Modeling Lateness for Workstations with Setup Cycles

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Abstract. Sequence-dependent setup times force companies to bundle similar products to avoid setup efforts. While this increases the output rate the schedule reliability tends to decrease due to the sequence deviations enfaced by this sequencing policy. Our paper presents a model to predict the impact of different strategies for setup-optimized sequencing and their actuating variables on the sequence deviation. Through this it enables a positioning in the trade-off between a high output rate and a high schedule reliability.

Keywords: sequence-dependent setup times, manufacturing control, production planning and control, schedule reliability

1 Introduction

An important objective of manufacturing companies is the reduction of setup efforts since high setup times negatively influence a workstation's productivity and flexibility. Two scenarios of setup times can be distinguished. In the first one, the setup time of the next order is independent from the currently processed order. In the second case, setup times depend on the predecessor of the currently processed job and are hence called sequence-dependent setup times [1].

Independent from the industry, companies often face the challenge of sequencing with sequence-dependent setup times at some of the workstations. Bundling similar orders in setup families and defining a repetitive pattern for a cyclic production of these families has become common practice. A changeover between orders within a setup family requires only minor setup efforts, while the changeover between setup families causes major setup efforts. Whereas the bundling of orders increases the output rate of the workstation, the production schedule is mixed up, as orders are either accelerated or delayed. Delayed orders negatively influence the delivery reliability which is the logistic objective mainly perceived by the customer. Orders which are finished too early increase inventory costs of the company [2].

Fig. 1 shows exemplarily the principle of building setup cycles. A FIFO (First-In-First-Out) processing sequence would require five major setups while the bundling reduces the amount to two major setup efforts. The potential for building setup families is also influenced by the WIP (work in process) level at the workstation: The higher the WIP level, the higher is the potential for bundling but also the resulting turbulences in the production schedule. Thus, companies with sequence-dependent setup times are in

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a trade-off between a high output rate, low WIP levels and a low variance of output lateness at the same time.

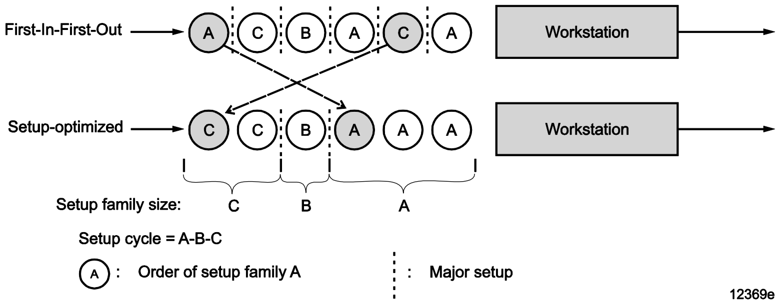

Fig. 1. Principle of building setup cycles

This paper is structured in five sections. After an introduction, we present the current state of research, on which the model presented in section three is based. Section four gives recommendations for a logistic positioning in the before mentioned trade-off. The last section gives a brief summary of the paper and an outlook on planned research.

2 Current State of Research

2.1 Modeling Output Lateness

Output lateness is the deviation of the actual and the planned end of order processing [3]:

$$L_{out}=EDO_{act}-EDO_{plan} \tag{1}$$

where L_{out} is the output lateness (shop calendar days (SCD)), EDO_{act} the actual end of order processing (SCD) and EDO_{plan} the planned end of order processing (SCD).

Hence, a positive output lateness indicates a late completion of an order and a negative lateness an early completion. Schedule reliability is defined as the percentage of orders that is manufactured within a defined lateness tolerance [4]:

$$SR=\frac{NO\ with\ L_{out,ll} \leq L_{out} \leq L_{out,ul}}{NO}\cdot 100 \tag{2}$$

where SR is the schedule reliability (%), NO the number of orders (-), $L_{out,ll}$ the lower limit for permissible output lateness (SCD), L_{out} the output lateness (SCD) and $L_{out,ul}$ the upper limit for permissible output lateness (SCD).

There are mainly two factors influencing schedule reliability: backlog and sequence deviation [2]. Backlog influences the mean value of output lateness while sequence deviation determines its standard deviation [5, 6]. The mean lateness is the ratio between the mean backlog and the mean output rate [4]:

$$L_{out,m}=\frac{BLO_m}{ROUTO_m} \tag{3}$$

where $L_{out,m}$ is the mean output lateness (SCD), BLO_m the mean backlog (-) and $ROUTO_m$ the mean output rate (orders/SCD).

By definition, the mean lateness does not reflect the effect of sequence deviations of single orders on output lateness. Sequence deviations are defined as [7]:

$$SDO_i = rankO_{act,i} - rankO_{plan,i} \tag{4}$$

where SDO_i is the sequence deviation of order i (-), $rankO_{act,i}$ the actual rank of order i (-) and $rankO_{plan,i}$ the planned rank of order i (-).

The rank of an order is determined by sorting the orders by their completion date and ranking them with consecutive numbers. The orders are sorted by their planned completion date to define the planned rank and by their actual completion date for the actual rank. Sequence-dependent lateness is then calculated by dividing the sequence deviation of an order by the planned output rate [5]:

$$L_{out,SD} = \frac{SDO_i}{ROUTO_{plan}} \tag{5}$$

where $L_{out,SD}$ is the sequence-dependent output lateness (SCD), SDO_i the sequence deviation of order i (-) and $ROUTO_{plan}$ the planned output rate (orders/SCD).

2.2 Modeling Output Lateness due to Setup-Optimized Sequencing

As mentioned in section 2.1, lateness can be partitioned in the two parts lateness due to sequence deviations and lateness due to backlog. In preliminary studies we focused on the forecast of the output rate resulting from setup-optimized sequencing [8]. Thus, we assume that output rate is forecast reliably. The only remaining influence on lateness is the sequence deviation and hence the standard deviation of lateness. The mean value of output lateness is zero.

Literature basically differentiates between class exhaustion and truncation rules for sequencing. Class exhaustion means the workstation will not change to another setup family as long as there are orders of the currently processed setup family in the queue. Truncation rules permit the changeover to another family while there are still orders of the currently produced family in the queue [9].

Eilmann et al. investigate different setup-optimized sequencing rules and their influence on productivity and standard deviation of throughput times. Scheduling with constant throughput times means the standard deviation of throughput times equals the standard deviation of output lateness. A FIFO sequencing results in the lowest productivity but also the lowest standard deviation of throughput times. Class exhaustion leads to the highest productivity but also increases standard deviation of throughput times. The authors also investigate the productivity of a truncation rule but do not show its effect on standard deviation of throughput times [10].

Bertsch investigates the effect of setup-optimized sequencing on output lateness. His strategy is to prioritize the setup family with the lowest ratio of setup effort and number of orders in the queue. To forecast the standard deviation of lateness due to setup-optimized sequencing he uses the same model as for a random sequence. The standard deviation increases with a higher WIP level and a higher number of setup families. The applied model works well as an approximation but the lower the number of setup families and the higher the WIP level at the workstation is, the higher is the difference between the forecast and simulated standard deviation [11].

Sawicki compares different class exhaustion rules with truncation rules in terms of tardiness. He also investigates the application of different setup family sequences. His results suggest that usually class exhaustion performs best while specific values for parameters of truncation rules outperform class exhaustion [12].

All above mentioned authors explain the effects of certain setup-optimized sequencing rules on lateness mostly based on simulation experiments. The authors neither model the influence of sequence-dependent setup times nor do they give recommendations for a positioning in the trade-off. Also most authors did not analyze the interdependency between the WIP level and configuration of the sequencing rules.

3 Sequence Deviation due to Setup Cycles

3.1 Strategies for Setup-Optimized Sequencing

The heuristic of class exhaustion is often suggested by literature for sequencing at workstations with sequence-dependent setup times. Its application is easy and for the sake of a higher output rate scattering throughput times are usually accepted. Class exhaustion, as it is referred to in this paper, means that a setup family will be produced until there is no order belonging to this family left in the waiting queue of the workstation.

Another strategy for setup-optimized sequencing is a truncation rule that fixes a maximum number of bundled orders without preventing the workstation setting up for the next setup family. A cyclic order is fixed for both strategies (e. g. A-B-C) to decide which setup family is produced next without taking due dates into account.

3.2 Sequence Deviations

Figure 2 left shows how the maximum sequence deviation is caused when applying class exhaustion with the help of an example. In the worst case, order A arrives when the workstation has just begun the setup for family B. Hence, the order has to wait until all the other setup families have been produced. Due to a random distribution of setup families in the WIP, the time for the production of all families, which is denoted as the setup cycle time in the following, varies for each setup cycle. As a consequence, also the waiting time varies for each setup cycle. The figure shows a situation with 6 orders in the waiting queue of the workstation. A new order will arrive at the workstation each time the processing of an order is completed.

Figure 2 right shows the effect of the truncation rule on sequence deviations. If an order of setup family A arrives when the workstation just started producing setup family B the order will wait at least until all other setup families have been produced. The upper limit causes the workstation to stop producing a setup family although further orders of the currently produced setup family could be present in the waiting queue (shaded order A in Fig. 2). In this case the waiting time for this order increases steeply by at least one setup cycle while the throughput times of orders of the other setup families are slightly reduced. With an upper limit maximum sequence deviations are not only defined by the length of one setup cycle but also by the amount of orders present in the waiting queue.

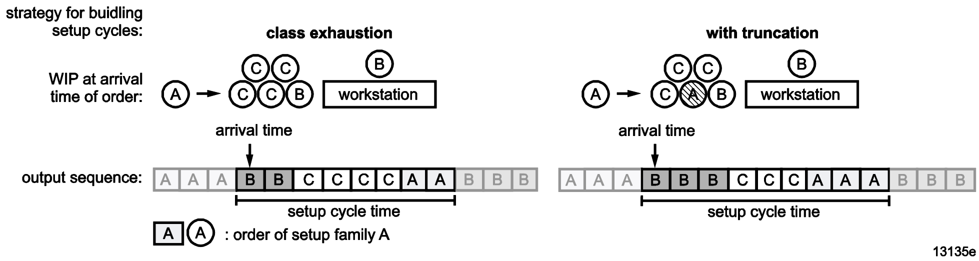

Fig. 2. Sequence deviation caused by setup cycles

The assumption is that in a job shop production the production schedule is made with constant planned throughput times which are independent from a setup-optimized sequence. This FIFO scheduling considers the WIP level and thus the planned rank of an order is increased by orders in the waiting queue which, according to the plan, would be processed before. If an order is processed within one setup cycle the maximum sequence deviation is only determined by the amount of orders processed until its respective setup family is produced. This equals the time of the current setup cycle less the size of the order's setup family in the current cycle. The setup cycle time is counted from the last production of the respective setup family. Thus, the maximum sequence deviation is:

$$SDO_{max,i}=TSC-SSF_i-WIPO \tag{6}$$

where $SDO_{max,i}$ is the maximum sequence deviation of an order belonging to setup family i (-), TSC the setup cycle time (-), SSF_i the setup family size of setup family i in current setup cycle (-) and WIPO the work in process in number of orders (-).

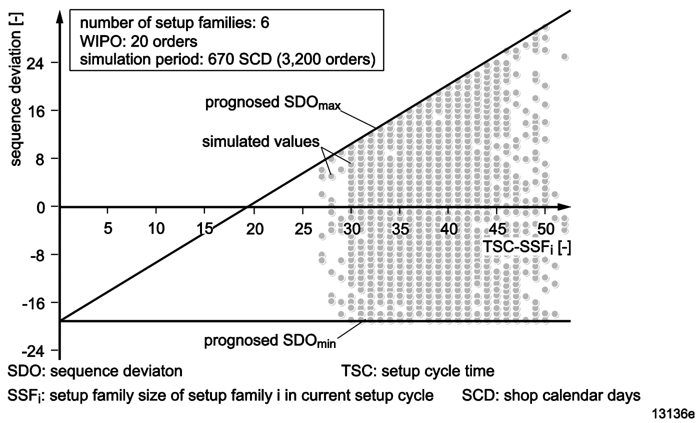

Fig. 3. Sequence deviation for setup cycles with class exhaustion

Since the setup cycle length increases with a higher WIP level, the maximum sequence deviation increases simultaneously. In contrast, the *minimum* sequence deviation is only determined by the WIP level at the workstation. An order is able to overtake maximally the whole WIP:

$$SDO_{min,i}=1\text{-}WIPO \tag{7}$$

where $SDO_{min,i}$ is the minimum sequence deviation of an order belonging to setup family i (-) and WIPO the work in process in number of orders (-).

The absolute value of the minimum sequence deviation linearly increases with the WIP level. As arriving orders are randomly distributed beneath the setup families, the setup cycle time highly varies depending on the amount of bundled orders. As a consequence, the maximum possible delay of an order scatters. Simulation experiments with class exhaustion have been conducted to evaluate the relationship between setup cycle time and sequence deviation. Fig. 3 shows the results of a simulation run with a WIPO of 20 orders. All measured sequence deviations are located within the limits determined by equations 6 and 7.

4 Recommendations for a Logistic Positioning

4.1 Output Lateness due to Setup Cycles

Assuming a random input sequence of orders, the setup family size depends on the WIP level at the workstation. The higher the WIP level the higher is the mean setup family size and thus, the higher the output rate of the workstation [8].

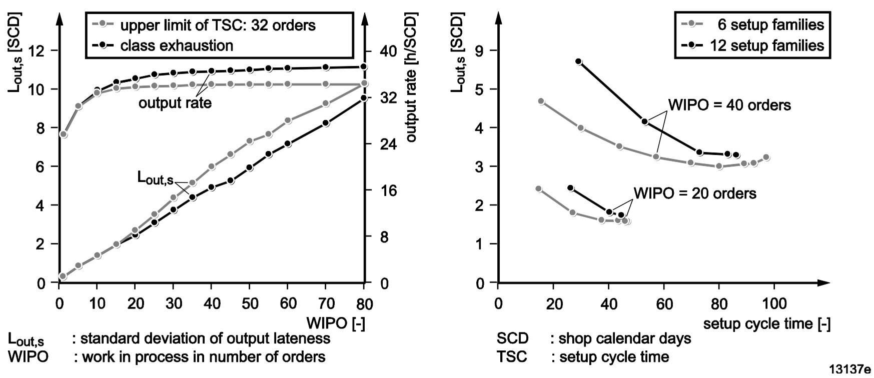

Fig. 4. Standard deviation of output lateness with setup cycles as a function of WIPO (left) and as a function of setup cycle time and number of setup families (right)

Fig. 4 left shows the output rate for the two investigated strategies. With class exhaustion, the output rate constantly increases with a higher WIP level while the truncation rule cuts the output rate increase as soon as the maximum setup family size is reached. The standard deviation of output lateness linearly increases with the WIP level. The reason is that the absolute value of both the maximum and the minimum sequence deviation increase with a higher WIP level (equation 7). Class exhaustion results in a slightly lower standard deviation than truncation rules since orders are never delayed beyond one setup cycle. The truncation rule leads to the effect that an order is occasionally delayed beyond one setup cycle.

Fig. 4 right shows the influence of the number of setup families on the standard deviation of output lateness when the truncation rule is applied. With the same setup cycle time a higher number of setup families causes a higher standard deviation of output lateness. With 12 families the sizes of the single families are lower than with 6 families so the production is cancelled earlier and orders have to wait while 11 other families are processed. Depending on the WIP level, the maximum setup cycle time converges towards a certain value which equals the setup cycle time reached by class exhaustion. With a WIP level of 20 orders the setup cycle time of approx. 46 orders cannot be exceeded.

4.2 Recommendations for a Logistic Positioning

Results show that an active planning is required to limit the standard deviation of sequence deviation and thereby avoiding the delay of orders beyond one setup cycle. A higher WIP level results in a higher standard deviation of sequence deviation for both investigated strategies for setup-optimized sequencing. Although results imply that class exhaustion leads both to a higher output rate and a lower standard deviation, the sequence deviation cause by class exhaustion is often still too high to declare it a systematic sequencing rule.

Applying class exhaustion means that mean setup cycle times only depend on the prevalent WIP level at the workstation. The higher the WIP level, the higher is the reached output rate but also the resulting standard deviation of sequence deviation (see Fig. 4 left). In contrast, the truncation rule has two control parameters: the WIP level and the upper limit for the setup family size. In general, increasing the WIP level offers the potential for a longer setup cycle time. However, if low values for the maximum setup family sizes are fixed, the production of a setup family is cancelled early. This leads to high waiting times for some orders of one or even two setup cycles.

Setup-optimized sequencing has the advantage of increasing a workstation’s output rate. Nevertheless, sequencing heuristics not considering the orders’ due dates increase the standard deviation of output lateness and thereby deteriorate schedule reliability. Applying simple sequencing rules as presented in this paper and investigated by above mentioned authors [10, 11, 12] has a rather negative influence on schedule reliability.

However, if one of the two investigated sequencing rules should be applied, class exhaustion is the more preferable rule as it reaches a higher output rate with a lower standard deviation of output lateness (Fig. 4 left).

5 Summary and Outlook

This paper explains the influence of two different setup-optimized sequencing rules on output lateness: class exhaustion and sequencing with a truncation of setup family sizes.

These rules affect the standard deviation of sequence deviation or output lateness respectively.

Standard deviation caused by class exhaustion linearly increases with the WIP level because a higher number of orders is bundled and thus the potential of mixing up the schedule increases. Sequencing with truncation leads to a disproportionately high increase of the standard deviation with the WIP level. The reason is that the production of a setup family is stopped although orders of the respective family are waiting in the queue. These orders will thus wait at least one whole setup cycle until being processed.

In summary, the application of sequencing heuristics to increase output rate or productivity of a workstation with sequence-dependent setup times without taking due dates into consideration crucially worsens schedule reliability.

Currently, it is planned to develop an easily applicable sequencing rule which takes not only the increase of output rate but also the orders' due dates into account. Thereby, it is guaranteed that setup-optimized sequencing has a positive influence on the output rate while only insignificantly worsening the schedule reliability.

The authors would like to thank Deutsche Forschungsgemeinschaft (DFG) for funding the project "Modeling the influence of set-up cycles on the logistic objectives" (LO 858/9-1).

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