\bar{SL}$/SL | 11.66 | $\bar{SL}$/TSPT |
| 7 | 37.18 | EDD/TSPT | 31.32 | $\bar{SL}$/SL | 13.03 | EDD/TSPT | 11.98 | $\bar{SL}$/SL |
| 8 | 37.37 | $\bar{SL}/\frac{SL}{RPT}$ | 34.53 | $\bar{SL}/\frac{SL}{RPT}$ | 15.54 | FCFS/FCFS | 17.60 | FCFS/FCFS |
| 9 | 38.04 | FCFS/FCFS | 35.55 | FCFS/FCFS | 18.11 | $\bar{SL}/\frac{SL}{RPT}$ | 20.37 | $\bar{SL}/\frac{SL}{RPT}$ |

| 5M Ranking | No dominating family/SDST Scenario I [%] | | No dominating family/SIST Scenario II [%] | | Family dominance/SDST Scenario III [%] | | Family dominance/SIST Scenario IV [%] | |
|---|---|---|---|---|---|---|---|---|
| 1 | 22.02 | $\frac{MS}{MJ}$/SPT | 22.37 | $\frac{MS}{MJ}$/SPT | 8.05 | MS/SPT | 9.33 | $\frac{MS}{MJ}$/SPT |
| 2 | 22.42 | MS/SPT | 22.91 | MS/SPT | 8.10 | $\frac{MS}{MJ}$/SPT | 9.53 | MS/SPT |
| 3 | 23.45 | $\frac{MS}{MJ}$/SPT+RPT | 23.85 | $\frac{MS}{MJ}$/SPT+RPT | 8.33 | $\frac{MS}{MJ}$/SL | 9.65 | $\frac{MS}{MJ}$/SL |
| 4 | 24.38 | $\frac{MS}{MJ}$/SL | 25.02 | $\frac{MS}{MJ}$/SL | 8.36 | $\frac{MS}{MJ}$/SPT+RPT | 9.92 | $\frac{MS}{MJ}$/SPT+RPT |
| 5 | 28.40 | $\bar{SL}$/TSPT | 26.99 | $\bar{SL}$/TSPT | 8.99 | EDD/TSPT | 10.23 | EDD/TSPT |
| 6 | 28.52 | EDD/TSPT | 27.01 | EDD/TSPT | 9.23 | $\bar{SL}$/TSPT | 10.42 | $\bar{SL}$/TSPT |
| 7 | 30.93 | $\bar{SL}$/SL | 30.64 | $\bar{SL}$/SL | 9.60 | $\bar{SL}$/SL | 10.82 | $\bar{SL}$/SL |
| 8 | 35.31 | $\bar{SL}/\frac{SL}{RPT}$ | 33.91 | $\bar{SL}/\frac{SL}{RPT}$ | 13.49 | FCFS/FCFS | 15.12 | FCFS/FCFS |
| 9 | 35.96 | FCFS/FCFS | 34.82 | FCFS/FCFS | 15.71 | $\bar{SL}/\frac{SL}{RPT}$ | 17.32 | $\bar{SL}/\frac{SL}{RPT}$ |

| ... performance differences are not statistically significant

### 4.6 Analysis of influencing factors

*Analyzed factors* Tables 3, 4 and 5 summarize the substantial impact of the studied influencing factors, i.e. setup type and family dominance. Besides, Table 7 displays the results of the conducted analysis of variance (ANOVA) while the nomenclature is given in Table 8. With a level of significance of 0.95 an influencing impact is indicated by a value $F \geq 3,9$. This value considers the quantity of simulation runs per scenario and heuristic as well as the number of specifications per factor. Furthermore, the total spread $SS_T$ consists of several spreads caused by the influencing factors *type of setup time* ($SS_{SDST/SIST}$) as well as *family dominance* ($SS_{eq/dom}$), their interaction ($SS_{interaction}$) and spread of errors $SS_E$.

*Family dominance* In general, a dominating family leads to a lower mean flow time and less tardy jobs. As shown in Table 7, almost the entire total spread is caused by the factor of part family dominance, regardless of the performance measure. Considering mean flow time this proportion is larger in 5M configuration compared to 3M, except for $\bar{SL}/\frac{SL}{RPT}$ heuristic. This indicates a stronger factor impact of part family dominance in larger cell configurations. It can be explained by a higher number of setup operations if more stages are taken into account. Regarding the proportion of tardy jobs the impact of family dominance is stronger particularly in the large cell configuration.

The effect size of dominating part families is pointed out in Table 9 and Figure 9. It is apparent that the dominance of a certain family has a strong impact on the performance of heuristics. Concerning the five machine configuration and mean flow time criterion for all heuristics, except for $\bar{SL}/\frac{SL}{RPT}$, over 95% of the total variance can be explained by the dominance of families, while this is the case for over 82% of the variance with mean tardiness criterion and even over 97% for proportion of tardy jobs criterion. This implies that the mean tardiness is less influenced by changes of the family dominance compared to flow time and proportion of tardy jobs. However, at the same time, mean tardiness is effected considerably by other influencing factors, such as variances of setup, processing or inter-arrival times, which is also indicated by a high spread of unaccountable errors ($SS_E$) as shown in Table 7. According to Table 4, for mean flow time and proportion of tardy jobs the ranking of heuristics remains unchanged independent of the underlying scenario while major differences can be identified for varying scenarios for mean tardiness. With a dominating family due-date-oriented heuristics lead to superior results, whereas production-flow-based heuristics performed best in settings with equally distributed family sizes.

*Type of setup time* As shown in Figure 2 SDST average to better results compared to SIST with family dominance, which indicates an impact of the type of setup times. This is

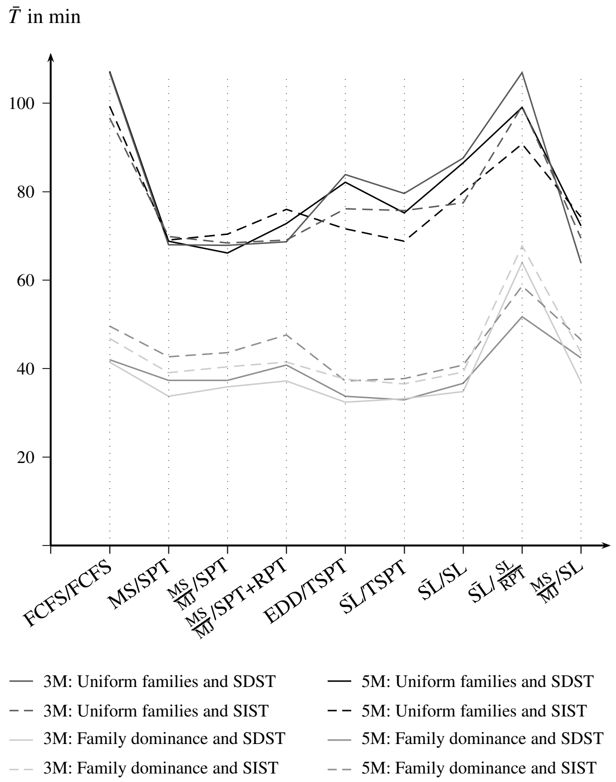


Fig. 3: Results: mean tardiness

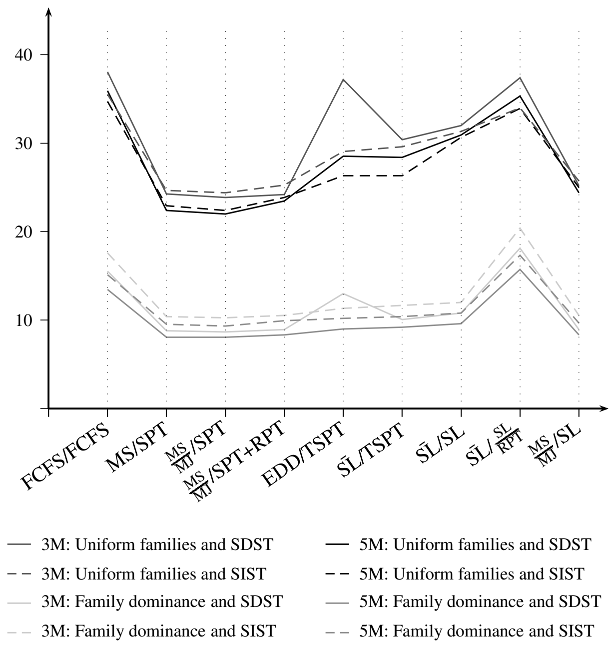


Fig. 4: Results: Proportion of tardy jobs

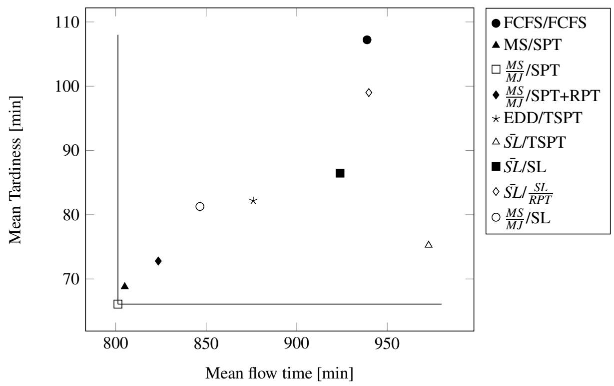


Fig. 5: Pareto Front: 5M Scenario I

reasonable since a dominating family results in fewer changeovers between jobs of different part families and, therewith, fewer setups. This also applies to mean tardiness and proportion of tardy jobs in the case of family dominance (see Figure 3 and 4). However, the results of Table 7 indicate a higher influence for heuristics with flowtime-based family rules compared to other heuristics (i.e. larger value $F_{SDST/SIST}$). This is plausible since respective heuristics choose the family according to setup information. Still, the influence of the type of setup times remains rather low. Furthermore, the type of setup time effects the performance measures much less than the family dominance as shown in Table 9. Considering mean flow time criterion even $\bar{\mathrm{SL}}/\mathrm{TSPT}$ proves to be effected significantly by the type of setup time considering both configurations. The remaining due date-based family rules seem not to be influenced significantly at all (e.g. $\bar{\mathrm{SL}}/\frac{\mathrm{SL}}{\mathrm{RPT}}$) or a very small influence is proven to be significant for only one certain configuration.

In general, regarding setup type the three flowtime-based heuristics MS/SPT, $\frac{\mathrm{MS}}{\mathrm{MJ}}$/SPT and $\frac{\mathrm{MS}}{\mathrm{MJ}}$/SPT+RPT and the novel $\frac{\mathrm{MS}}{\mathrm{MJ}}$/SL heuristic are much stronger influenced by the choice of sequence dependent or independent setup times than the rest of the tested heuristics. For example the spread caused by setup type using $\frac{\mathrm{MS}}{\mathrm{MJ}}$/SPT is more than 6,000 times higher compared to FCFS/FCFS (considering 5M and mean tardiness). Nevertheless, in total only a very small part of total spread is influenced by the setup type.

*Interaction of factors* Since the type of setup time has only low impact, a spread caused by interaction between both factors is very small as well. It should be emphasized that spread caused by uncountable errors ($SS_E$) is much higher considering mean tardiness compared to mean flow time or proportion of tardy jobs. Hence, the tested heuristics generally show higher performance variability and, therewith, less robustness concerning mean tardiness.

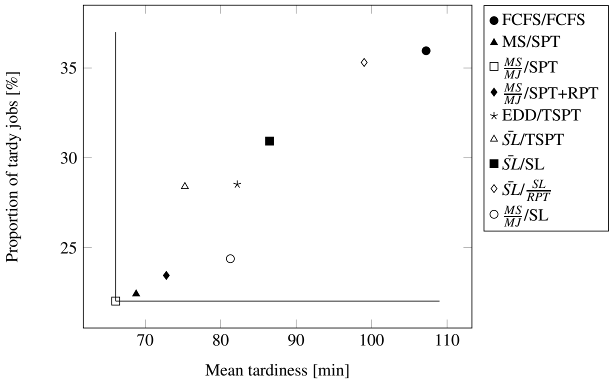


Fig. 6: Pareto Front: 5M Scenario II

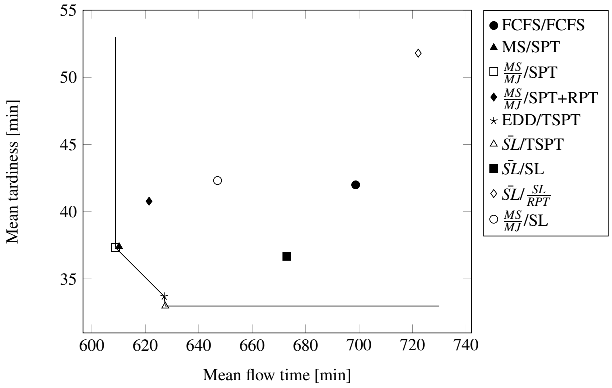


Fig. 7: Pareto Front: 5M Scenario III

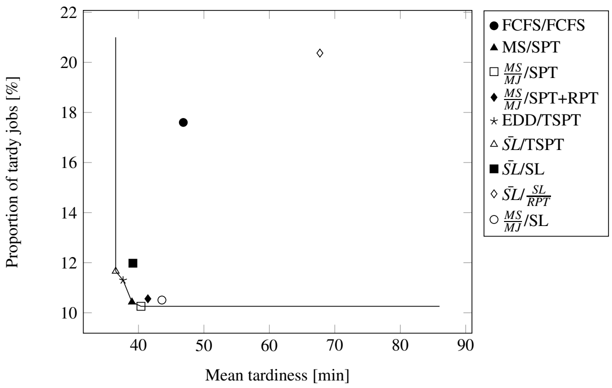


Fig. 8: Pareto Front: 3M Scenario IV

Considering the testing value $F_{interaction}$ all heuristics and scenarios show a significant interaction effect of both tested factors considering mean flow time. The same applies to the proportion of tardy jobs, except for $\frac{\text{MS}}{\text{MJ}}$/SPT+RPT heuristic in 3M. Considering mean tardiness, there is no significant interaction effect for $\frac{\text{MS}}{\text{MJ}}$/SL heuristic as well as $\frac{\text{MS}}{\text{MJ}}$/SPT+RPT and $\frac{\text{MS}}{\text{MJ}}$/SPT in 5M and MS/SPT in 3M. In general, the spread caused by both factors ($SS_{interaction}$) is much smaller considering flow time based family rules compared to the respective spread gained by other rules. This means that each effect independently impacts the performance measure. This is also indicated by a comparison of scenarios for each flow-time-based family rule with all three performance measures (see Tables 3-5). It reveals that SDST always lead to superior results than SIST. In contrast, all due date-based family rules as well as the FCFS/FCFS heuristic proved to be better using SIST under equal sized families and SDST under family dominance. Apparently, there is a considerably interaction effect of both factors which proved to be significant by the two-way ANOVA shown in Table 7. This means that one factor depends on the level of the other factor. Although the testing value $F_{SDST/SIST}$ and the spread $SS_{SDST/SIST}$ of the respective heuristics is very small, this might still indicate a significant impact for this special case. Therefore, we additionally exploited an one-way ANOVA by keeping the factor of family dominance constant. Since the impact of the type of setup time is uncertain for due date-based family rules and FCFS/FCFS heuristic only (i.e. high interaction effects), Table 6 summarizes testing values for these respective heuristics. Therefore, an influencing impact is indicated by an value of $F$ >3,96.

Table 6: Test values of the one-way ANOVA

| $F_{SDST/SIST}$ | | FCFS/FCFS | EDD/TSPT | S̄L/TSPT | S̄L/SL | S̄L/$\frac{\text{SL}}{\text{RPT}}$ |
|---|---|---|---|---|---|---|
| Mean flow time | | | | | | |
| 3M | Equal | 18,1647 | 9,0089 | 0,5114 | 22,5846 | 11,4895 |
| | Dom. | 55,1256 | 89,8298 | 86,5337 | 56,1145 | 43,4767 |
| 5M | Equal | 12,6488 | 42,5144 | 24,0417 | 18,2497 | 9,4290 |
| | Dom. | 108,4513 | 79,7259 | 97,5579 | 95,9727 | 6,1402 |
| Mean Tardiness | | | | | | |
| 3M | Equal | 18,6679 | 11,1278 | 3,8685 | 23,9096 | 8,7058 |
| | Dom. | 21,7590 | 32,3545 | 11,4243 | 13,2113 | 4,2137 |
| 5M | Equal | 13,7295 | 38,3179 | 17,2401 | 15,1724 | 12,3424 |
| | Dom. | 44,5560 | 10,6768 | 19,9137 | 18,2415 | 10,6738 |
| Proportion of tardy jobs | | | | | | |
| 3M | Equal | 46,8311 | 669,6829 | 5,7967 | 3,1386 | 72,0850 |
| | Dom. | 74,7683 | 74,2977 | 84,0365 | 37,7342 | 81,2760 |
| 5M | Equal | 27,7244 | 20,0308 | 16,8480 | 0,3861 | 11,3504 |
| | Dom. | 54,2628 | 64,6620 | 61,9810 | 49,9023 | 44,2369 |

The results shown in Table 6 generally prove, that the type of setup time significantly impacts all three performance measures in both configurations. No statistical significant effects are determined only for S̄L/TSPT considering mean flow time and mean tardiness in 3M as well as S̄L/SL considering proportion of tardy jobs in both configurations with equal sized families. Furthermore, the type of setup time impacts scenarios with family dominance much more than scenarios with equal sized families, except for EDD/TSPT considering mean tardiness and proportion of tardy jobs in 5M and 3M respectively. This applies also to flow time based

family rules, as shown in Figures 2-4.
Considering the testing value $F_{eq/dom}$ all results show a significant influence of the factor family dominance, with S̄L/$\frac{\text{SL}}{\text{RPT}}$ leading to the smallest values in almost all scenarios. This is reasonable since the respective factor spread $SS_{eq/dom}$ is lower and the error spread is higher compared to the respective spread caused by other heuristics. It indicates a generally low robustness or high performance variability of the respective heuristic.
Furthermore, Figure 2, 3 and 4 show a significantly higher variance concerning the achievement of objectives for mean tardiness and proportion of tardy jobs subject to the chosen heuristic. This implies that especially for due-date-based criteria the selection of an effective heuristic is crucial. This confirms the results by Wemmerlöv [43]. In general, the novel $\frac{\text{MS}}{\text{MJ}}$/SPT heuristic shows the least varying performance subject to the chosen scenario. The proposed S̄L/TSPT heuristic is more robust compared to EDD/TSPT, which is known as a preferable heuristic so far, but less robust than the novel $\frac{\text{MS}}{\text{MJ}}$/SL heuristic.

Table 8: Nomenclature of variance analysis

| Notation | Explanation |
|---|---|
| $SS_{SDST/SIST}$ | spread caused by type of setup |
| $SS_{eq/dom}$ | spread caused by family proportion |
| $SS_{interaction}$ | spread caused by both factors |
| $SS_E$ | spread caused by unaccountable errors |
| $SS_T$ | total spread, $SS_T = SS_{SDST/SIST} + SS_{eq/dom} + SS_{interaction} + SS_E$ |
| $\nu_E$ | degree of freedom $\nu_E = scenarios \cdot (runs - 1)$ |
| $F_{SDST/SIST}$ | test value for type of setup, $F_{SDST/SIST} = \frac{SS_{SDST/SIST}}{SS_E/\nu_E}$ |
| $F_{eq/dom}$ | test value for family proportion, $F_{eq/dom} = \frac{SS_{eq/dom}}{SS_E/\nu_E}$ |
| $F_{interaction}$ | test value for interaction, $F_{interaction} = \frac{SS_{interaction}}{SS_E/\nu_E}$ |

If $F_{***}$ >3.9 the impact of the respective influencing factor is statistical significant, considering a level of significance of 0.95.

Table 9: Effect size concerning family dominance

| $\eta^2_{GD}$ | Mean flow time 3M | 5M | Mean tardiness 3M | 5M | % Tardy 3M | 5M |
|---|---|---|---|---|---|---|
| FCFS/FCFS | 0.9545 | 0.9616 | 0.9075 | 0.9193 | 0.9701 | 0.9805 |
| MS/SPT | 0.9568 | 0.9656 | 0.8705 | 0.8732 | 0.9794 | 0.9786 |
| $\frac{\text{MS}}{\text{MJ}}$/SPT | 0.9573 | 0.9688 | 0.8537 | 0.8294 | 0.9778 | 0.9794 |
| $\frac{\text{MS}}{\text{MJ}}$/SPT+RPT | 0.9613 | 0.9621 | 0.8677 | 0.8224 | 0.9735 | 0.9811 |
| EDD/TSPT | 0.9647 | 0.9736 | 0.8734 | 0.8866 | 0.9171 | 0.9786 |
| S̄L/TSPT | 0.9505 | 0.9758 | 0.9045 | 0.8897 | 0.9799 | 0.9779 |
| S̄L/SL | 0.9622 | 0.9767 | 0.8800 | 0.9153 | 0.9805 | 0.9754 |
| S̄L/$\frac{\text{SL}}{\text{RPT}}$ | 0.9429 | 0.9120 | 0.7708 | 0.7815 | 0.9598 | 0.9668 |
| $\frac{\text{MS}}{\text{MJ}}$/SL | 0.9430 | 0.9632 | 0.8211 | 0.8332 | 0.9676 | 0.9817 |

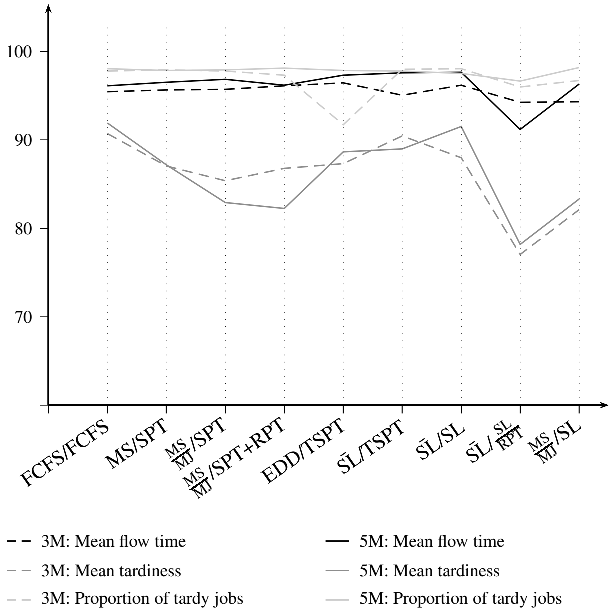


Fig. 9: Illustration of effect size concerning family dominance

## 5 Conclusions

In this study we applied several novel heuristics for dispatching a dynamic job shop manufacturing cell. Based on a thorough analysis of previous simulation studies, some research gaps concerning the influencing factors of the type of setup time as well as the dominance of a single part family could be identified and closed. In summary, following conclusions can be drawn:

- The selection of an effective heuristic is crucial for shop performance, particularly concerning mean tardiness and partly the proportion of tardy jobs. For mean flow time the ranking of heuristics proves to be robust with respect to the considered scenarios. In contrast, for mean tardiness criterion the variation regarding the advantageousness of certain heuristics is considerably higher. As an exception, production-flow-oriented dispatching heuristics lead to the least tardiness for scenarios with families of equal size.
- The dominance of a part family has a significant impact on the achievement of objectives. This can be explained by fewer setup operations with a dominating family. Scenarios with family dominance are strongly influenced by the type of setup time. In general, the influence of the type of setup times is significant but rather low. The factor family dominance and type of setup time showed statistical significant interaction effects, especially for due

Table 7: Results of two-way ANOVA

| Mean flow time [normalized] | | FCFS/FCFS | MS/SPT | $\frac{MS}{MJ}$/SPT | $\frac{MS}{MJ}$/SPT+RPT | EDD/TSPT | $\bar{SL}$/TSPT | $\bar{SL}$/SL | $\bar{SL}/\frac{SL}{RPT}$ | $\frac{MS}{MJ}$/SL |
|---|---|---|---|---|---|---|---|---|---|---|
| 3M | $SS_{SDST/SIST}$ | 0.0136 | 1.8458 | 1.4646 | 1.1844 | 0.1181 | 0.3219 | 0.0115 | 0.0631 | 3.1524 |
| | $SS_{eq/dom}$ | 151.7669 | 152.1320 | 152.2110 | 152.8462 | 153.3918 | 151.1300 | 152.9942 | 149.9247 | 149.9394 |
| | $SS_{interaction}$ | 1.9858 | 1.1312 | 0.9302 | 0.8288 | 1.4058 | 0.7161 | 1.8312 | 1.9861 | 0.8491 |
| | $SS_T$ | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 |
| | $SS_E$ | 5.2337 | 3.8910 | 4.3942 | 4.1406 | 4.0844 | 6.8320 | 4.1631 | 7.0262 | 5.0591 |
| | $F_{SDST/SIST}$ | 0.4064 | 74.0021 | 51.9946 | 44.6247 | 4.5115 | 7.3496 | 0.4317 | 1.4000 | 97.2045 |
| | $F_{eq/dom}$ | 4523.7042 | 6099.3156 | 5403.6477 | 5758.5783 | 5858.7286 | 3450.8345 | 5733.0612 | 3328.7236 | 4623.4219 |
| | $F_{interaction}$ | 59.1910 | 45.3512 | 33.0226 | 31.2246 | 53.6929 | 16.3516 | 68.6197 | 44.0964 | 26.1826 |
| 5M | $SS_{SDST/SIST}$ | 0.2939 | 1.3609 | 2.1374 | 1.9891 | 0.0012 | 0.0889 | 0.0765 | 0.0526 | 2.0368 |
| | $SS_{eq/dom}$ | 152.8927 | 153.5330 | 154.0453 | 152.9712 | 154.7947 | 155.1530 | 155.3008 | 145.0146 | 153.1415 |
| | $SS_{interaction}$ | 2.0271 | 0.8641 | 0.8393 | 0.8265 | 1.7626 | 1.4773 | 1.2722 | 1.0731 | 0.9329 |
| | $SS_T$ | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 |
| | $SS_E$ | 3.7862 | 3.2420 | 1.9780 | 3.2132 | 2.4415 | 2.2809 | 2.3504 | 12.8596 | 2.8888 |
| | $F_{SDST/SIST}$ | 12.1112 | 65.4847 | 168.5691 | 96.5738 | 0.0762 | 6.0777 | 5.0783 | 0.6384 | 109.9943 |
| | $F_{eq/dom}$ | 6299.4465 | 7387.7973 | 12148.9114 | 7426.8049 | 9890.6562 | 10611.7049 | 10307.4785 | 1759.1710 | 8269.9897 |
| | $F_{interaction}$ | 83.5209 | 41.5784 | 66.1912 | 40.1279 | 112.6198 | 101.0396 | 84.4382 | 13.0180 | 50.3785 |

| Mean tardiness [normalized] | | FCFS/FCFS | MS/SPT | $\frac{MS}{MJ}$/SPT | $\frac{MS}{MJ}$/SPT+RPT | EDD/TSPT | $\bar{SL}$/TSPT | $\bar{SL}$/SL | $\bar{SL}/\frac{SL}{RPT}$ | $\frac{MS}{MJ}$/SL |
|---|---|---|---|---|---|---|---|---|---|---|
| 3M | $SS_{SDST/SIST}$ | 0.2577 | 1.6456 | 0.9422 | 0.7974 | 0.1182 | 0.0032 | 0.5647 | 0.3274 | 4.8819 |
| | $SS_{eq/dom}$ | 144.2866 | 138.4077 | 135.7324 | 137.9672 | 138.8756 | 143.8157 | 139.9234 | 122.5530 | 130.5492 |
| | $SS_{interaction}$ | 2.6558 | 0.4079 | 0.6225 | 0.5943 | 2.9319 | 0.9922 | 3.5191 | 2.7625 | 0.1749 |
| | $SS_T$ | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 |
| | $SS_E$ | 11.7999 | 18.5389 | 21.7029 | 19.6411 | 17.0742 | 14.1889 | 14.9927 | 33.3571 | 23.3941 |
| | $F_{SDST/SIST}$ | 3.4072 | 13.8471 | 6.7724 | 6.3332 | 1.0804 | 0.0356 | 5.8762 | 1.5310 | 32.5542 |
| | $F_{eq/dom}$ | 1907.5374 | 1164.6667 | 975.6401 | 1095.8071 | 1268.8474 | 1581.1856 | 1455.9090 | 573.1397 | 870.5488 |
| | $F_{interaction}$ | 35.1108 | 3.4322 | 4.4743 | 4.7202 | 26.7873 | 10.9084 | 36.6164 | 12.9194 | 1.1662 |
| 5M | $SS_{SDST/SIST}$ | 0.0008 | 1.2816 | 4.8456 | 3.6017 | 1.0354 | 0.0738 | 0.1157 | 0.0322 | 1.5232 |
| | $SS_{eq/dom}$ | 146.1733 | 138.8330 | 131.8781 | 130.7644 | 140.9730 | 141.4658 | 145.5322 | 124.2593 | 132.4822 |
| | $SS_{interaction}$ | 2.6803 | 1.0565 | 0.1770 | 0.4691 | 4.0458 | 3.2281 | 2.1676 | 4.4619 | 0.2088 |
| | $SS_T$ | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 |
| | $SS_E$ | 10.1456 | 17.8289 | 22.0993 | 24.1648 | 12.9459 | 14.2324 | 11.1844 | 30.2466 | 24.7857 |
| | $F_{SDST/SIST}$ | 0.0124 | 11.2140 | 34.2056 | 23.2514 | 12.4766 | 0.8084 | 1.6145 | 0.1663 | 9.5871 |
| | $F_{eq/dom}$ | 2247.5829 | 1214.7697 | 930.9338 | 844.1738 | 1698.7443 | 1550.5984 | 2029.8833 | 640.8809 | 833.8351 |
| | $F_{interaction}$ | 41.2127 | 9.2443 | 1.2492 | 3.0285 | 48.7519 | 35.3833 | 30.2340 | 23.0126 | 1.3142 |

| Proportion of tardy jobs [normalized] | | FCFS/FCFS | MS/SPT | $\frac{MS}{MJ}$/SPT | $\frac{MS}{MJ}$/SPT+RPT | EDD/TSPT | $\bar{SL}$/TSPT | $\bar{SL}$/SL | $\bar{SL}/\frac{SL}{RPT}$ | $\frac{MS}{MJ}$/SL |
|---|---|---|---|---|---|---|---|---|---|---|
| 3M | $SS_{SDST/SIST}$ | 0.0173 | 0.7461 | 0.7992 | 1.2248 | 8.0178 | 0.0544 | 0.0211 | 0.0463 | 0.6830 |
| | $SS_{eq/dom}$ | 154.2501 | 155.7167 | 155.4629 | 154.7882 | 145.8145 | 155.7990 | 155.9012 | 151.7051 | 153.8457 |
| | $SS_{interaction}$ | 1.9517 | 0.2588 | 0.1947 | 0.0692 | 3.3798 | 0.6163 | 0.3234 | 3.5390 | 0.1932 |
| | $SS_T$ | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 |
| | $SS_E$ | 2.7809 | 2.2784 | 2.5432 | 2.9179 | 1.7878 | 2.5303 | 2.7543 | 3.7096 | 4.2781 |
| | $F_{SDST/SIST}$ | 0.9679 | 51.0871 | 49.0226 | 65.4859 | 699.6081 | 3.3524 | 1.1956 | 1.9455 | 24.9038 |
| | $F_{eq/dom}$ | 8652.8303 | 10661.8398 | 9536.2835 | 8275.6998 | 12723.2462 | 9605.5439 | 8830.0645 | 6379.6569 | 5609.9317 |
| | $F_{interaction}$ | 109.4827 | 17.7206 | 11.9459 | 3.6993 | 294.9071 | 37.9980 | 18.3165 | 148.8253 | 7.0448 |
| 5M | $SS_{SDST/SIST}$ | 0.0002 | 0.7912 | 0.5416 | 0.7162 | 0.0084 | 0.0061 | 0.0783 | 0.0053 | 0.6067 |
| | $SS_{eq/dom}$ | 155.8829 | 155.5904 | 155.7178 | 155.9904 | 155.5898 | 155.4899 | 155.0816 | 153.7241 | 156.0914 |
| | $SS_{interaction}$ | 0.9905 | 0.1998 | 0.1657 | 0.2508 | 0.8866 | 0.8232 | 0.2098 | 1.0586 | 0.0744 |
| | $SS_T$ | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 | 159.0000 |
| | $SS_E$ | 2.1264 | 2.4186 | 2.5749 | 2.0426 | 2.5151 | 2.6807 | 3.6303 | 4.2120 | 2.2276 |
| | $F_{SDST/SIST}$ | 0.0167 | 51.0304 | 32.8153 | 54.6946 | 0.5238 | 0.3556 | 3.3664 | 0.1949 | 42.4852 |
| | $F_{eq/dom}$ | 11436.1373 | 10035.7441 | 9434.2224 | 11913.3987 | 9650.3272 | 9048.4673 | 6664.0741 | 5693.4645 | 10931.1341 |
| | $F_{interaction}$ | 72.6677 | 12.8901 | 10.0405 | 19.1529 | 54.9930 | 47.9066 | 9.0145 | 39.2071 | 5.2075 |

date-oriented heuristics. Cell configuration has very little impact on the performance of heuristics. However, in small cells the choice of a good heuristic is more important compared to large cells. Significant differences between effective heuristics are more frequent in large cell configurations.

- In general, no significant differences could be identified between the family rules MS- and $\frac{\text{MS}}{\text{MJ}}$ as well as between $\bar{\text{S}}$L and EDD. However, for the scenario with no dominating family and SDST, the proposed novel rules lead to a substantial improvement considering the mean tardiness. Furthermore, a significant improvement through $\frac{\text{MS}}{\text{MJ}}$/SPT could be shown in the scenario of no dominating family and SIST considering the proportion of tardy jobs. $\frac{\text{MS}}{\text{MJ}}$/SPT dominates other heuristics most frequently. Job rules are proven to have a great impact on the heuristics performance. Furthermore, for most simulation runs, combined job rules lead to inferior results compared to elementary dispatching rules.
- While the ranking of heuristics is strongly influenced by the chosen performance measure, the $\bar{\text{S}}$L/TSPT heuristic appears to be robust with a satisfying ranking position among all measures and scenarios and even with top ranking position in scenarios of family dominance taking mean tardiness into account. In total, $\frac{\text{MS}}{\text{MJ}}$/SPT is identified as the preferable heuristic for mean flow time, proportion of tardy jobs and even for mean tardiness on scenarios of no dominating part family. With family dominance $\bar{\text{S}}$L/TSPT is a favorable choice to minimize mean tardiness.
- The well-known FCFS/FCFS and the novel $\bar{\text{S}}$L/$\frac{\text{SL}}{\text{RPT}}$ showed the weakest performance regardless of the performance measure and the scenario. Thus, they should be avoided for practical applications.

Summing up, it can be concluded that not all heuristics that have previously been identified to be superior (see Table 1) are suitable for dispatching manufacturing cells effectively. Additionally, some novel superior heuristics like $\frac{\text{MS}}{\text{MJ}}$/SPT and $\bar{\text{S}}$L/TSPT should be considered for future research.

The presented results also point to interesting directions for future research. In particular, a validation of results of this work and previous studies with real time data from practical manufacturing environments is necessary. Due to the extensive simulation study no significant differences concerning the effectiveness of dispatching rules and influencing factors should be expected. Nevertheless, nearly no case study on group scheduling production systems has been reported in literature, which proves theoretical results from simulation surveys in practice. Besides, the gained insights still have to be verified for flow shop manufacturing cells. Furthermore, the interaction of other influencing factors and their effect on the performance of heuristics should be integrated in future simulation studies. Especially, the influence of varying cell configurations and layouts as well as buffers has not been analyzed exhaustively. Even how the proposed heuristics are effected by different, well studied parameters concerning job arrival, processing times and due dates requires further investigation. An integration of flexible process plans or workforce would increase the applicability of these results for real-world manufacturing systems. In this paper, different cell configurations were considered for the first time. Since previous research included varying cell utilization, further research might concentrate on the impact of diverse cell utilization rates with different types of cells.

In this study we were able to show that combined family rules can improve the performance and particularly the robustness of two-stage heuristics. Future research should test further combinations of dispatching rules. Moreover, beside dispatching rules more sophisticated heuristics, e.g. based on constructive heuristics such as NEH, could be tested in dynamic environments. Generally, future research should focus on approaches that are able to meet the challenges of practical scheduling systems with changing and uncertain conditions.

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