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Determining the potential to improve schedule compliance

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Abstract

High schedule compliance is very important but rarely achieved in make-to-order productions. Especially when orders are released too late (e. g. due to missing raw material) it is challenging to identify how many orders can still be produced in time. This paper shows how companies can identify their potential to increase schedule compliance by earliest operation due-date sequencing. The simple model shows that five parameters determine the potential to increase schedule compliance through sequencing: the input sequence deviation, the WIP level, the number of operations, planned sequence interchanges in the order throughput, and the number of parallel machines.

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1. Introduction

Delivery reliability is the major logistic objective perceived by customers [1]. Naturally, it is necessary to produce on time to achieve a high delivery reliability. Two major factors determine whether orders are produced on time or not: backlog and sequence deviations (see figure 1).

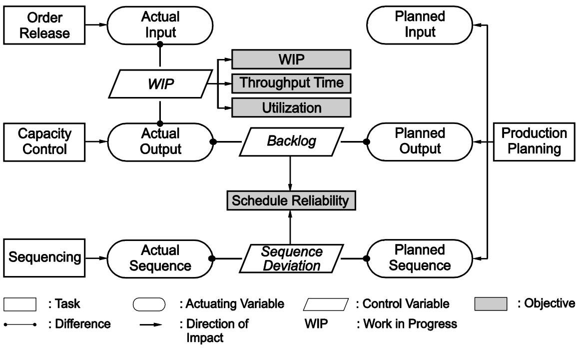

Fig. 1. Manufacturing control model [2]

Both are influenced by the input. When raw material is not available and orders cannot be released on time, a loss in utilization can arise which can result in backlog. But more important is the influence of the order release on sequence deviations. Even if enough orders are released to guarantee the planned utilization, input sequence deviations negatively influence the achievable schedule reliability.

It is well-known, that sequencing influences schedule reliability and that the earliest due date rule supports minimising the maximum lateness on a single machine [3, 4]. While the effect is qualitatively known and proven with simulation experiments [3, 5] simple models that can quantify the effect for complex systems are mostly missing. The model presented in this paper shows how companies can determine which schedule compliance the production can achieve based on present input deviations when sequencing with the earliest-operation-due-date rule.

The paper is structured in five sections. After the introduction, we present the current state of research on which the model described in section three is built upon. Section four evaluates the presented model in simulation runs that show its accuracy. The paper closes with a summary and an outlook in section five.

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2. Current state of research

2.1 Definitions

Lateness is the deviation between the order's actual and planned end date. Consequently, a negative lateness indicates an early order completion and a positive lateness a late order completion.

Schedule reliability is defined as the number of orders that are manufactured within a defined lateness tolerance divided by all orders [2, 6].

$$SR = \frac{NO \ with \ L_{ll} \leq L \leq L_{ul}}{NO} \qquad (1)$$

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

Customers perceive late deliveries more negatively than too early deliveries. Therefore the schedule compliance is more customer oriented than the schedule reliability. It is defined as the number of orders that are manufactured with a lateness of zero or smaller than zero divided by all orders [2].

$$SC = \frac{NO \ with \ L \leq 0}{NO} \qquad (2)$$

where SC is the schedule compliance (%), NO the number of orders, L the lateness (SCD).

2.2 Partitioning lateness

In analogy to the funnel formula, Yu [6] derived the mean lateness as the ratio between the backlog and the output rate:

$$L_m = \frac{BLO_m}{ROUTO_m} \qquad (3)$$

where L_m is the mean lateness (days), BLO_m mean backlog (-), $ROUTO_m$ the mean output rate (orders/SCD).

The equation shows that orders are late on average if a backlog (planned - actual output) develops at a workstation. Naturally, the mean lateness does not reflect the lateness for every single order. Moreover, the influence of sequence deviations is not visible.

It is possible to partition the lateness of an order into backlog-dependent and sequence-dependent lateness [7, 8]. Sequence deviations can cause lateness for single orders. To derive how sequence deviations influence lateness Kuyumcu [7] and Lödding et al. [8] first define the difference between the actual and planned rank as the sequence deviation of an order.

$$SDO_i = rankO_{act,i} - rankO_{plan,i} \qquad (4)$$

where SDO_i is the sequence deviation of order i (-), $rankO_{act,i}$ the actual rank in number of orders (-), $rankO_{plan}$, the planned rank in no. of orders (-).

To determine the orders' ranks, the orders are sorted by the completion dates and ranked with consecutive numbers. Consequently, for the planned ranks orders are sequenced by their planned completion date and for the actual rank by their actual completion date accordingly (Table 1).

Table 1. Defining ranks and calculating sequence deviation

Order	$TOUT_{plan}$	$TOUT_{act}$	$rankO_{plan}$	$rankO_{act}$	SDO
A	10	11	1	2	1
B	11	10	2	1	-1
C	12	12	3	3	0

where TOUT is the time of output (days), $rankO_{act}$ the actual rank (-), $rankO_{plan}$ the planned rank (-).

Figure 2 shows how the sequence- and backlog-dependent lateness can be calculated for single orders with simple trigonometry in the throughput diagram. Thus, the sequence-dependent lateness can be calculated by dividing the sequence deviation by the planned output rate ($ROUTO_{plan}$):

$$L_{SD} = \frac{SDO_i}{ROUTO_{plan}} \qquad (5)$$

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

The backlog dependent lateness follows from the ratio between the backlog at the sequence-dependent output time ($BLO(TOUT_{SD})$) and the actual output rate.

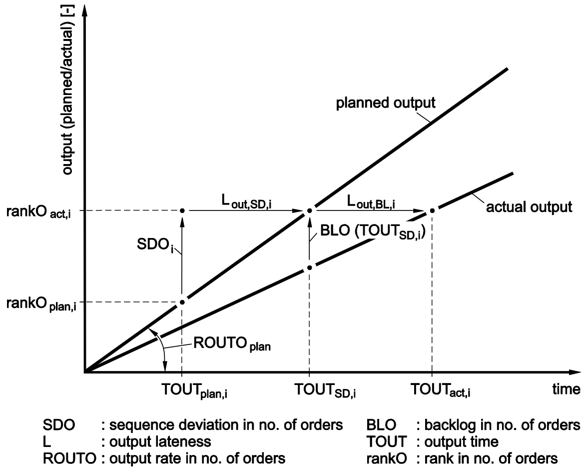


Fig. 2. Determining the sequence- and backlog-dependent lateness [7, 8]

2.3 Determining the minimal sequence deviation for single workstations

Bertsch presented in his dissertation [9] a precise model that shows how lateness can be forecast for different sequencing rules when planned throughput times are constant. In extensive simulation runs, he shows that the complex mathematical model can forecast lateness distributions.

For earliest-operation-due-date (EODD) sequencing Lödding and Piontek [10] derived a simpler model to calculate the minimal output rank and hence a minimal sequence deviation for single workstations without the restriction of constant planned throughput times. Based on the calculated minimal sequence deviation it is possible to forecast the sequence-dependent lateness. As the model is the basis for the presented model extension in section three, the following paragraphs introduce it briefly.

When an order arrives at a workstation and is accelerated maximally, it will either leave the workstation as the next order if the machine is idle at the arrival or it will leave the workstation after the order that occupies the machine at the arrival. Therefore Lödding and Piontek [10] define the minimal output rank as:

$$rankO_{\min,i} = \begin{cases} OUTO(TIN_i) + n + 1, & WS \text{ is occupied} \\ OUTO(TIN_i) + n, & WS \text{ is idle} \end{cases} \quad (6)$$

where $rankO_{min,i}$ is the minimal rank (-), $OUTO(TIN_i)$ the output at the time of input (-), n the number of machines (-), WS workstation.

The following explanations consider a workstation with one machine that is usually occupied at the time of the order arrival. For calculating the minimal sequence deviation the actual rank ($rankO_{act,i}$) in Equation (4) is exchanged by the equation for the minimal rank of an occupied workstation from Equation (5):

$$SDO_{\min,i} = OUTO(TIN_i) + 2 - rankO_{plan,i} \quad (7)$$

where $SDO_{min,i}$ is the minimal sequence deviation (-), $OUTO(TIN_i)$ the output at the time of input (-), $rankO_{plan,i}$ the planned rank of order i (-).

Figure 3 shows two more adaptions of Equation (7): First, the output at the actual arrival ($OUTO(TIN_i)$) can be calculated by deducting the work in process from the input. Second, the input can be exchanged by the actual input rank of the order as they are equivalent.

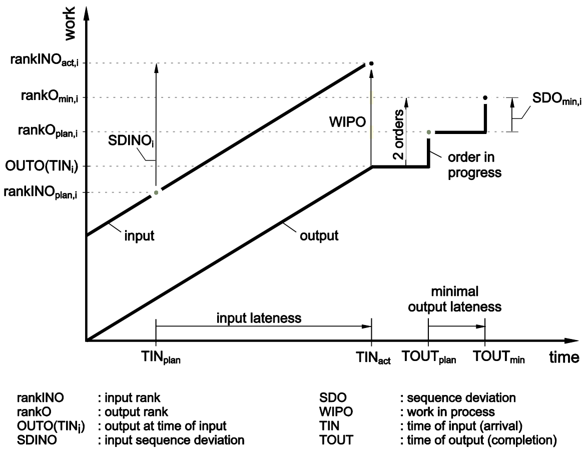


Fig. 3. Determining the minimal output rank in the throughput diagram [10]

Considering that the input sequence deviation is defined accordingly to Equation (4) but with the actual and planned input rank instead of the output ranks, the input rank can be calculated by:

$$rankINO_{act,i} = rankINO_{plan,i} + SDINO_i \quad (8)$$

where $rankINO_{act,i}$ is the actual input rank of order i, $SDINO_i$ is the input sequence deviation of order i (-), $rankINO_{plan,i}$ the planned input rank of order i (-).

Taking both aspects into consideration, Equation (9) follows [10]:

$$SDO_{\min,i} = rankINO_{plan,i} + SDINO_i - WIPO(TIN_i) + 2 - rankO_{plan,i} \quad (9)$$

where $SDO_{min,i}$ is the minimal sequence deviation in no. of orders (-), $rankINO_{plan,i}$ the planned input rank of order i (-), $SDINO_i$ is the input sequence deviation (-), $WIPO(TIN_i)$ the work in process at the time of input of order i (-), $rankO_{plan,i}$ the planned rank of order i (-).

The model assumes that orders are accelerated maximally. Therefore orders arriving on time or ahead of the planned sequence have a negative minimal sequence deviation whereas orders with a delayed input are either accelerated to the minimal positive sequence deviation according to Equation (9) or zero.

$$SDO_{i,SDINO>0} = \max(SDO_{\min,i}; 0) \quad (10)$$

where $SDO_{i,SDINO>0}$ is the sequence deviation of order i, when the input sequence deviation is bigger than 0 (-), $SDO_{min,i}$ the minimal sequence deviation of order i (-).

As the sum of all sequence deviations is always zero [7, 10] all orders with an input sequence deviation of zero or smaller zero are assigned with an average value that guarantees an average forecasting error of zero:

$$SDO_{i,SDINO\le 0} = -\frac{\sum SDO_{i,SDINO>0}}{NO_{SDINO\le 0}} \quad (11)$$

where $SDO_{i,SDINO\le 0}$ is the sequence deviation of order i, when the input sequence deviation is smaller than zero or zero (-), $SDO_{i,SDINO>0}$ is the sequence deviation of order i, when the input sequence deviation is bigger than 0 (-), $NO_{SDINO\le 0}$ the no. of orders with an input sequence deviation smaller than zero or zero.

As described in section 2.2 the sequence-dependent lateness can be calculated by dividing the sequence deviation by the planned output rate. As all orders with an input sequence deviation smaller than 0 are rated with an average negative sequence deviation, it is not possible to calculate the schedule reliability for the workstation. But Lödding and Piontek [10] show with simulation experiments that the schedule compliance can be forecast very well as the number of late orders is forecast accurately.

The following section extends the basic model to a production department with multiple workstations.

3. Determining schedule compliance potential for a production department

Based on the findings for one workstation, the potential of earliest-operation-due-date sequencing can also be calculated for an entire production department. While at a single workstation the minimal output rank is only dependent on the output at the order arrival, the number of machines, and whether the workstation is idle at the arrival or not, it is more complex for production departments.

Assuming an order with two operations at two different workstations that are part of a production department it is necessary to find out how many orders the production department completes while the order is processed at the workstations. While Figure 4a and 4b show the minimal output ranks the order has at the respective workstation, Figure 4c shows how many orders are produced in the production department while the order is processed at the two workstations. In the given example workstation 1 has an output rate of 3 orders per day and workstation 2 works at the output rate of 4 orders per day. Whereas the production department's output rate (6 orders per day) is higher as other workstations also process orders. The time at which the order arrives at the first workstation is equivalent to the time of input (TIN) to the production department. Similarly, the time of completion at workstation 2 is equivalent to the time of output of the production department (TOUT).

While workstation 1 processes the order with the maximal acceleration 4 orders leave the production department. Whereas 3 orders leave the production department while workstation 2 accelerates the order maximally. This behaviour is modelled with the relation of the output rates of the production department and the workstations. This leads to the extension of Equation (6):

$$rankO_{\min,i} = OUTO(TIN_i) + \sum_{i=1}^{m} \frac{ROUTO_{prod}}{ROUTO_{WSi}} \cdot 2 \quad (12)$$

where $rankO_{min,i}$ is the minimal rank (-), $OUTO(TIN_i)$ is the output at the time of input, $ROUTO_{prod}$ the output rate of the production department (orders/day), $ROUTO_{WSi}$ the output rate at the workstation of operation i (orders/day), m the number of operations.

Figure 4 over-simplifies the reality as 1) orders usually do not arrive at the moment when a new order has just been placed on the machine and 2) not all orders have the same operation time. Therefor it is necessary to adapt Equation (12) to improve the model's accuracy. Statistically an order arrives when half of the order on the machine is already processed. So instead of 2 orders we assume that it is one rank for the considered order plus half a rank for the order processed on the machine at the time of arrival. Moreover, to improve the accuracy of the model it is necessary to consider the orders' different work contents. This is done in analogy to the calculation of the ideal minimum WIP by Nyhuis and Wiendahl [11] with the coefficient of variation for the work content (WC_v). This leads to Equation (13):

$$rankO_{\min,i} = OUTO(TIN_i) + \sum_{i=1}^{m} \frac{ROUTO_{prod}}{ROUTO_{WSi}} \cdot (1 + 0.5 \cdot (1 + WC_{v,WSi}^2)) \quad (13)$$

where $rankO_{min,i}$ is the minimal rank (-), $OUTO(TIN_i)$ is the output at the time of input, $ROUTO_{prod}$ the output rate of the production department (orders/day), $ROUTO_{WSi}$ the output rate at the workstation of operation i (orders/day), m the number of operations, $WC_{v,WSi}$ is the coefficient of variation for the work content (-).

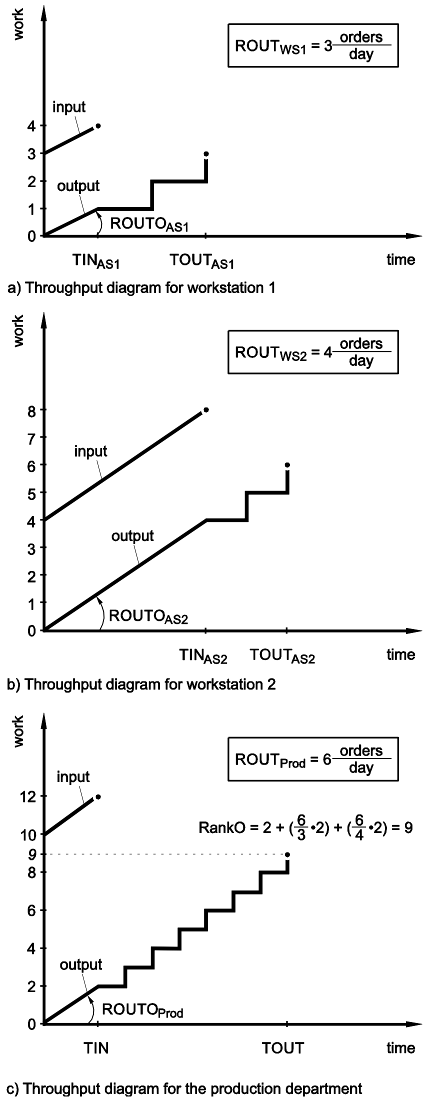


Fig. 4. Determining the minimal output rank for a production department

Adapting Equation (9) with Equation (13) leads to the minimal sequence deviation for an order on production department level:

$$SDO_{\min,i} = rankINO_{plan,i} + SDINO_i - WIPO(TIN_i) + \sum_{i=1}^{m} \frac{ROUTO_{prod}}{ROUTO_{WSi}} \cdot (1 + 0.5 \cdot (1 + WC_{v,WSi}^2)) - rankO_{plan,i} \quad (14)$$

where $SDO_{min,i}$ is the minimal sequence deviation (-), $rankINO_{plan,i}$ the planned input rank of order i (-), $SDINO_i$ is the input sequence deviation (-), $WIPO(TIN_i)$ is the work in process at the time of input (-), $ROUTO_{prod}$ the output rate of the production department (orders/day), $ROUTO_{WSi}$ the output rate at the workstation of operation i (-), m the number of operations, $WC_{v,WSi}$ is the coefficient of variation for the work content (-), $rankO_{plan,i}$ the planned rank of order i (-).

As the work in process at the time of input is not always known, the mean work in process can be used as an approximation. The WIP is usually higher than the average WIP level at the time of the order arrival. Therefore the work in process at the order arrival can be approximated with:

$$WIPO(TIN_i) = WIPO_m + \frac{1}{2} \quad (15)$$

where $WIPO(TIN_i)$ is the work in process at the time of input (-), and the $WIPO_m$ the mean work in process (-).

For calculating the minimal sequence deviation of the orders the extended Equation (14) can be used with the exact WIP-level or with the approximation as shown in Equation (15). To forecast the minimal sequence deviation accurately it is necessary to evaluate the calculated sequence deviation with the Equations (10) and (11) from the basic model. An accurate value for the minimal sequence deviation for every order, and the planned output rate allow the forecast of the number of late orders and so the schedule compliance.

4. Model evaluation

The model is evaluated in a simulation study. The following paragraphs present the results of test series that show the potential of EODD sequencing (Table 2) and the accuracy of the forecasting model (Figures 5 and 6) for a realistic production scenario. The simulation model represents a job shop production with ten workstations and 10 different products with varying routings (3 to 7 operations) and work contents. The simulated job shop works with a high capacity flexibility and almost without backlogs.

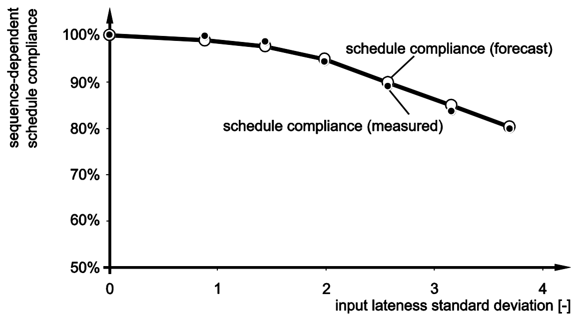
All simulation experiments show that sequencing with the EODD rule has a high potential to increase the schedule compliance of productions. Table 2 comprises the results of two simulation series where the input schedule compliance was varied by alternating the input lateness' variance, and the schedule compliance was measured. The mean improvement potential was 32 % through all simulation experiments with comparatively low WIP-levels (30 orders) and up to 43 % with a doubled WIP-level.

Table 2. Measured schedule compliance improvement potential for earliest-operation-due-date sequencing (work content variation coefficient 0.4)

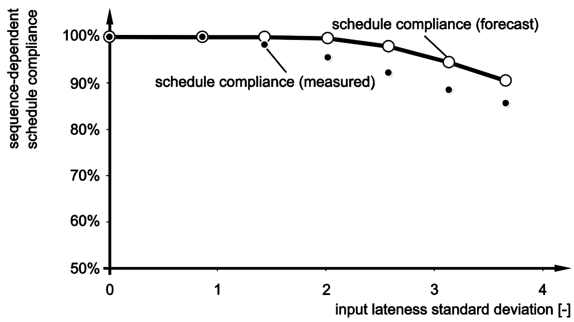
$L_{in,SD}$	SC_{input}	SC_{output} (WIPO=30)	$SC_{potential}$ (WIPO=30)	SC_{output} (WIPO=60)	$SC_{potential}$ (WIPO=60)
0	100 %	100 %	0 %	100 %	0 %
0.9	71 %	100 %	29 %	100 %	29 %
1.4	62 %	99 %	37 %	100 %	38 %
2.0	59 %	94 %	35 %	100 %	41 %
2.6	56 %	89 %	33 %	99 %	43 %
3.2	55 %	84 %	29 %	98 %	43 %
3.7	54 %	80 %	26 %	95 %	41 %

where $L_{in,SD}$ is the input lateness standard deviation (days); SC the schedule compliance; $SC_{potential} = SC_{output} - SC_{input}$.

The results of the simulation study show that the model derived in section 3 can forecast this potential. The first test series shows the simulated and modelled values for the schedule compliance for varying input lateness variances. The error of the model is relatively low (maximum absolute error of 1.3 %) for a moderate work content variation (Figure 5a). With increasing work content variation the model loses accuracy (Figure 5b). The maximum absolute error between the modelled and measured schedule compliance is 6 % at an input variance of 3.1 days and a coefficient of variation for the work content of 1.0.



a) Forecast and measured schedule compliance (work content variation coefficient 0.4)



b) Forecast and measured schedule compliance (work content variation coefficient 1.0)

Fig. 5. Model evaluation with different work content variations

Figure 6 shows exemplarily the error of the forecasting model for orders with a positive input sequence deviation (see Equation (10)) for one simulation experiment. Orders were released with an input lateness variance of 3.1 days and the work content variance coefficient was 0.4. The experiment comprises 702 orders with an input sequence deviation bigger than zero and for 55 % of those orders the lateness was forecast exactly. Moreover, for 89 % of the orders the lateness forecast was in a range of plus or minus one day. This shows exemplarily the accuracy of the model for single orders.

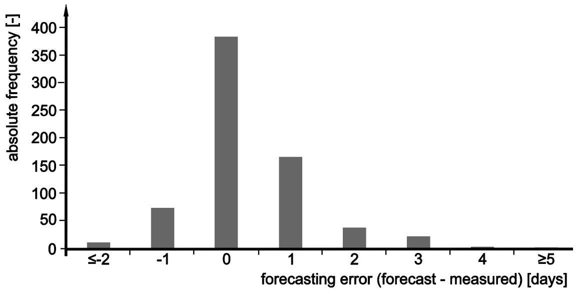


Fig. 6. Forecasting error for orders with positive input sequence deviation

Two factors mainly influence the accuracy of the model: first the WIP-level fluctuation, when using the WIP approximation (Equation (15)) and secondly the relation between the production's output rate and the workstations' output rates has to constant. In the performed simulation experiments the WIP-level's standard deviation is between 5 and 20 orders. In the experiments the forecast quality with the exact WIP is not significantly better than with the approximated WIP value. Though the output rates fluctuated within the experiments, the effect of fluctuating output rates was not investigated in-depth in the performed simulation experiments. However, both factors should be investigated in greater depth in future research.

5. Summary and Outlook

The presented model can be used to analyse the ability of production departments to improve their schedule compliance by applying the earliest-operation-due-date sequencing with respect to input sequence deviations. The presented results from simulation experiments show that 1) there is a high potential to improve schedule compliance by sequencing and 2) that the model is capable to determine that improvement potential with a high accuracy for moderate work content variations. Currently, it is only capable of forecasting the positive lateness values with a high accuracy as the negative values are only described with a single average value for all. Therefore future research will focus on extending the model to also forecast the schedule reliability. Moreover, only the influence of sequence deviations is considered currently. Modelling backlog lateness and integrating both models would lead to a powerful tool for industry to completely analyse their schedule reliability potential.

Acknowledgements

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