View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Institutionelles Repositorium der Leibniz Universität Hannover

CPSL CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2020

1st Conference on Production Systems and Logistics

Deriving of Sequencing Strategies for Multi-Stage Productions Supported by Logistic Models and Software Tools

Alexander Mütze[1], Peter Nyhuis[1]
[1] *Institute of Production Systems and Logistics (IFA), Leibniz University Hannover, Germany*

Abstract

Sequencing as a core task of production control has a significant influence on the logistical performance and efficiency of a single work system. Particularly in the presence of sequence dependent setup times, systematic sequencing can increase the productivity of a work system by saving them. This, however, leads to a decreasing schedule reliability of the work system, which creates an area of conflict. In recent years, mathematical models have been developed at the Institute of Production Systems and Logistics (IFA) that describe the influence of different sequencing rules on the schedule reliability and productivity of a work system. In a further step, these single so-called partial models can be linked with each other. This allows a calculation of the lateness behaviour of a multi-stage production in dependency of the sequencing rules assigned to the individual work system and thus of the overall sequencing strategy.

This paper presents the possibilities of linking different logistic models in order to quantify the influence of sequencing on logistic target values as well as two software tools by which the impact and combination of various sequencing rules can be examined based on production feedback data or by means of a generic supply chain. As a result, it is possible to assess different sequence configurations of a multi-stage production and thus strategically align the production in the area of conflict between productivity and schedule reliability.

Keywords

Production Planning and Control; Sequencing; Supply Chain Configuration; Software Tool; Demonstrator

1. Introduction

Manufacturing companies today are increasingly faced with the challenge of offering an ever-larger number of product variants and reacting to individual customer requirements while at the same time satisfying the demands for short delivery times and high due date compliance [1]. For companies in the manufacturing industry, the best possible fulfilment of these requirements at the lowest possible cost represents a main logistical challenge [2]. In order to meet these market requirements, high productivity in production is necessary, which can be achieved by eliminating processes that do not add value [3]. In addition to factors affecting the entire production process, such as unnecessary transports or multiple handling of products, scientific research and industrial optimization projects also focus non-value-adding activities on individual work systems. This includes in particular the handling and management of unavoidable machine setup processes [4–7].

In general, setup processes are required in case of switching between two orders. For example, a milling machine usually requires the tool table to be rebuild, while manual workstations may require fixtures to be

DOI: https://doi.org/10.15488/9661 publish-Ing.

set up or tools to be changed. The setup time linked to the processes, during which no physical processing of work pieces takes place, can be subdivided into two components: a sequence dependent component, whose amount depends on which order was previously processed, and a sequence independent component, whose amount does not depend on the predecessor process. In case that parts of the setup time are sequence dependent and technologically (e.g. through externalization) or organizationally unavoidable, the setup time at a work system can be reduced by a setup time optimized sequence in order to achieve productivity gains [7,8]. This further means that products or orders that have similar setup requirements, e.g. require the same clamping system or a very similar tool set, can thus be assigned to a so-called setup family and have to be processed successively one after the other in order to decrease the total setup efforts at the work system [5,8].

However, the productivity increases due to a reduction of incurring setup times by setup-optimized sequencing are accompanied by a negative impact on the lateness behaviour of work systems, since such a prioritization of orders lead to an increase in the spread of the lateness in the output of the work systems [6,8,9]. As a result, the important logistic objective of single work systems as well as of the whole production schedule reliability is influenced directly and in a negative way [10].

In comparison to setup time optimizing sequencing rules, due date-oriented sequencing rules have a positive impact on the schedule reliability of a work system, as they reduce the spread of the lateness in the output compared to the spread in the input of the system [11,12]. Nevertheless, prioritization by due-dates results in no systematic sequencing in the sense of a setup time optimization takes place, because reductions in setup time only occur coincidentally and the intensity is thus significantly lower. In addition, it should be noted that sequencing and thus prioritising orders by due-dates provokes a more or less strong deviation from the incoming sequence of the orders, depending on the lateness in the input. Consequently, a more or less strong re-sorting of the orders is required, leading to rising searching and sorting efforts. As a result, a reduction in productivity may occur at the work systems, whose severity depends for instance on the ratio of necessary efforts to the average operation time.

The order sequencing according to a First-in-First-Out (FIFO) logic on the contrary does not lead to any change in the order sequence between the input and the output at a work system [13]. Nonetheless, sequencing according to FIFO leads also to randomly occurring setup time savings [5]. An actively intended impact on the productivity as well as on the lateness behaviour and thus on the schedule reliability of a work system is therefore not derivable.

Consequently, it can be stated that order sequencing, as part of the major task production control, takes place in a field of tension between the cost-oriented objective productivity and the performance-oriented objective schedule reliability [5,9]. Due to the high relevance of the adherence to delivery dates, as one of the most important indicators for assessing logistical performance [14], and the influence of productivity on economic efficiency a target-oriented positioning in this field of tension through the selection of suitable sequencing rules in the planning and control of production systems is of great importance.

From the perspective of the practical user, however, the question arises as to how the various sequencing rules and possible configurations influence the schedule reliability and productivity on an explicit work system and, in particular, how they influence further the entire production consisting of several work systems and stages. Only by the possibility of building-up a calculable chain of action, it is possible to configure a closed multi-stage production in such a way that based on the general preconditions, e.g. requirements for throughput and delivery times, and strategic specifications, the best possible positioning in the area of conflict between productivity and schedule reliability can be found.

At this point, this contribution applies and presents the linking logic between the single logistic models developed at IFA for the description of the impact of sequencing rules on the logistic objectives as well as two software tools with whose help an exact calculation or a generic and didactic discourse is made possible.

2. Sequencing at work systems and its influence on logistic objectives

The following section gives a brief overview of order sequencing at work systems and subsequently deals with the influence of different sequencing rules on the lateness behaviour and productivity of work systems. However, this chapter can only give a general overview about the individual models and their derivation. Therefore, reference is made to the authors and publications at the specific passages.

2.1 Order sequencing at work systems

Sequencing rules for the formation of order sequences at work systems determine the priority with which orders are to be processed [15]. Through this prioritization according to specific criteria, the processing sequence of the orders is determined. On the one hand, this can lead to deviations from the planned order sequence created by detailed production planning. On the other hand, existing deviations from the planned sequence caused by predecessor processes can be partially compensated [16]. According to various studies, the most frequently used sequencing rules in industrial practice are the First-in-First-Out (FIFO) rule, followed by schedule-oriented and setup time-optimizing sequencing rules. [17,18]

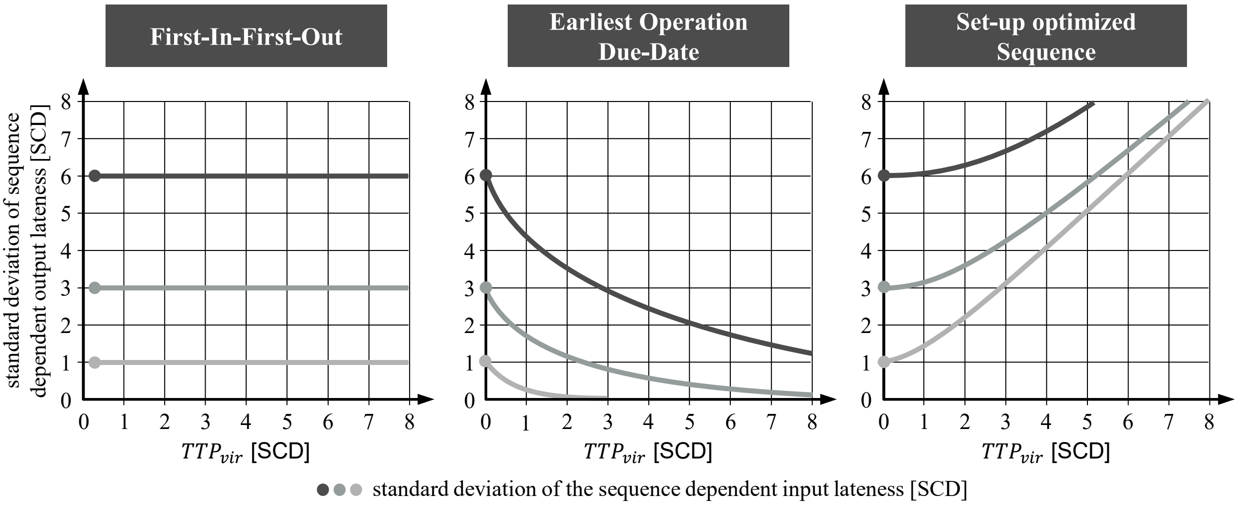
If FIFO is used, orders are processed in accordance to the actual sequence in the input of a work system. Consequently, the order with the highest waiting time in the waiting queue is given the highest priority. Schedule-oriented sequencing rules are considering the planned completion or planned dispatching dates of orders determined by detailed production planning when prioritizing orders. One of the most used and known schedule-oriented sequencing rule is the earliest operation due-date (EODD) rule. Out of all waiting orders, it assigns the highest priority to the order with the earliest planned operation due-date. [12,13,15]

In contrast, setup-optimizing (SO) rules aim to reduce setup times and setup costs. Consequently, this is only achievable if the setup times at a work system have a distinct sequence dependent component for the orders of the current order spectrum and thus a reduction of the total setup time at the work system is possible due to reprioritization of the orders. For a more detailed description of various rules for the creation of setup time optimizing order sequences, reference is made here to [4–6,8–10].

2.2 Influence of sequencing rules on the lateness behaviour of work systems

For sequencing in accordance to the FIFO, EODD as well as to the SO sequencing rule, BERTSCH developed logistic impact models [11,19]. These models enable a description of the lateness behaviour of work systems under consideration of structure-relevant variables and are based on two fundamental principles.

The first fundamental modelling principle is the differentiation between backlog-related and sequence related lateness at a work system. The backlog-related lateness, as the name suggests, is influenced in particular by the backlog of a work system compared to the production plan. The sequence related lateness, which is in the focus of this contribution, can be derived directly from the prioritization of work orders and the related sequence changes compared to the planned sequence. The exact derivation of these two components can be found in [11]. The second fundamental modelling basis is that the output lateness behaviour of a work system can be described by an output lateness distribution and by the distribution key figures mean output lateness and standard deviation of output lateness. Further investigations have shown that sequencing, if it is independent of work content and any productivity gains are compensated by balancing capacity and load, only leads to a change in the standard deviation but not to a shift of the mean value of output lateness. The reason for this is that any acceleration of an order as a result of a sequence reversal also leads to a corresponding deceleration of one or more other orders. [11,20]



Approximated formulas for the determination of the standard deviation of sequence dependent output lateness

$\sigma_{L_{out,SEQ}} \cong \sigma_{L_{in,SEQ}}$

$\sigma_{L_{out,SEQ}} \cong \sigma_{L_{in,SEQ}} * \sqrt[0,6]{1-\left(\frac{TTP_{vir}}{3 * \sigma_{L_{in,SEQ}}}\right)^{0,6}}$

$\sigma_{L_{out,SEQ}} \cong \sqrt{\left(\sigma_{L_{in,SEQ}}\right)^{2} + \left(TTP_{vir}\right)^{2}}$

$\sigma_{L_{out,SEQ}}$	standard deviation of the sequence dependent output lateness [SCD]
$\sigma_{L_{in,SEQ}}$	standard deviation of the sequence dependent input lateness [SCD]
TTP_{vir}	mean virtual throughput time [SCD]

Figure 1: Partial Models for the calculation of the sequence dependent output lateness of a work system in dependency of the mean virtual throughput time and the sequence dependent input lateness with approximated formulas (extended; illustration based on [9,10,21])

In recent research activities at IFA, logistic models have been developed based on the findings of BERTSCH using Littles Law [22] to quantitatively describe the relationship between the work in process (WIP) at a work system and the resulting standard deviation of the sequence dependent output lateness in dependence on the sequencing rule used [5,9,11,21]. The mathematical partial models, valid in case of constant planned throughput times, for the sequencing rules FIFO, EODD and SO, verified by means of a parameter study, are shown in Figure 1 in the form of ISO-curves for the standard deviation of the sequence dependent input lateness of 1, 3 and 5 shop calendar days (SCD). Below the illustrated ISO-curves, the approximated calculation formulas for the calculation of the standard deviation of the sequence dependent output lateness of a work system are given for each sequencing rule. The WIP of a work system is modelled in accordance with LITTLE [22] by the mean virtual throughput time (TTP_{vir}) as a parameter of time, which is calculated by dividing the mean work in process ($WIPO_m$) measured in number of orders by the unweighted mean output rate ($ROUTO_m$) measured in number of completed orders per SCD. Thus, it describes how long an order stays on average at a work system [19]. The standard deviation of the sequence dependent input lateness is an external or given influencing variable in the models and can be influenced, for example, by predecessor processes or the selected method and parameterization of order release, which influences the input sequence of orders at a work system [16].

The models confirm the assertions made in chapters 1 and 2.1. Thus, given constant planned throughput times, it can be recognised that the sequence dependent standard deviation of the lateness in the output of a work system is independent of the virtual throughput time in the of FIFO sequencing and depends exclusively on the sequence dependent standard deviation of the lateness in the input. The reason for this is that sequencing according to the FIFO logic does not result in sequence reversals and therefore the sequence in the output corresponds to the sequence in the input of a work system. However, if sequences are made in accordance to the EODD rule, sequence reversals between input and output can be observed in order to re-establish the planned sequence as far as possible resulting in a decreasing standard deviation of the sequence dependent lateness in the output. Hereby, it applies that the larger the virtual throughput time at a work system is the more deviations between the input and the originally planned sequence can be compensated. Furthermore, the model shows that the marginal utility of increasing the virtual throughput time decreases and the standard deviation of the sequence dependent lateness in the output asymptotically approaches the x-axis (see Figure 1). This result is explainable by the assumption of a normal distribution for the lateness distribution.

If the processing sequence at a work system is created using a setup-optimizing (SO) logic, the orders are placed in a random sequence from a scheduling point of view. The reason for this is that the distribution of setup time relevant characteristics like the affiliation to setup families is independent of the due-dates of the orders. As Figure 1 and the related formula show, converges the standard deviation of the sequence dependent lateness in the output asymptotically against the virtual throughput time with their rise. The prerequisite for the application of the partial model for setup-optimized sequencing is that the productivity gained, which will be discussed in the next chapter, is compensated to the extent that the virtual throughput time and thus the operating point of the work system remain fixed on the ISO-curve.

For a more detailed description of the influence of the described sequencing rules on the standard deviation of the sequence dependent lateness in the output of a work system as well as the detailed derivation of causal relationships between the discussed influencing variables, reference is made here to [5,9–11,21].

2.3 Influence of sequencing on productivity

The productivity gain on a work system that can be achieved by the creation of setup-optimized order sequences are describable according to various research activities of NYHUIS and MAYER [5,10]. A basic assumption of NYHUIS and MAYER is that the order spectrum on a work system can be divided into setup families. Within such a setup family, an order change at a work system does not cause any setup time. However, the setup time for changing between orders of two different setup classes depends on the predecessor/successor relationship of these setup families, which is often not symmetrical. For the modelling of setup-optimized sequencing, NYHUIS and MAYER are using a rule that chooses the next setup family according to the Minimum Marginal Setup Time [5,23]. According to this rule, a new family is chosen by the lowest quotient of setup time and the number of jobs belonging to that family waiting in the waiting queue at this moment, if the current setup family is empty.

In general, the productivity gain of a work system achievable through setup-optimized sequencing can result from two effects illustrated in Figure 2. On the one hand, there may be a setup time saving resulting from the fact that an order is produced directly after an order of the same setup family (Figure 2 case "II"). This saves the setup time of the order completely and the processing can take place directly after completion of the previous order. Another possibility is a setup time reduction when switching between the different setup families, which results from a sophisticated, setup time reducing sequence creation due to the sequence dependency of the setup times (Figure 2 case "I"). As an example, it can be seen in the figure that the sequence formation C-B-A-(C) results in a total setup time of 57 units per cycle, while another order sequence leads to significantly longer setup times. It follows that sequencing in the order A-B-C-(A) would result in a setup time of 75 units per cycle.

In general, it applies that, given the same virtual throughput time at the work system is considered, the effect of setup time savings dominates with few setup families, while with many setup families the setup time reduction is dominant. This is explainable by the constant length of the queue in front of the work system and the accompanying probability of having more than one order of a setup family in the waiting queue [5].

At this point, reference is made to [5,10] for the detailed derivation of the cause-effect relationships and the calculation formulas which would go beyond the scope of this paper due to their complexity and the need for explanation.

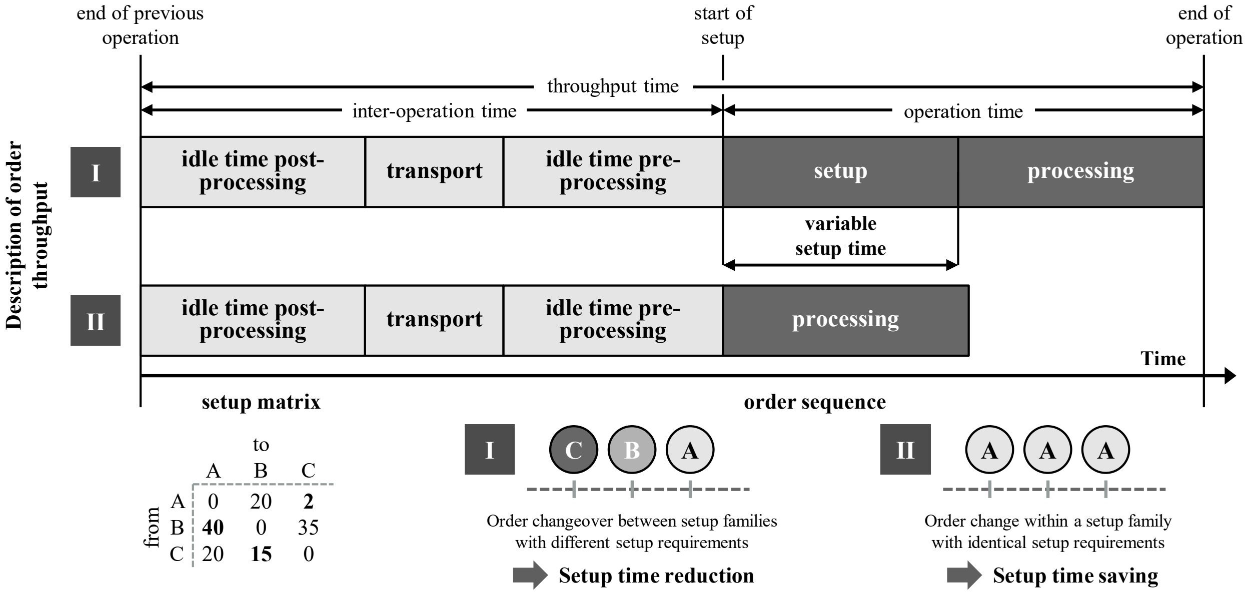


Figure 2: Comparison of Setup time reduction and Setup time saving (based on [5,24])

In summary, it can be concluded that productivity gains can be achieved with setup-optimized sequencing, while these are accompanied by an increase in the standard deviation of the sequence dependent lateness in the output. Thus, there is a conflict of objectives between productivity and schedule reliability and there is a need for the strategic positioning of a company in this area of tension [5,9,10].

3. The logic for linking the described models to a chain of action

The partial models presented in chapter 2 can be linked with each other via different coupling sizes in such a way that it is possible to calculate the impact of sequencing strategies on schedule reliability and productivity for a multi-stage production and thus for a production area. Therefore, the developed partial models for the calculation of the impact of sequencing rules on the lateness behaviour of work systems can be linked via the coupling size standard deviation of sequence dependent lateness. The models developed by NYHUIS and MAYER to calculate possible productivity gains can be linked via the virtual throughput time with the partial model to describe the impact of a setup-optimized sequencing on the lateness behaviour of a work system.

Figure 3 shows as an example a production area consisting of three linearly linked work systems. The logic for linking the different models is explained using this example. The production area, and thus the first work system, receives the orders with a standard deviation of sequence dependent lateness of 3 SCDs. The first work system processes the incoming orders according to the FIFO logic, so that the orders leave the first work system also with a standard deviation of sequence dependent lateness of 3 SCD and reach the second work system. A setup-optimized sequencing is selected for the second work system, as the aim is to increase the productivity of the work system. Reasons for this could be, for example, that additional shifts on this system should be reduced in the future. On the basis of the virtual throughput time, which has an average amount of 5 SCD on this work system at the time under consideration, it follows that the orders leave the work system with a distribution with a standard deviation of sequence dependent lateness of approx. 6 SCD and reach the last work system of the production area. In return, a productivity gain of 20% can be expected. At the last work system of the production area EODD is chosen as sequencing rule in order to reduce the standard deviation of sequence dependent lateness in the output of the work system and thus of the entire production area. It follows, given a virtual throughput time of 3 SCD, that the orders leave the production area with a lateness distribution according to a standard deviation of sequence dependent lateness of 3 SCD.

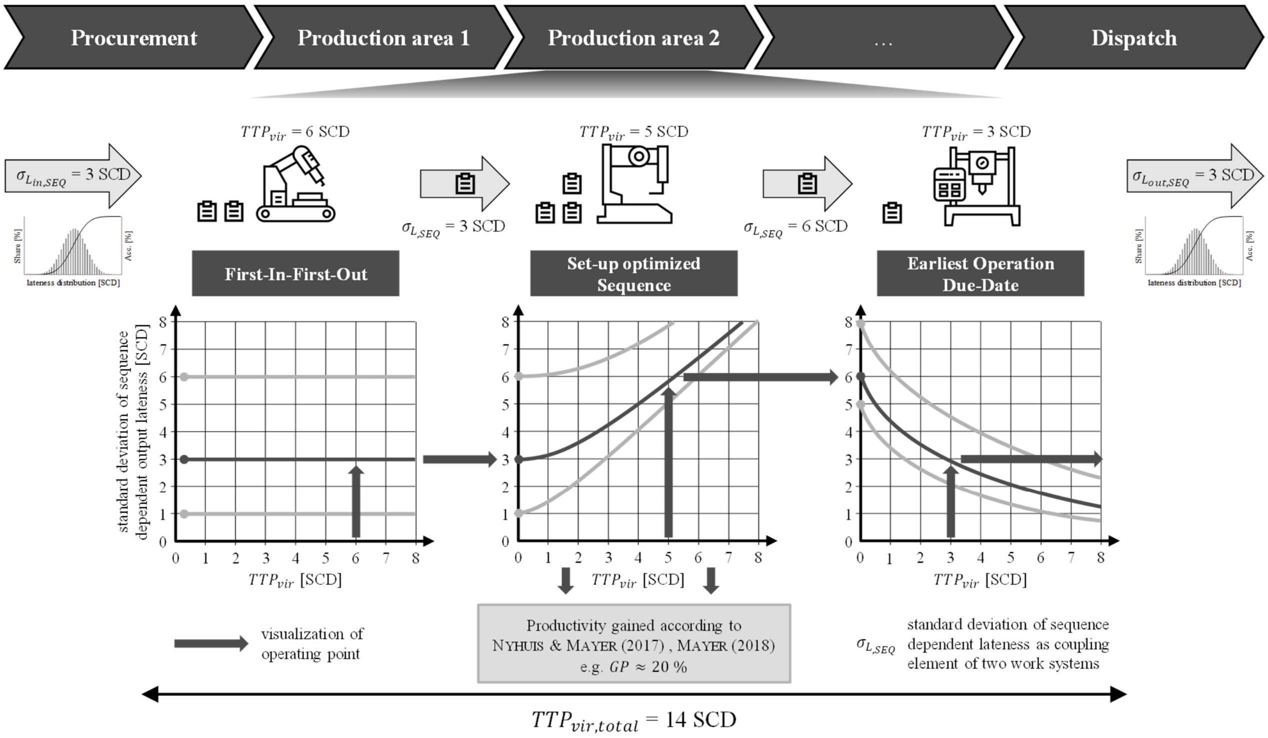


Figure 3: Example for linking the individual logistic models to calculate the influence of sequencing on logistic objectives in a production area

As the example shows, the impact of the sequencing rules on the production area can be calculated by linking the models by means of the coupling variables standard deviation of sequence dependent lateness and virtual throughput time. The models can, however, be used further to calculate various different configuration-cases and help to develop a sequencing strategy for a production area and thus a multi-stage production. For example, the spread of lateness in the output of the production area could be further reduced by an increase of the virtual throughput time through planning measures at work system 3. In addition, the productivity gain at work system 2 could be further increased with the consequences for the standard deviation of sequence dependent lateness in the output of the system already discussed. To ensure a constant total virtual throughput time, a reduction at work system 1 equivalent to the possible increases could be carried out objective neutral.

To enable strategic positioning based on actual production feedback data and to support users in designing their production, two intuitive software tools for use in practice were developed at IFA providing the findings and research results described above. Both tools are presented in the following.

4. Software tools for analysing & describing the influence of sequencing rules in production

The developed software tools were both programmed in Microsoft Excel® using the programming language Visual Basic for Applications (VBA). This ensured that the tools can be used in as many companies as possible and that no software licenses have to be purchased to use the tools. In the following, the presentation of both tools is limited to their general functionality, the adjustable parameters as well as the necessary input variables. The first developed tool gives the user the possibility to carry out a what-if analysis based on production feedback data for a real multi-stage production and to determine the impact of sequencing strategies on a production area. In this tool, the main emphasis is on the lateness behaviour of the single work systems as well as on the whole production. The second programmed tool is comparable to a demonstrator and contains a generic reference supply chain enabling studies of the influence of sequencing strategies on a multi-stage production in an easy way. It also includes the possibility to calculate the possible productivity gain through setup-optimized sequencing according to NYHUIS and MAYER [5,10].

4.1 Software tool for analysis on the basis of production feedback data

The developed software tool enables the user to calculate the impact of individual sequencing strategies based on production feedback data for a production area of up to 80 work systems. As input data, the tool requires, on the one hand, the production feedback data for the actual input and output at the work systems, sorted according to order and process number and assigned to a work system of the area, as well as the corresponding planned values and the work content of the orders at every work system. Furthermore, a capacity table can be inserted, that is used by the tool to determine all SCDs per work system in the time period provided by the inserted production feedback data.

Using the entered input variables, the tool automatically calculates the predecessor/successor relationships and thus the material flow relationships between the individual work systems and establishes an impact chain between the work systems. Here, a specially developed algorithm is applied which eliminates circular references between work systems and thus enables a clear direction of action from the entrance to the exit of the production area, so that the calculation of the impact of sequencing rules is made possible.

In the output, the tool can display distribution diagrams and key figures for each work system related to the theory of the presented partial models for the examination of the impact of sequencing rules on the sequence dependent lateness behaviour. In addition, the most frequent successors of a work system are determined.

Based on the presented values and diagrams and the made calculations in the backend, the user can change the sequencing rule (FIFO, EODD or SO) for every work system, resulting in an automated presentation of the changed distribution and key figures by the tool considering the inserted production feedback data. Furthermore, the user can set any sequencing rule in order to define a sequencing strategy, which is used to recalculate the distribution and key figures in the input of every work system and the entire production area. This allows the user to set up a sequencing strategy for his production area. For comparison purposes, the values for the case of a "pure" sequencing strategy (all work systems create the order sequence according to the same logic) are also compared at the observation level of the entire production.

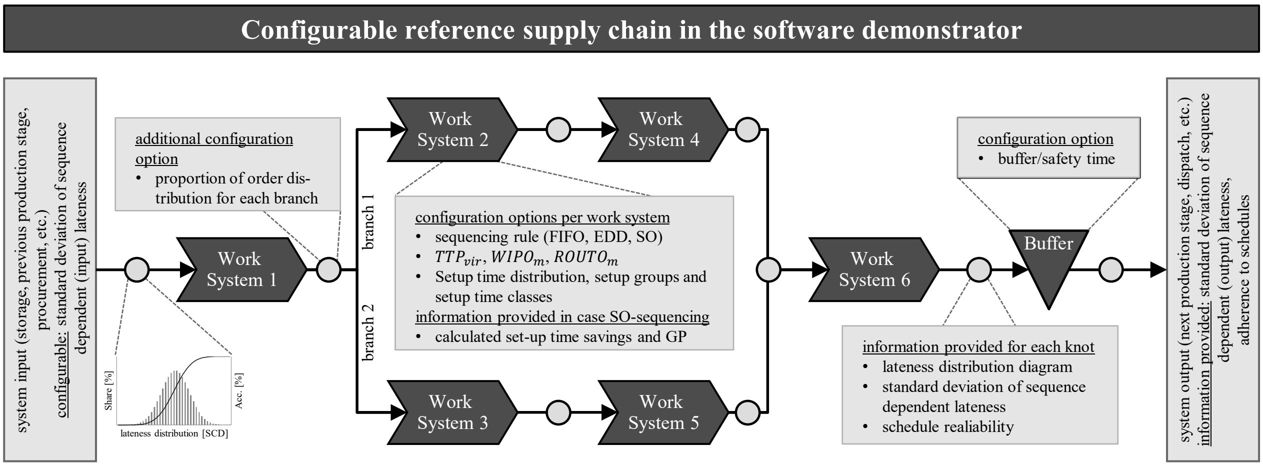
To use the software tool, it is necessary to provide well-prepared production feedback data. In order to enable the practical user to derive initial findings for the configuration of sequencing in his own production, even without the available or sufficiently consistent feedback data, the second software tool was developed.

4.2 Software tool based on a generic supply chain for instant use

The second software tool, as mentioned above, comprises a generic reference supply chain consisting of one input, six work systems and a buffer towards the output (see Figure 4). In the process of creating the software tool care was especially taken while designing the reference supply chain to cover as many order flow relationships as possible but also providing an easy and understandable application. For this reason, one spreading point (behind work system 1) and one merging point (in front of work system 6) are established.

The user can set the individual parameters in the software tool by simply entering numerical values or using logical connected buttons. The configuration options range from the “external” standard deviation of the sequence dependent lateness in the input, the configuration of the individual work systems (virtual throughput time, WIP, output rate, sequencing rule) to the proportion of the order flow between the upper (work system 2 & 4) and the lower branch (work system 3 & 5). In addition, the expected productivity gain according to NYHUIS and MAYER under variable configurations can be calculated. Therefore the number of setup families as well as the distribution form of the setup time (Erlang distribution, equal distribution, and others), which have a direct impact on the possible productivity gain, are included as configurable values.

An especially noteworthy element is the buffer, which has been integrated as an additional supply chain element and makes it possible to integrate a safety time into the consideration of the lateness behaviour of a multi-stage production. This allows to auxiliary integrate the adherence to delivery dates into considerations.



$WIPO_m$ mean WIP [number of orders]

$ROUTO_m$ mean output rate of the work system [number of orders / SCD]

GP gained productivity [%]

Figure 4: Schematic representation of the elements and configuration possibilities within the software tool

Equivalent to the first software tool, the user can view various key figures and distributions and influence the result in the system output by changing the parameters mentioned. Any changes are executed by the tool in real time so that the user gets direct feedback. For easier operation and a better understanding, the software tool also includes an integrated operating manual.

5. Conclusion

In this paper, the theoretical foundations for describing the impact of sequencing rules in relation to the virtual throughput time on the lateness behaviour and the productivity for single work systems were discussed and the possibilities for linking the models in an easy way via coupling sizes were presented. Thereby it is made possible to calculate the influence of sequencing rules on the logistic objectives schedule reliability and productivity in a multi-stage production and to derive an individual elaborated sequencing strategy.

The considerations made in this paper always assume that any productivity gains are compensated by measures of production planning and control in the interest of having a stable system (stock and throughput time). The same also applies to productivity losses due to, for example, sorting efforts in case of sequencing in accordance to the EODD logic, which are not included in the models and were therefore not discussed further in this contribution, but should not be neglected in practice.

In order to support the practical user in deriving a sequencing strategy for his production area, two lightweight software tools with different approaches have been developed at the Institute of Production Systems and Logistics, which can be downloaded from the website http://go.lu-h.de/sequencing.

Acknowledgements

The contribution was created within the knowledge transfer project "Logistics-Oriented Sequencing strategies for multi-stage production", funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 409759709. In addition, the authors would like to thank the Koenig & Bauer Industrial AG & Co. KG as transfer partner for the valuable input and contribution to the project.

For the correctness of the calculations in the software tools, no liability is taken over by the authors nor the Institute of Production Systems and Logistics belonging to Leibniz University Hannover.

References

[1] Lindemann, U., Reichwald, Reichwald, R., Zäh, M. (Eds.), 2006. Individualisierte Produkte — Komplexität beherrschen in Entwicklung und Produktion. Springer, Berlin, Heidelberg.

[2] Schuh, G., 2007. Effizient, schnell und erfolgreich: Strategien im Maschinen- und Anlagenbau. VDMA-Verl., Frankfurt, M., 94 pp.

[3] Ōno, T., Bodek, N., 1988. Toyota production system: Beyond large-scale production. Productivity Press, New York, NY, 143 S.

[4] Almomani, M.A., Aladeemy, M., Abdelhadi, A., Mumani, A., 2013. A proposed approach for setup time reduction through integrating conventional SMED method with multiple criteria decision-making techniques. Computers & Industrial Engineering 66 (2), 461–469.

[5] Mayer, J., 2018. Quantitative Modellierung logistischer Auswirkungen von rüstoptimalen Auftragsreihenfolgen an Arbeitssystemen. Dissertation, 255 pp.

[6] Engehausen, F., Lödding, H., 2017. Modeling Lateness for Workstations with Setup Cycles, in: Lödding, H., Riedel, R., Thoben, K.-D., Cieminski, G. von, Kiritsis, D. (Eds.), Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing. IFIP WG 5.7 International Conference, APMS 2017, Hamburg, Germany, September 3-7, 2017, Proceedings, Part I, pp. 509–517.

[7] Allahverdi, A., 2015. The third comprehensive survey on scheduling problems with setup times/costs. European journal of operational research: EJOR 246 (2), 345–378.

[8] Eilmann, J., Münzberg, B., Nyhuis, P., 2013. Optimierung der Rüstreihenfolge. PRODUCTIVITY Management 18 (5), 61–64.

[9] Mayer, J., Nyhuis, P., 2017. Describing the influence of set-up optimised sequencing on output lateness of workstations. Production Planning & Control 28 (10), 791–801.

[10] Nyhuis, P., Mayer, J., 2017. Modelling the influence of setup optimized sequencing on lateness and productivity behaviour of workstations. CIRP Annals 66 (1), 421–424.

[11] Bertsch, S., 2015. Modellbasierte Berechnung der Termintreue. Zugl.: Hannover, Univ., Diss., 2014. PZH-Verl., Garbsen, 238 pp.

[12] Lödding, H., Piontek, A., 2017. The surprising effectiveness of earliest operation due-date sequencing. Production Planning & Control 28 (5), 459–471.

[13] Bertsch, S., Schmidt, M., Nyhuis, P., 2014. Modeling of lateness distributions depending on the sequencing method with respect to productivity effects. CIRP Annals 63 (1), 429–432.

[14] Mayer, J., Pielmeier, J., Berger, C., Engehausen, F., Hempel, T., Hünnekes, P., 2016. Aktuellen Herausforderungen der Produktionsplanung und -steuerung mittels Industrie 4.0 begegnen: Studienergebnisse. PZH Verlag, Garbsen, 24 pp.

[15] Conway, R.W., Maxwell, W.L., Miller, L.W., 1967. Theory of scheduling. Addison-Wesley, Reading, Mass., X, 294 S.

[16] Lödding, H., 2013. Handbook of manufacturing control: Fundamentals, description, configuration. Springer, Heidelberg, Online-Ressource (XXV, 577 S.).

[17] Seitz, M., Härtel, L., Hübner, M., Merkel, L., be Isa, J., Engehausen, F., Meluzov, N., Rost, R., Schmidhuber, M., Sauermann, F., Hünnekes, P., 2018. PPS-Report 2017/18: Studienergebnisse, 1. Erstausgabe ed. TEWISS, Garbsen, 42 Seiten.

[18] Schuh, G., Stich, V. (Eds.), 2013. Produktion am Standort Deutschland: Ergebnisse der Untersuchung 2013, Ausg. 2013 ed. FIR an der RWTH Aachen, Aachen, 61 pp.

[19] Nyhuis, P., Wiendahl, H.-P., 2009. Fundamentals of production logistics: Theory, tools and applications, Softcover re-print of the hardcover 1st edition 2009 ed. Springer, Berlin, Heidelberg, 312 pp.

[20] Lödding, H., Kuyumcu, A., 2015. Modelling schedule reliability. International Journal of Production Research 53 (9), 2871–2884.

[21] Bertsch, S., Felix, C., Nyhuis, P., 2016. Modeling the Sequence Dependent Lateness of a Single Workstation. AMR 1140, 443–448.

[22] Little, J.D.C., 1961. A Proof for the Queuing Formula: L= λ W. Operations Research 9 (3), 383–387.

[23] Pickardt, C.W., Branke, J., 2012. Setup-oriented dispatching rules: A survey. International Journal of Production Research 50 (20), 5823–5842.

[24] Heinemeyer, W., 1974. Die Analyse der Fertigungsdurchlaufzeit im Industriebetrieb. Techn. Univ. Hannover, Dissertation.

Biography

Alexander Mütze, M.Sc. (*1994) studied industrial engineering at Leibniz University Hannover and has been working as a research assistant at the Institute of Production Systems and Logistics (IFA) since 2018 in the field of production management with a focus on production planning and control.

Prof. Dr.-Ing. habil. Peter Nyhuis (*1957) studied mechanical engineering at the Leibniz University Hanover and subsequently worked as a research associate at the Institute of Production Systems and Logistics (IFA). After obtaining his Dr.-Ing. doctorate, he was habilitated before working as an executive in the field of supply chain management in the electronics and mechanical engineering industry. He has been head of IFA since 2003.