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SIMULATION BASED APPROACH FOR RECONFIGURATION AND RAMP UP SCENARIO ANALYSIS IN FACTORY PLANNING

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ABSTRACT

Structural changes in production entail a potential economic risk for manufacturing companies. It is necessary to identify a suitable strategy for the reconfiguration process and to continue to meet the demand during the change in the factory structure and ramp-up phase. A simulation offers the possibility to analyse different ramp-up scenarios for the factory structure and to select a suitable concept for the reconfiguration process. A discrete event simulation approach is presented that can be used to evaluate variants of structural changes and serves as a basis for deciding on a reconfiguration strategy. This approach is demonstrated using a specific production step of a plant producing hydrogen electrolyzers, the results and generalized conclusions are discussed.

1 INTRODUCTION

Successful manufacturing companies must necessarily address growth and scale in their business development to ensure the profitability of the company as demand increases. In this context, a manufacturing system reconfiguration offers opportunities to increase productivity and thus reduce manufacturing costs in order to scale with increasing quantities. But a reconfiguration process implies a change in the factory structure, the factory's components and the degree of automation. For this reason, it is important to plan the manufacturing process, evaluate possible reconfiguration options, and identify a suitable approach for reconfiguring the factory. During the development and identification process, different concepts of expansion stages emerge the need to be evaluated. Production interruptions need to be taken into account in order to meet the demand during the reconfiguration process. After a reconfiguration, the ramp-up phase of a manufacturing system must also be considered. The ramp-up phase is "commonly defined as the period from the production of the first item after a system reconfiguration until the achievement of a stable target output rate (Colledani et al. 2018)." As here the system is exposed to several disruptive influences, that result in a reduced production capacity. During the ramp-up of production, these disturbances are continuously reduced. (Glock et al. 2012) A simulation of the reconfiguration process including the ramp-up phase provides added value as an objective decision support system, since insights into production are provided (Glock and Grosse 2015). A methodology is presented using a scenario in

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which the structural change in production is modelled and the ramp-up phase is subsequently analysed. This approach allows different variants of expansion stages to be compared and evaluated.

2 RELATED WORKS

In order to expand production capacity, structural and organizational changes to existing production systems are necessary. When new equipment is put into operation, technical problems may initially cause disruptions that affects overall performance negatively for a certain period of time. The exact impact is difficult to estimate without computational methods because a factory is a complex system with many-sided interrelationships. Complex interrelationships can be analyzed with the help of discrete event simulation and can thus be used to support decision-making, for example in system selection (Hoellthaler et al. 2019). Simulation-based approaches can serve as a useful tool for decision support during the ramp-up of production systems, since real world behaviors can be represented in the models (Glock and Grosse 2015). The focus of this work is the simulation of reconfiguration of a production system, i.e. the previously described reconfiguration over time in combination with the production ramp-up. The ramp-up process is characterized by frequent disturbances or quality problems, which have a negative influence on production performance. For this reason time dependent performance optimization should be considered in an overall simulation approach analyzing expansion stages of a factory. The focus of the research refers to discrete event simulation approaches which study the ramp up phase or dynamic changes in the production environment.

2.1 Modeling structural dynamic Production Systems in Discrete Event Simulation

As early as 1995, Barros F. J. developed a formalism to represent a time-varying system in an event-oriented simulation environment. Basis of the approach is a modular structure, which allows to make dynamic changes on all system levels of a production model during the simulation. A control element contains the information about the dynamic structure. Thus a dynamic change of the model can be initiated due to an appropriate event in the simulation (Barros 1995).

Hoellthaler et al. combine material flow simulation and optimization methods to support the decision for a reconfiguration process in production. The objective is to select an optimal reconfiguration scenario for a production system. The need for a tool-based decision support is based on the fact that different departments are involved in the reconfiguration of a system, which are provided with discussion and data basis by using a shared tool. This makes the decision-making process transparent and easier. Optimization is first used to calculate an ideal production plan and then to derive reconfiguration measures. Alternative layout variants compared to the initial variant are determined using a heuristic. The preselection of layout and production plan serves as input for the simulation, which is used to represent the change of the system over time. The task of the simulation is not only to determine relevant KPIs for the decision-making process, but also to coordinate the rebuild. For example, it must be ensured that when an old system is dismantled, there is no overlap with the ramp-up of the new system. The KPIs of the investigated system and different scenarios, e.g. overall equipment effectiveness or delivery performance, are finally presented to all persons involved in the decision-making process (Hoellthaler et al. 2019).

Voith et al. use agent-based simulation to select appropriate configurations of modular and scalable manufacturing cells. A simulation consists of different components. One of them is the system component representing the manufacturing cell. The cell in turn consists of sub-modules, which differ in their degree of automation. In the event of a varying demand scenario, the simulation uses rules to determine which automation level must be switched to. The aim of the approach is to find the best possible configuration of the manufacturing cell for different expansion stages in the production life cycle (Voit et al. 2021).

When analyzing the previously described approaches, it is noticeable that while the dynamic change of the system or production is dealt with, the production ramp-up after a reconfiguration is not considered. In many cases, a change in the production system is in practice accompanied by a successive increase in system performance. This behavior is due to the fact that new equipment must first be gradually optimized, unexpected errors occur, or employees are slower to learn new activities. These examples are continuous processes that take time and can slow down the ramp-up of a production. For this reason, the next subchapter presents research articles that take the ramp-up process into account in discrete event simulation for an accurate prediction of the production ramp-up.

2.2 Integration of Production Ramp-Up into Discrete Event Simulation

The ramp-up of a production corresponds to an increase in throughput. A ramp-up is a time- and quantity-dependent improvement process that depends on many factors and is therefore difficult to predict. Peter Nyhuis et al. developed a forecast tool to predict the ramp-up curve. The software is based on two different types of simulations that are combined. On the one hand, a quality simulation is performed to predict the plant availability and the quality rate. The data required for the simulation is collected by expert surveys and regular comparison with past values. On the other hand, a material flow simulation is created, that can be used to predict a ramp up curve. To simulate realistic ramp-up behavior, the availability and quality data from the previous calculation are used. These display the increasing improvement mentioned at the beginning. The combined approach provides a way to a more accurate ramp-up prognosis (Nyhuis et al. 2005).

In addition to the availability and quality of equipment and processes, the improvement of manual activities in repetitive processing steps is also a factor that influences ramp-up. An integration of the learning behavior of workers in simulation models is another partial aspect that makes the ramp-up behavior in the model more realistic. In Neumann and Medbo, learning and the associated process optimization in the simulation model depend on the number of pieces produced. The worker learns after performing his activity and therefore becomes faster. The reason for integrating this factor into the material flow simulation was to compare the ramp-up behavior of serial and parallel production processes. It could be shown that parallel systems ramp up slower than serial ones. The period until the systems became equivalent was still relatively early in the ramp-up phase (Neumann and Medbo 2017).

In general, it can be derived from the research that simulating the ramp-up phase is challenging because many factors affect the process. However, the importance of looking at ramp-up using simulation can often be emphasized. In the simulation of reconfiguration scenarios described in the previous section, ramp-up is not addressed. The gap to consider the dynamic system change and the ramp-up combined will be closed in the next chapters. A simulation approach is presented that realistically depicts the reconfiguration of production systems and the associated ramp-up. The simulation is intended to provide insights into the effects of reconfiguration scenarios during factory planning and to support decision making.

3 SIMULATION-BASED MODELING OF RECONFIGURABLE SYSTEMS

A typical approach in the implementation of simulation projects is the modeling of one state of a production. This can be, for example, the actual or the target state of a factory. For a state, experiments are conducted in which parameters of machines or order data are varied for each experiment. However, the structure of the model does not change during a simulation run. The goal of this work is to develop an approach for structure-variable modeling. This makes it possible to simulate and investigate reconfiguration processes within a single simulation run in detail. This adds a dimension to the experiments described at the beginning, because different reconfiguration scenarios can be investigated for each experiment. In the following, the modeling approach is explained. It is implemented on the basis of a concrete use case in the software Plant Simulation.

A factory can be divided into individual segments and also further subdivided down to machine level. In the approach presented here, the model is built and structured hierarchically and the segments are called submodels in the further course. Accordingly submodels can be further subdivided down to machine level. In the software Plant Simulation a hierarchical structuring can be implemented with the help of the module "Network". During a reconfiguration process of a factory, the segments are rebuilt or machines are replaced. Accordingly, submodels are exchanged in the simulation model. In order to replace a submodel by another submodel, their functionality is guaranteed in the submodels themselves. Thus a problem-free exchange of submodels can be ensured. In addition to the submodels, the model also consists of a central control unit in which various reconfiguration scenarios are defined. A scenario is defined by the exchange of submodels at a certain point in time, the duration of the reconfiguration and the type of reconfiguration. Since a reconfiguration does not always involve the immediate dismantling of the old system, the reconfiguration type defines in which order submodels are exchanged respectively in which order rebuilding takes place. This option is applicable in cases that allow parallel operation of the old and new systems.

In contrast to the static model described at the beginning of the chapter, this enables the simulation of the production systems life cycle in order to examine the effects of rebuild processes and test measures to eliminate negative effects. Bridging the rebuild can be realized, for example, with the help of inventory buildup in production. Increased quality deficiencies can occur during the ramp-up of a new production. To ensure the quality of the products, additional quality control can be introduced. The introduction and the impact of an additional quality control on other production processes or the whole factory can be tested with the help of simulation.

The following figure shows two models of the use case described in chapter 5 and two corresponding reconfiguration process. They are the models of a production system, that can be reconfigured by exchanging the material supply stations with a higher automated version. The exchange takes place, when a defined event, like a point of time or the reaching of a defined stock level occurs in the simulation run. If it appears the system is shut down and a timer for the reconfiguration duration is set. When the timer expires, the submodels of the material supply stations are exchanged by deleting the old submodel and creating the new one. Afterward the new submodels are initialized and the system is put back into operation.

The reconfiguration for the presented system can be realized in two ways. In the first one both stations are exchanged. In the other case they are successively exchanged during the reconfiguration process. Hereby, a central control unit coordinates, for example, that first only the left side of the material supply stations are reconfigured and then the system is put back into operation. At a later point in time, the remaining material supply stations are reconfigured by triggering the event again.

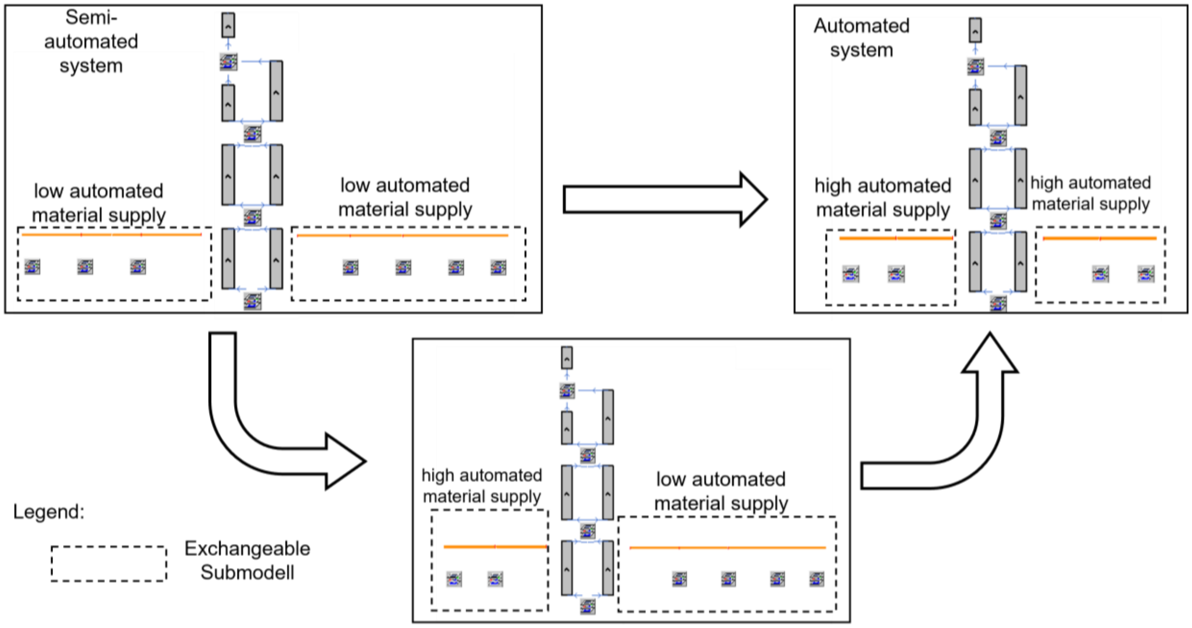

Figure 1: Schematic representation of a reconfiguration process during a simulation run with simulation models from the software Plant Simulation.

System reconfigurations in real production are often accompanied by an unstable ramp-up phase of the system. Technical problems, or initial difficulties of a worker in the execution of a new activity, lead to performance losses. The losses play a role in the planning of new systems and also influence the entire production system. Frequent failures or quality problems may occur at this stage of a production life cycle (Baloff 1970; Almgren 2000). Accordingly, the new simulation-based approach must also realistically represent the ramp-up behavior, since it can have an influence on the decision to build a new system. The implementation of the ramp-up in the simulation is presented in the next chapter.

4 INTEGRATION OF PRODUCTION RAMP UP

Apart from the structure of the model, in material flow simulations parameters of machines such as processing times and availabilities are not changed during a simulation run (Nyhuis et al. 2005). But during the ramp-up of a production system, these parameters change due to the experience gained by employees and the adjustment of the production system. Depending on the system, the ramp-up can take up to several years. During this time, the full production potential of the system cannot be fully exploited. Accordingly, for the simulation of reconfigurations, it is necessary to integrate a continuous improvement of the parameters during the simulation run.

In this regard, the concept of integrating a ramp-up behavior in discrete event simulation models is based on the approach of Nyhuis et al.. But instead of predicting machining times and quality rates in an external quality simulation (Nyhuis et al. 2005), a machine specific ramp-up behavior is integrated into selected stations of the simulation model. The ramp-up behavior of the machines is reflected by the parameters processing time, availability and quality rate. They are transferred from an initial "unstable" state to a stable one. Therefore, at the start of the ramp-up, the parameters are reduced respectively increased from the planned value $p_i(n_{max})$ to an initial value $p_i(0)$ with the percentual reduction factor r (1).

$$p_i(0) = p_i(n_{max}) \cdot (1 \pm r) \tag{1}$$

In the ramp up p_0 is successively improved until $p_i(n_{max})$ is reached. This rate of improvement depends on the degree of automation of a station. At manual processing stations for example, the parameters processing time and quality rate are influenced by the operators experience. Accordingly an improvement of theses parameter takes place as soon as the employee gains experience with his task. The gain in experience can be described with learning curves like the Stanford learning curve (Neumann und Medbo 2017). The Stanford learning curve can be described with the sigmoid function (2) (Leibowitz et al. 2010). Accordingly, it is possible to calculate the current experience level $f(n)$ of an employee with the learning rate b after each completion of a manual activity (n).

$$f(n) = f(\infty) \cdot \frac{1}{1+e^{-b \cdot f(\infty) \cdot n} \cdot \left(\frac{f(n_{max})}{f(0)} - 1\right)} \tag{2}$$

$f(n)$ ranges from 0 to 1, where zero corresponds to no experience and 1 to absolute experience with the task. Accordingly, the experience level $f(n)$serves as a scaling factor for the further calculation of the new parameter value p_n. For this purpose, the experience level $f(n)$ is multiplied by the range of improvement I. I is the range from $p_i(0)$ to $p_i(n_{max})$. Finally the new value of the parameter p_i can be calculated with (3). Thus the improvement of a parameter can be reduced to the fulfillment of a manual activity respectively the occurrence of an event within the simulation run.

$$p_i(n) = p_i(n-1) \pm I \cdot f(n) \tag{3}$$

The availability η, on the other hand, is hardly influenced by the experience of an employee. For this reason, the improvement of technical aspects is attributed to the completion of an optimization project, where the parameters improve on a percentual rate. This can be described by (4), with p_{opt} as the mean improvement rate of an optimization project.

$$\eta_n = \eta_{n-1} \cdot (1 + p_{opt}) \tag{4}$$

Consequently, a change in the parameter value can be caused by two events: the completion of an optimization project and the exit of an item from a station. With this it's possible to model a specific ramp up behavior by defining a station as manual or automated and adjusting the ramp up parameters r, b and p_{opt}. To illustrate the described functionality of the concept, the reconfiguration process of a production step is shown. Based on a practical example of an electrolyzer production, first simulation runs and results are presented. The next chapter describes the mentioned use case.

5 USE CASE AND IMPLEMENTATION

In the StaR (Stack Revolution) research project as part of the overarching H2Giga project, both a new technology for hydrogen electrolysers and the associated production are being planned. Since the project partner is a start-up, flexibility and growing structures must be taken into account within the greenfield planning of the production system due to the high growth potential. In the beginning, a manual production is planned in order to keep the acquisition costs and the entrepreneurial risk low. After the start of production, experience with the product is to be gathered and incorporated into the planning of the next expansion stages. The next expansion stages will ultimately each have a higher degree of automation in order to be able to increase throughput in the future.

However, several aspects have to be taken into account when moving the system to a higher level of automation. For example, the system structure, the number of subprocesses and the system chaining change. Because of this, a modular approach is taken by dividing the overall production into segments and designing variants with different levels of automation for each segment. In this context, the reconfigurations of the first segment was investigated. The bonding process for electrolysis stacks. A total of three system variants with different degrees of automation were designed for this subprocess. For the reconfiguration of the variants a total of six scenarios result, that are shown in table 1. They differ in how the systems are rebuild and what variants are involved. In a complete reconfiguration for example, as can be seen in Figure 2a, the initial system is first completely dismantled before the higher automated system is built and put into operation. In the case of a parallel rebuild, the new production system is set up and operated parallel with the initial system (cf. Figure 2b). Only when the new system achieves a stable production, the initial system will be shut down . Due to the fact, that the semi-automated and highly automated system differ only in the type of material supply stations (cf. Figure 1), the material supply stations can be converted successively. Consequently the sequential reconfiguration is a special case of two separate "complete" reconfigurations.

Table 1: reconfiguration scenarios for the bonding process.

Initial system	**End system**	**Type of reconfiguration**
manual	Semi-automated	Complete
manual	Semi-automated	Parallel
manual	automated	Complete
Manual	automated	Parallel
Semi-automated	automated	Complete
Semi-automated	automated	sequential

Nevertheless leads a reconfiguration process to unavoidable deficits in the production output. For example, in a complete or sequential reconfiguration the production must be interrupted in order to rebuild the existing system. Accordingly measures are necessary during the reconfiguration in order to continuously supply the subsequent process and ensure the delivery capability of the system. Preparatory measures for example aim to build up sufficient stock to bridge the duration of rebuilding the system. Post processing measures, on the other hand, aim to compensate the deficits in the ramp-up phase. They can be differentiated according to whether they scale up the production volume, as in the case of shift expansions, or if they are intended to shorten the ramp-up time. One of these measures for example is a more frequent adjustment of the system in order to achieve a stable production sooner.

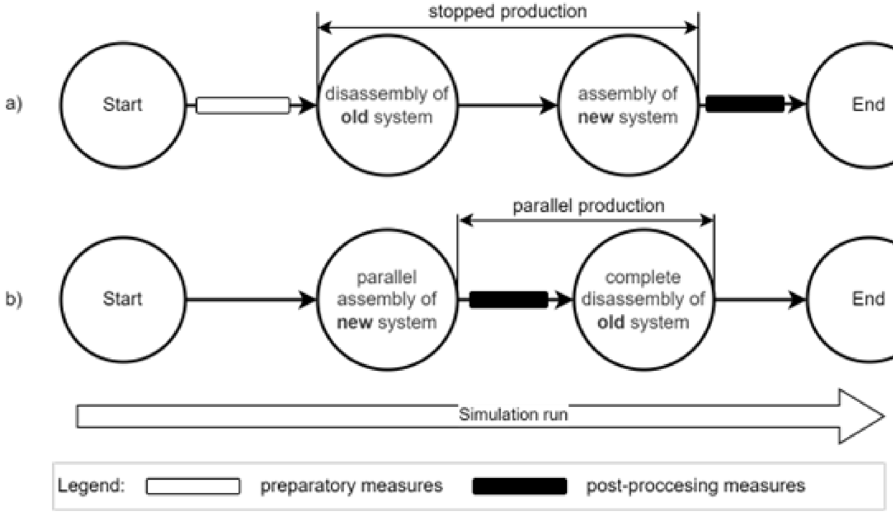

Figure 2: Progress of a complete reconfiguration (a) and parallel reconfiguration (b).

In Plant simulation the three variants of the production systems and the material supply stations of the semi- and high automated versions were finally modeled with the described structure-variable modelling approach. This enables that whole systems can be exchanged during the simulation run as well as only the material supply stations. The reconfiguration is controlled by a central control method which sets up the scenario, the duration of the rebuilding and the measures to counteract the deficits within the reconfiguration. For the integration of the ramp up a central control method and a Plant Simulation data table were used. In it all station that are affected by the ramp and their specific ramp up parameters reduction factor (r), learning rate (b), mean improvement rate (p_{opt}) and the interval of optimization projects are listed. If an object (BE) leaves an affected station or an optimization project is completed, the central ramp-up control method is called. It calculates the new parameter values of processing time, availability and quality rate based on the information in the table and assigns it to the referred station.

6 EXPERIMENTS AND RESULTS

In the simulation experiments the influence of preparatory and post-processing measures were examined based on their ability to fulfill the demand of the subsequent process and their effect on the ramp up time during a reconfiguration process. Within this paper the complete and parallel reconfiguration of the manual to the automated system is presented. Therefore the parameters in Table 2 were set and two measures were examined, shift expansions from a one shift production to a two shift production and more frequent optimization projects by reducing the interval between projects to three days.

Table 2: Reconfiguration parameters for the experiments.

Duration of reconfiguration	**Parameter reduction factor**	**Learning rate**	**mean project interval**	**Mean improvement rate**
30 days	20%	15%	6 days	10%

In a primary investigation of a complete reconfiguration without any measures, it was shown that a deficit in the coverage of the demand occurs. As can be seen in Figure 3 on the left side, this deficit is caused by the duration of the reconfiguration and results further from the reduced production performance in the ramp-up period. For example a deficit of 1,408 units occurs from the break in production while the ramp-up causes a deficit of 3,820 units in total. Accordingly, measures must be taken to counteract these deficits. If shift expansions are introduced in the preparatory as well as during the ramp-up, deficits from the reconfiguration and ramp-up are counteracted (cf. Figure 3 right side) .

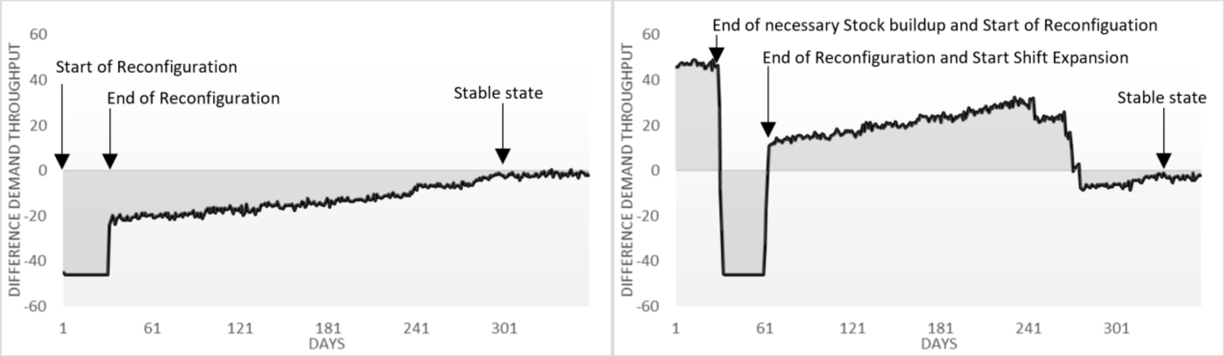

Figure 3: Difference demand and throughput in a complete reconfiguration process without measures(left) and with shift expansions(right).

Considering the preparatory first, a daily stock increase of 46.6 units is achieved in a two-shift production. This equals the demand of the subsequent process. Accordingly, the time taken to build up the required stock correlates 1:1 with the planed duration for rebuilding the system (cf. Figure 3 right side) For shift expansions in the ramp-up phase, the pattern is similar. The daily throughput is higher than the daily demand and thus there is no deficit in demand coverage. However, it was also shown that ending the shift expansion too early causes the production output to fall short of demand. More precisely, the production volume drops to the same level as it would be achieved without shift expansions. This means that despite the shift expansions, the production system is continuously in an unstable state and the increased production volume is based exclusively on the longer daily production time. Even though the minimum of MTTR is reached earlier, no shorter ramp-up time is achieved because the reduced availability has a more critical effect on the system. Consequently, in our model the introduction of shift expansions have no influence on the ramp up duration due to the automated system. If the system components are optimized more frequently during the ramp-up instead, the duration of the ramp-up phase can reduced by 97 days. As can be seen in Figure 6 the system reaches a stable state more rapidly. But despite this, the demand of the subsequent process cannot be fulfilled continuously, accordingly a deficit of 2,158 units arises.

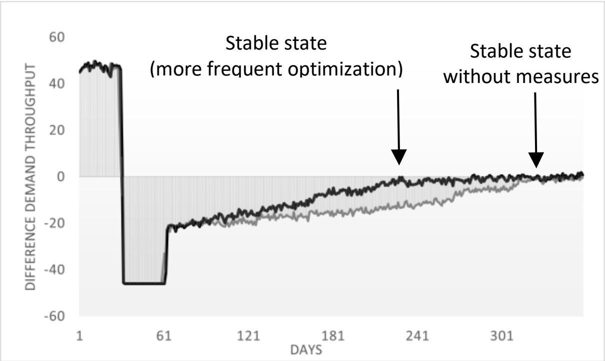

Figure 4: Influence of more frequent optimization projects in a complete reconfiguration.

In a parallel reconfiguration on the other hand, it was shown that the demand of the subsequent process is continuously covered due to the non-stop production of the initial system. Thus, the ability to deliver is ensured. But since the original system will not be dismantled until the new build system reaches a stable state, a higher stock is built up depending on the duration of the ramp up (cf. Figure 5). In Consequence a stock of 6,778 units will be achieved until the initial system is shut down. Accordingly measures like shift expansion would be counterproductive because they would increase the stock further. A more frequent optimization on the other hand shortens the duration of parallel production and thereby the period in which overproduction takes place(cf. Figure 5 right side). As a result, a 2,598 units reduced stock is build-up.

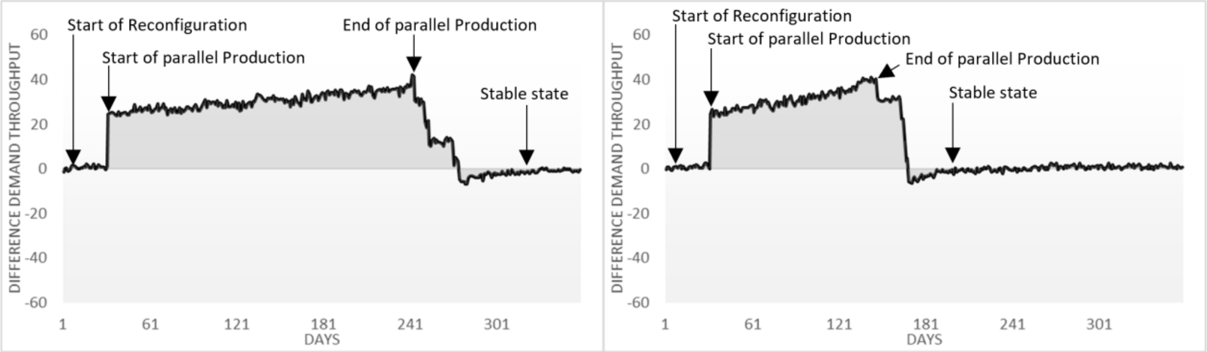

Figure 5: Difference throughput and demand in a parallel reconfiguration process without measures (left) and with more frequent optimization projects (right).

Comparing the reconfiguration scenarios using measures to consistently fulfill the demand of the subsequent process the main problem for both reconfiguration processes is that a high amount of inventory stock is build up (cf. Figure 6). A high level of stock is usually associated with higher costs. In the parallel reconfiguration (cf. Figure 6 left side) there is no further possibility to counteract this with the two measures. But in in a complete reconfiguration the build-up stock can be reduced if both measures are used simultaneously. Through the reduced ramp up duration, shift expansion could be terminated earlier. Accordingly the duration in which stock is build up in the ramp up is reduced and lower costs could be achieved.

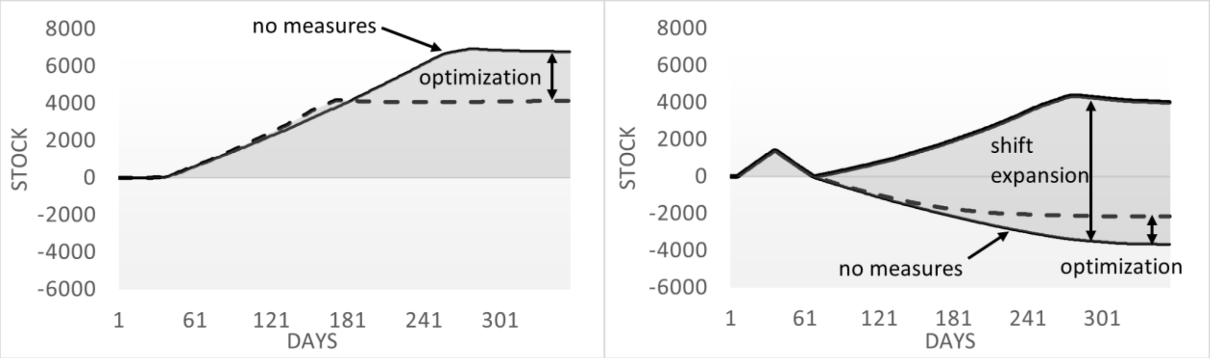

Figure 6: Stock development in a complete (right) and a parallel reconfiguration (left).

7 CONCLUSION

The paper presents an approach to investigate reconfiguration scenarios of a production process. For this purpose, a structure-dynamic discrete-event simulation model is developed in Technomatix Plant Simulation. The simulation model has a modular hierarchical structure so that reconfiguration processes can be simulated within one simulation run. In addition to the dynamic structure, the ramp-up of the modified system is also integrated. Hereby the improvement of availability, process time, MTTR and quality rate are taken into account. Furthermore the systems degree of automation is considered in the ramp up phase by dividing the stations resp. their parameters improvement in manual or technical affected. In first simulation experiments the influence of preparatory and postprocessing measures for reconfiguration processes were examined. It shows that despite the interrupted production, a complete reconfiguration of the system should be considered more closely, since the combination of measures in the postprocessing could lead to a lower maximum stock than in the case of a parallel reconfiguration.

It should be noted that the method presented here provides a good way to in making decisions that affect reconfiguration. Getting a sense of the duration and nature of the ramp-up after the restructuring the system improves the planning of the expansion stages. The build-up of necessary inventories to ensure the ability to deliver can be better calculated. Furthermore, the influence of changes to a subsystem on the entire production can be analyzed. In order for the simulation to provide more reliable data, the parameters reduction factor (r), learning rate (b) and mean improvement rate $\left(p_{opt}\right)$ that have an influence on the ramp-up must be examined in future work. One challenge here is data acquisition in the case of a greenfield factory planning. In future work, the approach will be applied to an entire production. For even better decision support, a cost model will be integrated so that pre- and post-processing measures can also be evaluated in monetary terms. For example, building up stock of very expensive materials may not be economically viable, allowing to accept lower delivery performance. The approach provides a good basis for future projects in this area and allows a deeper insight into the complex interrelationships involved in a reconfiguration process of a factory.

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REFERENCES

Almgren, H. 2000."Pilot Production and Manufacturing Start-up: The Case of Volvo". *International Journal of Production Research* 38(17):4577–4588.

Baloff, N. 1970. "Startup Management". *IEEE Transactions on Engineering Management* 17(4):132–141.

Barros, F. J. 1995. "Dynamic Structure Discrete Event System Specification: a New Formalism for Dynamic Structure Modeling and Simulation". In *Proceedings of the 1995 Winter Simulation Conference*, edited by . C. Alexopoulos, K. Kang, W. R. Lilegdon, and D. Goldsman, 781–785. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Colledani, M., T. Tolio, and A. Yemane. 2018. "Production Quality Improvement during Manufacturing Systems Ramp-up". *CIRP Journal of Manufacturing Science and Technology* 23:197–206.

Glock, C., Grosse, E. 2015. "Decision Support Models for Production Ramp-up: A Systematic Literature Review." *International Journal of Production Research* 53:1–15.

Glock, C. H., , M. Y. Jaber, and S. Zolfaghari. 2012 "Production Planning for a Ramp-up Process with Learning in Production and Growth in Demand". *International Journal of Production Research* 50 (20):5707–5718.

Hoellthaler, G., M. Schreiber, K. Vernickel, J. Isa, J. Fischer, and N. Weinert. 2019. "Reconfiguration of Production Systems using Optimization and Material Flow Simulation". In: *CIRP Conference on Manufacturing Systems (CMS),* edited by P. Butala, E. Govekar, and R. Vrabič, 133–138. Ljubljana, Slovenia: Elsevier Ltd.

Leibowitz, N., B. Baum, G. Enden, and A. Karniel. 2010. "The Exponential Learning Equation as A Function of Successful Trials Results in Sigmoid Performance". *Journal of Mathematical Psychology* 54 (3):338–340.

Neumann, W. P., P. Medbo. 2017 "Simulating Operator Learning during Production Ramp-up in Parallel vs. Serial Flow Production". *International Journal of Production Research* 55(3):1-13.

Nyhuis, P., M. Heins, P. Großhennig, J. Fleischer, G. Lanza, and T. Ender. 2005. "Simulationsunterstützte Wirkbeziehungsanalyse im Produktionsanlauf". *Zeitschrift für wirtschaftlichen Fabrikbetrieb* 100 (12):746–751.

Voit, P., M. Jira, M. Horn, and C. Seidel. 2021. "Agentenbasierte Simulation für CPPS: Simulationsgestützte Modellierung und Bewertung von modular, skalierbaren Fertigungszellen für Cyber-physische Produktionssysteme (CPPS)". *Zeitschrift für wirtschaftlichen Fabrikbetrieb* 116 (11):841–846.

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