FLOW SHOP SCHEDULING OPTIMIZATION IN THE CHIPBOARD INDUSTRY: A SIMULATION-BASED ANALYSIS USING PRIORITY DISPATCHING RULES

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Abstract
This paper gives insights on the usability of single priority and multi-criteria dispatching rules for production scheduling based on the results for a German chipboard manufacturing plant. A discrete-event simulation of the manufacturing process has been modeled to compare different priority rules with an expert-based sequence for a real set of jobs. The simulation results show that using one single or multi-criteria priority dispatching rule on the total production system basically leads to a poor performance, whereas using different rules for each machine will enhance the overall performance. Higher performance can be achieved by the expert-based scheduling and individual multi-criteria dispatching rules. Hence, a dynamic modification of the production schedule by switching the dispatching rules according to the current performance is proposed, considering unforeseen disturbances.

Keywords:
Flow shop scheduling problem, production scheduling, priority dispatching rules, discrete event simulation, two-machine flow shop

1 INTRODUCTION
The flow shop sequencing problem is one of the most discussed production planning problems in scientific literature. The main goal is to reduce the makespan of a defined number of jobs, i.e. the time between the start of the first job on the first machine and the end of the last job on the last machine [1], [2]. Since the computation of all possible sequences is in most of the cases expensive and inefficient, heuristics have been developed, like the Johnson’s algorithm [3] or the NEH algorithm [1], to improve the calculation time. In scientific research several assumptions are made to simplify the problem, such as [2], [4]:

- Every job has to be processed at most once on a machine.
- The machine order equals for every job.
- A machine can process only one job at a time.
- The operations are not preemptable.
- All jobs for the production period are known.
- All jobs have the same priority and there are no due dates.
- The setup times for an operation are included in the processing time and do not depend on the sequence.

A special form of the flow shop problem is the permutation flow shop, where the job sequence is the same on every machine [5]. In practice, some of these simplifications can not be made due to real-time events, e.g. job cancellation, due date changes or machine breakdowns [6], [7]. Therefore, many companies perform a predictive-reactive scheduling, where the predefined schedule is revised in order to deal with real-time events, or a completely reactive scheduling, where the next job is selected locally in real-time using priority dispatching rules [6], [8]. Some well-known and easy to handle priority dispatching rules are First In First Out (FIFO), Earliest Due Date (EDD) or Minimum Slack Time (MSLT) [9], [10]. Moreover, companies are formulating individual rules for their scheduling problem taking into account the specific production process and job characteristics. Each rule is supporting one or more goals of the scheduling process. Typical goals are [10]:

- To minimize the makespan.
- To minimize the work in progress.
- To minimize the production costs.
- To maximize the machine utilization.
- To maximize the number of finished products.
- To maximize the delivery reliability.

This paper is comparing the benefit of different priority dispatching rules with the aim of improving the overall performance of a chipboard manufacturing plant. While the setup costs are minimized and the utilization of machines is maximized by continuous modification of the production schedule, the delivery reliability remains low compared to other plants of the enterprise. The desired goal is to improve the delivery reliability, while keeping the remaining indicators on a good level. A simulation-based analysis is conducted in order to prove the possibility of achieving this goal.

The paper is structured as follows. In section 2, the product, the main job characteristics, the production process and the usual way of scheduling of the company are explained. Next, the simulation model with the formulated priority dispatching rules is described in section 3. Section 4 focuses on the comparison of the simulation results using one dispatching rule for the whole production system and different dispatching rules for every machine. Finally, a discussion and conclusion are presented in section 5.

2 DEFINING THE FIELD OF INVESTIGATION

2.1 Product and job characteristics
The investigated company is producing chipboards made from wood chips and is serving mainly the furniture industry. There are two main product lines, medium-density fiberboards (MDF) and high-density fiberboards (HDF); these are divided into different product families. Each family determines the specific product characteristics, highlighting especially properties as the width, length and thickness of the raw and finished chipboards, the necessary material combinations or the required grain size for the grinding belt of the sanding line. Hence, the related product family, the ordered number of finished chipboards and the agreed delivery date define the characteristics of a job.

2.2 Description of the production process
Mainly four parts are determining the structure of the production system: (1) a pressing machine followed by a crosscutting saw; (2) a raw board storage system; (3) a sanding line with inline saw and (4) a packaging line. As the
preprocessing of the wood chips for the pressing machine is not relevant for the investigation, it will be neglected in the further description. For the scheduling process the pressing machine and the crosscutting saw can be handled as one machine. Same can be done for the sanding line with inline saw and the packaging line. Hence, the company’s productions system can be categorized as a two-machine flow shop. Due to varying product characteristics and customer requirements every job has a different processing time on the pressing machine and the sanding line. In addition, the order sequence itself is influencing especially the necessity of setups on the sanding line and therefore the setup time, that can be zero or a fixed amount of time for every job.

A new job can only be processed on the pressing machine after the last job has been completely finished and the pressing machine is empty. This will result in a waiting time for the next job. After getting pressed, cut and stacked on pallets, the job-related pallets have to wait in the raw board storage system a fixed amount of time for them to dry that is depending on the thickness of the raw boards. Therefore, the storage system itself could be seen as a processing center with parallel machines, able to process several jobs at a time. In addition, the real raw board storage system consist of a railway system with several lines. For this investigation it is treated as a black box in the simulation model, without technical restrictions. On the sanding line jobs will be combined if they have equal characteristics and can be assigned to the same customer. In this case, these jobs will be processed continuously, but one by one. If these conditions are not met, the next job has to wait until the last job has been completely finished and the sanding line is empty. Figure 1 illustrates the explained production process.

Figure 1. The four main steps of the simplified production process of chipboards.

2.3 Production scheduling in the company

The production schedule is set up offline as a predictive schedule for a time period between two and three weeks and will be modified during the production period in reaction of real-time events. Each production period ends with planned maintenance. The basic schedule is determined aiming the reduction of changes between product subfamilies, i.e. the necessary material combination, on the pressing machine. A large number of changes will result in financial losses due to specific process characteristics. The agreed delivery date is considered subsequently.

The raw board storage system is the only part of the process, where the order sequence can be modified in consideration of the technical restrictions. For the sanding line a separate schedule is determined, following the reactive scheduling approach. In the scheduling process for the sanding line only the stack of dried raw boards is considered. The main goal is to reduce the setup time on the sanding line. Therefore, all available jobs that require the same grain size of the grinding belt are combined, as the sanding line has to be set up only once for this group of jobs. This will reduce the total setup time and therefore improve the utilization of the sanding line. Moreover, the utilization of the grinding belts gets maximized. As they will not be reused after a change, every setup will result in financial losses due to the under exploitation of the available operating life of the grinding belt.

2.4 Problem formulation

For the company specific sequencing problem, the following assumptions are made: (1) every job has to be processed at most once on the pressing machine and the sanding line; (2) the machine order equals for every job; (3) the pressing machine can process only one job at a time; (4) the sanding line can process jobs continuously if they can be combined (same customer, same product characteristics); (5) the operations are not preemptable; (6) the setup time on the sanding line are not included in the processing time and depend on the sequence; (7) the raw board storage system is handled as a black box and (8) the job sequence can vary on the pressing machine and the sanding line.

The main goals of the scheduling process are (from highest to lowest importance):

1. To minimize the production costs represented by the number of material changes on the pressing machine.
2. To maximize the delivery capability.
3. To minimize the setup time and setup costs on the sanding line represented by the number of setups.
4. To minimize the total makespan.
5. To maximize the utilization of the pressing machine and the sanding line.

The utilization of the pressing machine can not be improved directly by the job sequence on the machine, as there are no setup times that have to be considered. The setup of the pressing machine for the next job is done, while the current job gets processed. Yet, the raw board storage system has a defined capacity and the pressing machine has to stop when the raw board storage capacity is at its maximum.

Once the sanding line has processed several pallets of chipboards, the pressing machine can be restarted. This will reduce the utilization of the pressing machine. A reduction of the pressing machine utilization can be avoided by improving the utilization of the sanding line that is directly influenced by the corresponding setup time.

3 SIMULATION MODELING

The production and scheduling process have been modelled in AnyLogic combining a discrete-event simulation with agent-based modeling. AnyLogic is a simulation software providing a multi-method modeling environment. The software is JAVA-based and offers flexibility in the modelling process [11].

3.1 Scheduling process and process simulation

The simulation model consists of two main parts: (1) the production process and (2) the scheduling process with specific priority dispatching rule algorithms. The modelled production process includes all of the above mentioned parts of the production system, i.e. the pressing machine and crosscutting saw, the raw board storage system, the sanding line with inline saw and the packaging line.

All upcoming jobs are described in a database and will enter the scheduling process flow via the defined source. The jobs are created as agents that will join the group of jobs. Every agent has a set of parameters that are necessary to characterize the job. First, all jobs are waiting to get processed. According to the chosen priority dispatching rule the algorithm will choose the first job for the pressing
machine and the necessary amount of material will be released into the production process. After the job has been processed, the next job will be chosen from all available jobs considering the characteristics of the previous job. Meanwhile, the previous job will enter the raw board storage system to dry. The dry time depends on the thickness of the raw chipboards. Afterwards, the job will wait to get processed on the sanding line.

The scheduling process for the sanding line is performed in the same way as the scheduling process for the pressing machine. Jobs are chosen according to the defined priority dispatching rule. The algorithm considers the last job that has entered the sanding line, as well as all available jobs that are waiting in front of it. When a specific job is chosen, the corresponding pallets will leave the raw board storage system of the production process model. After sanding, the chipboards will be packed as it is described in the real process. At the same time, the job agent will be directed to the sink of the scheduling process model. For making the model more realistic and reducing biases, a second source has been integrated that can generate jobs that have not been processed in the last production period and are waiting in the raw board storage system at the start of a simulation run. Figure 2 illustrates the explained scheduling process.

![Figure 2. Scheduling process flow of the simulation model.](image)

### 3.2 Formulation of the priority dispatching rules

The following part gives a brief explanation of the used priority dispatching rules. As mentioned before, there are two points in the scheduling process flow, where the next job is selected based on the chosen rule.

**Expert-based predefined sequence (PREDEF)**

The first rule represents the company specific scheduling process. Therefore the supply chain manager of the company has predefined the sequence of all jobs. The sequence is focusing on, first, reducing material changes on the pressing line and the setup time on the sanding line and, second, the agreed delivery date of the customer. The jobs will have specific priority numbers for the pressing machine and the sanding line. This rule is supporting the goals 1, 3 and 5.

**First in First Out (FIFO)**

As many studies have already shown the FIFO rule performs similar to random selection and will not support the introduced goals. Yet, the rule will be integrated for comparison only. The main purpose of the rule is to simplify the scheduling process [12]. At the machine, the jobs will be processed in the same order as they arrive. For the pressing machine the sequence is defined by the sequence as the orders are received by the company. For the sanding line the sequence is defined by the time that all raw chipboards of the job have been dried the defined time in the raw board storage and the job is waiting for getting sanded.

**Earliest Due Date (EDD)**

This rule is sorting the jobs according to the agreed delivery date with focus on goal 2. The job with the closest delivery date will be processed next on the respective machine.

**Minimum Slack Time (MSLK)**

The slack time is the remaining time between the agreed delivery date and the remaining processing time of the job. In the simulation, the slack time will be recalculated for all waiting jobs every time, the algorithm is searching for the next job that can be processed on the pressing machine or the sanding line. As already mentioned the setup time on the sanding line depends on the order sequence. For simplification, the setup time is considered for every job in the calculated slack time, as the rule can not predict the necessity of a setup. The job with the lowest slack time gets the highest priority. MSLK is supporting goal 2.

**Reduced Material Change (RMC)**

The RMC rule is focusing on the reduction of material changes on the pressing line and basically supports goal 1. All jobs that need the same material combination will be processed in sequence.

**Reduced Setup Time (RST)**

The RST rule is focusing on the reduction of setups on the sanding line and supports the goals 1, 4 and 5. As already explained, a job that needs the same grain size of the grinding belt as the previous job will be prioritized.

**Minimum Slack Time and Reduced Material Change (MSLKRMC)**

This rule is combining the MSLK rule with the RMC rule, with a focus on the slack time of the job. An urgent job will be preferred, even if this will increase the number of material changes on the pressing machine. The aim is to achieve an optimum between goal 1 and goal 2, with a focus on goal 2.

**Reduced Material Change and Minimum Slack Time (RMCRMLK)**

RMCRMLK is combining the MSLK rule with the RMC rule, with a focus on reducing the material changes on the pressing machine. The algorithm is searching for all jobs with the same material combination as the previous processed job. Next, the group of selected jobs will be evaluated and the job with the minimum slack time will be prioritized. The aim is to achieve an optimum between goal 1 and goal 2, with a focus on goal 1.
Minimum Slack Time and Reduced Setup Time (MSLKRST)
This rule is combining the MSLK rule and the RST rule, with a focus on the slack time of the job. An urgent job will be preferred, even if this will increase the number of setups on the sanding line. The aim is to achieve an optimum between goal 2 and goal 3, with a focus on goal 2.

Reduced Setup Time and Minimum Slack Time (RSTMSLK)
This rule is combining the MSLK rule with the RMC rule, with a focus on avoiding a setup on the sanding line. The algorithm is searching for all jobs that can be sanded on the same grinding belt as the previous job. Next, the group of selected jobs will be evaluated and the job with the minimum slack time will be prioritized. The aim is to achieve an optimum between goal 2 and goal 3, with a focus on goal 3.

FIFO, EDD, MSLK, RMC and RST can be assigned to the group of single priority dispatching rules, as each rule is focusing on one specific job characteristic. The remaining rules can be assigned to the group of multi-criteria dispatching rules, as they are trying to achieve an optimum between several goals using different job characteristics.

4 EXPERIMENT SETUP AND SIMULATION RESULTS

The introduced rules are implemented in permutations for the production system. An example is RMC/EDD. The combination is representing the case of using RMC to dispatch jobs for the pressing machine and EDD to dispatch jobs for the sanding line. It has to be mentioned that the RMC rule and the corresponding multi-criteria rules will not be used for the sanding line, as they are especially designed for the pressing machine. In contrast RST and its variations will be used for dispatching jobs for the pressing machine.

As the possible sequence on the sanding line will depend on the resulting sequence of the pressing machine, it is expected that using RST for the pressing machine will improve the utilization of the sanding line. Hence, unnecessary stops of the pressing machine can be prevented as explained in section 2.4. PREDEF, i.e. the expert-based sequence, will not be combined with any other rule. This will lead to a total of 55 permutations for the experiment. In addition, the production system will be treated as a one-machine flow shop to compare the results with the proposed machine-specific scheduling in the two-machine flow shop. Therefore, every rule will be used for dispatching the jobs for the pressing machine. The assigned priority number will be reused for defining the sequence on the sanding line. Hence, the experiment will consist of 65 runs.

For the simulation a set of 105 jobs has been extracted from the real backlog of the company. 23 jobs will be generated as the initial stock of the raw board storage. The remaining 82 jobs will be waiting in front of the pressing machine. To choose the best run a score is calculated as a sum of the following measurement criteria using a company specific weighting (w): (1) the makespan of all jobs (w=0,125); (2) the delivery reliability (w=0,25); (3) the number of material changes on the pressing machine (w=0,25); (4) the number of setups on the sanding line (w=0,2); (5) the utilization of the pressing machine (w=0,0875) and (6) the utilization of the sanding line (w=0,0875). Prior to the calculation of the score the results of each criteria will be normalized and transferred to a scale of 1 to 10. Hence, the maximum score for a run can be 10.

4.1 Results for treating the productions system as a one-machine flow shop

Treating the production system as a one-machine flow shop, i.e. as a permutation flow shop, could be a desirable way of reducing the planning effort for production scheduling. The simulation results for the one-machine flow shop scenario are summarized in Table 1. The table is also showing the best and worst rule for each measurement criteria. As the results show, the proposed sequence of the supply chain manager, i.e. the PREDEF rule, will perform quite good in this scenario and reaches place seven in the total rank of all simulation runs. RST and RMC are on rank 11 and 17. While RMC will reduce the material changes, RST is improving the delivery reliability, reduces the number of setups and the makespan and therefore gains a better score. RMCMSLK is slightly better than RMC due to the expected improvement in the delivery reliability. The number of material changes remains equal compared to RMC, whereas the makespan can be improved. Surprisingly, the sanding line utilization is rising, while the number of setups is increasing simultaneously.

Table 1. Results of treating the production system as a one-machine flow shop.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Rank²</th>
<th>Score</th>
<th>Makespan [days]</th>
<th>Delivery reliability</th>
<th>Material changes (P)</th>
<th>Setups (S)</th>
<th>Utilization (P)</th>
<th>Utilization (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSTMSLK</td>
<td>4</td>
<td>7,935</td>
<td>14,798</td>
<td>0,829</td>
<td>38</td>
<td>17</td>
<td>0,892</td>
<td>0,734</td>
</tr>
<tr>
<td>PREDEF¹</td>
<td>7</td>
<td>7,913</td>
<td>15,299</td>
<td>0,933</td>
<td>18</td>
<td>39</td>
<td>0,892</td>
<td>0,711</td>
</tr>
<tr>
<td>RST</td>
<td>11</td>
<td>7,697</td>
<td>15,068</td>
<td>0,848</td>
<td>40</td>
<td>18</td>
<td>0,893</td>
<td>0,721</td>
</tr>
<tr>
<td>RMCMSLK</td>
<td>15</td>
<td>7,633</td>
<td>15,536</td>
<td>0,781</td>
<td>8</td>
<td>43</td>
<td>0,893</td>
<td>0,699</td>
</tr>
<tr>
<td>RMC</td>
<td>17</td>
<td>7,558</td>
<td>15,873</td>
<td>0,771</td>
<td>8</td>
<td>38</td>
<td>0,893</td>
<td>0,685</td>
</tr>
<tr>
<td>MSLKRST</td>
<td>39</td>
<td>6,589</td>
<td>15,512</td>
<td>0,838</td>
<td>45</td>
<td>36</td>
<td>0,892</td>
<td>0,700</td>
</tr>
<tr>
<td>MSLKRMC</td>
<td>40</td>
<td>6,585</td>
<td>16,147</td>
<td>0,790</td>
<td>22</td>
<td>47</td>
<td>0,893</td>
<td>0,673</td>
</tr>
<tr>
<td>MSLK</td>
<td>53</td>
<td>5,915</td>
<td>16,187</td>
<td>0,943</td>
<td>45</td>
<td>51</td>
<td>0,892</td>
<td>0,671</td>
</tr>
<tr>
<td>EDD</td>
<td>58</td>
<td>5,707</td>
<td>16,130</td>
<td>1,000</td>
<td>49</td>
<td>58</td>
<td>0,892</td>
<td>0,675</td>
</tr>
<tr>
<td>FIFO</td>
<td>65</td>
<td>4,005</td>
<td>16,114</td>
<td>0,752</td>
<td>66</td>
<td>71</td>
<td>0,891</td>
<td>0,677</td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td>7,935</td>
<td>16,187</td>
<td>1,000</td>
<td>66</td>
<td>71</td>
<td>0,893</td>
<td>0,734</td>
</tr>
<tr>
<td>Mean</td>
<td>6,754</td>
<td>15,666</td>
<td>0,849</td>
<td>33,9</td>
<td>41,8</td>
<td>0,892</td>
<td>0,695</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>4,005</td>
<td>14,798</td>
<td>0,752</td>
<td>8</td>
<td>24</td>
<td>0,891</td>
<td>0,671</td>
<td></td>
</tr>
<tr>
<td>Best rule</td>
<td>RSTMSLK</td>
<td>RSTMSLK</td>
<td>EDD</td>
<td>RMC</td>
<td>RSTMSLK</td>
<td>various</td>
<td>RSTMSLK</td>
<td></td>
</tr>
<tr>
<td>Worst rule</td>
<td>FIFO</td>
<td>MSLK</td>
<td>FIFO</td>
<td>FIFO</td>
<td>FIFO</td>
<td>FIFO</td>
<td>MSLK</td>
<td></td>
</tr>
</tbody>
</table>

¹Expert-based sequence; ²Total rank of all 65 simulation runs; P = Pressing machine; S = Sanding line
Table 2. Best results of treating the production system as a two-machine flow shop.

<table>
<thead>
<tr>
<th>Rule combination</th>
<th>Rank(^2)</th>
<th>Score</th>
<th>Makespan [days]</th>
<th>Delivery reliability</th>
<th>Material changes (P)</th>
<th>Setups (S)</th>
<th>Utilization (P)</th>
<th>Utilization (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P: RMC S: RST</td>
<td>1</td>
<td>8,379</td>
<td>15,577</td>
<td>0,810</td>
<td>8</td>
<td>22</td>
<td>0,893</td>
<td>0,697</td>
</tr>
<tr>
<td>P: RMC S: RSTMSLK</td>
<td>2</td>
<td>8,179</td>
<td>15,634</td>
<td>0,771</td>
<td>8</td>
<td>24</td>
<td>0,893</td>
<td>0,695</td>
</tr>
<tr>
<td>P: RMC S: RSTMSLK</td>
<td>3</td>
<td>8,062</td>
<td>15,299</td>
<td>0,771</td>
<td>8</td>
<td>34</td>
<td>0,893</td>
<td>0,710</td>
</tr>
<tr>
<td>P: RSTMSLK S: RST</td>
<td>5</td>
<td>7,925</td>
<td>14,558</td>
<td>0,829</td>
<td>38</td>
<td>22</td>
<td>0,892</td>
<td>0,746</td>
</tr>
<tr>
<td>P: PREDEF S: PREDEF(^1)</td>
<td>6</td>
<td>7,915</td>
<td>16,134</td>
<td>0,857</td>
<td>18</td>
<td>17</td>
<td>0,892</td>
<td>0,673</td>
</tr>
<tr>
<td>P: RMC S: RSTMSLK</td>
<td>8</td>
<td>7,911</td>
<td>15,416</td>
<td>0,781</td>
<td>8</td>
<td>37</td>
<td>0,893</td>
<td>0,704</td>
</tr>
<tr>
<td>P: RSTMSLK S: MSLKRST</td>
<td>9</td>
<td>7,762</td>
<td>14,677</td>
<td>0,848</td>
<td>38</td>
<td>26</td>
<td>0,892</td>
<td>0,740</td>
</tr>
<tr>
<td>P: RMC S: MSLKRST</td>
<td>10</td>
<td>7,723</td>
<td>15,535</td>
<td>0,790</td>
<td>8</td>
<td>41</td>
<td>0,893</td>
<td>0,699</td>
</tr>
</tbody>
</table>

Max 8,379 16,406 1,000 66 67 0,893 0,746
Mean 6,752 15,572 0,856 35,3 42,6 0,892 0,699
Min 4,231 14,558 0,705 8 17 0,891 0,664

Best rule combination:
- P: RMC S: RST
- P: RSTMSLK S: RSTMSLK
- P: EDD/MSLK S: various\(^3\)
- P: RMC\(^4\) S: any rule
- P: PREDEF S: PREDEF
- P: various S: various
- P: RSTMSLK

Worst rule combination:
- P: FIFO S: FIFO
- P: RMC S: EDD
- P: MSLKRMC S: FIFO
- P: FIFO S: FIFO
- P: FIFO S: FIFO
- P: RMC S: any rule

\(^1\) Expert-based sequence; \(^2\) Total rank of all 65 simulation runs; \(^3\) primarily MSLK, EDD and FIFO; \(^4\) RMC and all variations

P = Pressing machine; S = Sanding line

An explanation can be found in the dry time of a job. There are jobs that will enter the raw board storage after another job but will leave it earlier due to a shorter dry time. In the simulation run of RMC, the sanding line was waiting for the next job, while other jobs have been already waiting for getting sanded. In contrast, the RMCMSLK rule is improving the sequence for the total production system, as the dry time is calculated in the slack time and the slack time is considered subsequently in this rule. The best rule in this scenario is RSTMSLK with a total score of 7,935. The rule was able to improve every criteria, except for the delivery reliability and the number of material changes on the pressing machine. As expected FIFO is the worst performing rule and reaches the last place.

4.2 Results for treating the production system as a two-machine flow shop

Planning the sequence for each machine separately will improve the overall score. The simulation results for the best rule combinations are summarized in Table 2. As the results show, the maximum values for each measurement criteria can be improved or are equal and consequently the maximum score can be improved by rescheduling the jobs for the sanding line. The best rule combination is RMC/RST with a score of 8,379. In this case, the number of material changes on the pressing machine get minimized and the number of setups is near the minimum. Yet, the delivery reliability is below the mean value. The delivery reliability could be maximized by using EDD or MSLK for the pressing machine. This would lead to a number of 45 to 49 material changes and 41 to 61 setups for every associated combination.

RSTMSLK/RSTMSLK is the best rule combination for minimizing the makespan. On the pressing machine the suitable job sequence is predefined for improving the number of setups of the sanding line and the corresponding utilization. Against expectations, the number of setups is remaining above the minimum. The explanation is the same as for the missing correlation between the number of setups and sanding line utilization in the one-machine flow shop scenario using RMCMSLK. While the sequence will be predefined at the pressing machine in order to minimize the setups of the sanding line, the possible sequence will change automatically due to the varying dry times of each job.

A good performance can be also achieved by the associated variations of RMC and RST that are taking into account the slack time. As the results show for the best corresponding combinations, the number of material changes will remain on the minimum if RMC or a variation is combined with RST or an equivalent variation. In addition, the number of setups stays below the mean value. Yet, the delivery reliability is below the mean value. While the consideration of the slack time should improve the delivery reliability due to the fact, that urgent jobs will be prioritized, this approach leads to more setups on the sanding line for the available set of jobs. Hence, with the given data, it can not be concluded that RMC/RST will always perform better than the multi-criteria rules, as the performance of each rule combination will be influenced by the varying job characteristics in every production period. Moreover, the mean total score for using a combination of single-criteria rules is 6,248, whereas the mean total score for using a combination of multi-criteria rules is 7,480.

PREDEF/PREDEF is not performing significantly better than the expert-based sequence in the one-machine scenario. While the number of setups on the sanding line can be more than halved, the delivery reliability will decrease from 0,933
the product range and the large number of exception rules that had to be integrated. Ouelhadj and Petrovic [6] have compared different dynamic scheduling methods, i.e. heuristics, meta-heuristics, knowledge-based systems, fuzzy logic, neuronal networks, Petri nets, hybrid techniques and multi-agent systems, on the basis of a literature review. It has to be verified if other approaches not relying on the formulation of defined dispatching rules, can achieve even better results than those discussed in this paper.

6 REFERENCES