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Development of a Pull Concept with a Simulation Model for the Start-up Phase of a Fuel Cell Series Production

Entwicklung eines pull-Konzepts mittels eines Simulationsmodells zur Betreuung der Anlaufphase der Serienfertigung von Brennstoffzellen

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Abstract: As technology advances, alternatives to the internal combustion engine, such as battery and fuel cell-driven electric mobility, are becoming increasingly attractive. Sustainable propulsion by battery has already been widely researched and is being mass-produced. The fuel cell, on the other hand, is not yet being produced to the same extent. To develop the fuel cell into a serious competitor to the battery, its series production must be targeted to further reduce costs. In addition, the increasing demand for fuel cells can only be satisfied through series production. For the flexible use of fuel cells in buses, trucks, and cars, production with a wide range of variants is also necessary. For the conception of series production, a realistic simulation of the material flow is an important component. This paper presents an approach for an intelligent pull concept to decouple material flow and at the same time reduce setup cost.

1 Introduction

Fuel cell technology is considered one of the most promising technologies being developed in line with the increasing renewable energy supply. The use of fuel cells eliminates the pollution caused by the combustion of fossil fuels since the only by-product is water. In addition, they do not rely on conventional fuels such as oil or gas and can therefore eliminate economic dependence on politically unstable countries. Fuel cell systems have the highest efficiency compared to conventional distributed energy systems and can produce almost zero greenhouse gas emissions when operating with renewable, clean resources (Wilberforce et al., 2016).

The fuel cell market is growing every year (Das et al., 2017). To meet this demand, companies must produce fuel cells more economically. This paper serves as a support for companies in the start-up phase of the series production of fuel cells. Practical cooperation is carried out with an industry partner.

The work extends an existing model by a higher level of detail, by a greater practical relevance and by the multi-variant case. The approach will be modelled according to the principle of pull control. The simulation model will be used to conduct experiments that optimize the output quantity through pull control concepts. Special attention will be paid to the order allocation and the minimization of the accumulated setup times, under different demand scenarios by using genetic algorithms. Experiments are also being conducted to see how the output changes when the developed order control is implemented in upstream stations such as stamping.

2 Literature Review

Dyckhoff et al. (2012) looks at the current research landscape on series production ramp-ups from the perspective of production theory. Progressive learning effects of the personnel, induced technical progress on the machines, initial lack of mastery of production quality and varying production intensity in operationalizing the ramp-up policy form the essential characteristics of the production start-up. Existing models are examined to determine the extent to which they are able to depict the empirical phenomenon of production ramp-up outlined in this way. By reverting to and concretizing individual elements of these models and adding further considerations, a lean, dynamic basic model of the production ramp-up is developed in the tradition of Gutenberg's production theory, which is able to explain the ideal-typical course of the start-up curve solely on the basis of the features mentioned.

The integration of series production ramp-up planning and scheduling strategies is a critical aspect of modern manufacturing systems. Many researchers have explored different methods and algorithms for optimizing the scheduling and ordering process in manufacturing systems, with the ultimate goal of minimizing the total cost of production and inventory while maximizing the system's throughput. In recent years, there has been an increasing focus on the integration of pull-control mechanisms

Chou and Huang (2013) propose a novel method for integrating machine scheduling and self-healing maintenance in manufacturing systems using job-mix pull control. Their approach aims to optimize system performance by dynamically adjusting the mix of jobs processed based on machine status and maintenance needs while proactively monitoring machines for failures. Simulations show that their method outperforms other scheduling and maintenance strategies in terms of system throughput and machine utilization. Ni et al. (2013) present a mathematical model to optimize scheduling and ordering processes in manufacturing systems with delayed differentiation. Their model considers production capacity, order demand, and inventory costs to minimize the total cost of production and inventory. A heuristic algorithm is proposed to efficiently find a solution to the optimization problem. The effectiveness of the proposed model and algorithm is demonstrated through a case study. Lee et al.im (2002) conduct an experimental study on scheduling algorithms for semiconductor fabrication lines. They propose two algorithms and compare them to a baseline First-Come-First-Serve algorithm based on several performance metrics. The input scheduling algorithm outperforms the other two algorithms in terms of cycle time and throughput, while the bottleneck scheduling algorithm performs the best in reducing work-in-process inventory. The authors conclude that the choice of scheduling algorithm should depend on specific objectives and constraints. Tošanović & Štefanić (2022) investigate the effects of pull control mechanisms on lead time under different production conditions. Simulation experiments are conducted to analyse and compare how different mechanisms affect lead time, with focused parameters of process variability, operating time, and the presence of bottlenecks. Results show that optimal pull control mechanisms vary for different production conditions. However, only single-product production was investigated in this study.. Kaiser et al. (2019) investigate pull control and the multi-variant case. The goal is to implement dynamic value stream simulation through a modular system. The advantages of a material flow simulation are the capture of dynamic processes and the quantitative detection of optimization potentials. In this approach, standard modules have been developed in Plant Simulation from Siemens. These standard modules allow for variant manufacturing, the implementation of pull and push control, and the use of kanban control. Kaiser et al. (2019) perform a variant-specific determination of the process times to capture the multiple influences and interactions of the variants. For this, it is necessary to determine in which way the customer cycle is represented by the different variants. The result is a variant-specific processing time for each process step (Kaiser et al. 2019).

In the following approach, the different process levels are decoupled by implementing a high-rack warehouse. Such an approach makes sense, for example, if lot sizes at the different process stages do not have a meaningful smallest common divisor (e.g., due to roll-to-roll processes). Despite the advancements in manufacturing systems proposed in the literature, there is a lack of research on how to reduce setup times in manufacturing processes with a high-rack warehouse. The studies by Chou & Huang (2013), Ni et al. (2013), Lee, Park & KIM (2002), Tošanović and Štefanić (2022), and Kaiser et al. (2019) give us meaningful ideas on optimizing scheduling and control mechanisms but have not considered the use of high-rack warehouse and reactive control to reduce setup times. Therefore, there is a research gap in investigating the effectiveness of reactive control in high-rack warehouse systems to minimize setup times and improve manufacturing system performance.

3 A detailed multi-variant Approach

The approach is used to implement a discrete-event simulation model of fuel cell production in which pull control and the multi-variant case are applied. To reduce costs for fuel cell production, a key factor will be, if the highly heterogeneous needs for different car purposes can be produced efficiently in one production system to ensure the utilization of the highly expensive machines. This can only be achieved by an intelligent pull system. For production to work according to the pull principle, a supermarket is created at a defined interface between production and the customer. This stores parts and places an order to a defined predecessor. Suppliers are warehouses, sources, or other supermarkets. Along the production line, other supermarkets are implemented and configured with the materials and their corresponding minimum, maximum and initial stocks, as well as the suppliers. The intermediate products are stored centrally in a high-rack warehouse. If the stock of a product in the high-rack warehouse falls below the minimum stock level, this product is ordered in the corresponding upstream stations. As a result, pull control in production is created by the supermarket at the customer interface ordering new parts from the high-rack warehouse, which then orders its new parts from an upstream supermarket, and so on.

For the simulation model to simulate the production of multiple variants of fuel cells, the variants must first be generated. These distinctions enable realistic simulation, the implementation of setup changes, and the modelling of assembly and disassembly list changes. The next step is to optimize the model.

The approach pursues the goal of maximizing throughput by reducing cumulative setup time. This goal is achieved through intelligent automated job assignments. A certain amount of orders is collected in an order warehouse. The implemented control system assigns each machine the job for which it is set up. This is done until the control system concludes that a machine needs to be retooled. For this purpose, the predicted orders in the order warehouse are compared with the set-up of the machines. The principle of control is shown in Figure 1.

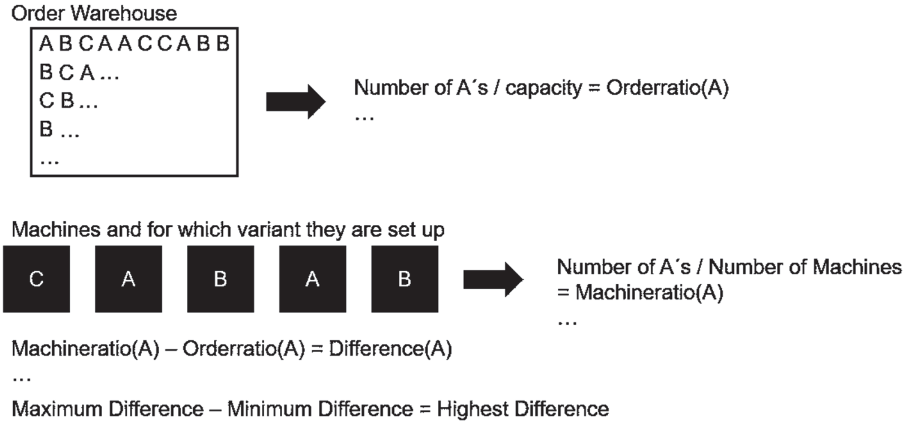

Figure 1: Principle of the intelligent automatic control

In the order warehouse, the ratio is evaluated in which the orders of the different variants are present. At the same time, the number of machines set up for each variant is evaluated. This value is set to the total number of machines. The ratios of each variant are compared. The highest value of the difference values is stored in the variable *Maximum Difference* and the lowest difference value is stored in the variable *Minimum Difference*. If the value of the variable *Highest Difference* is greater than a fixed value, the command to change over is given. A machine that is set up for the variant with the highest differential value is scaled down and set up for the variant with the lowest differential value. The meaning behind this method is that it is an intelligent control, which automatically determines when a machine should change over to which variant. The changeover command must be dependent on a fixed value. The value can be optimized, for example by an algorithm. This allows the order assignment to be optimized.

The approach was tested on a use case of the industry partner. The verification of the automated intelligent order assignment was performed through several experiments.

4 Use Case

The approach from Chapter 3 was applied in practice in collaboration with an industry partner. The industry partner would like to use this approach to optimize the large-scale production of high-performance fuel cell stacks. The software used for the practical application is Plant Simulation.

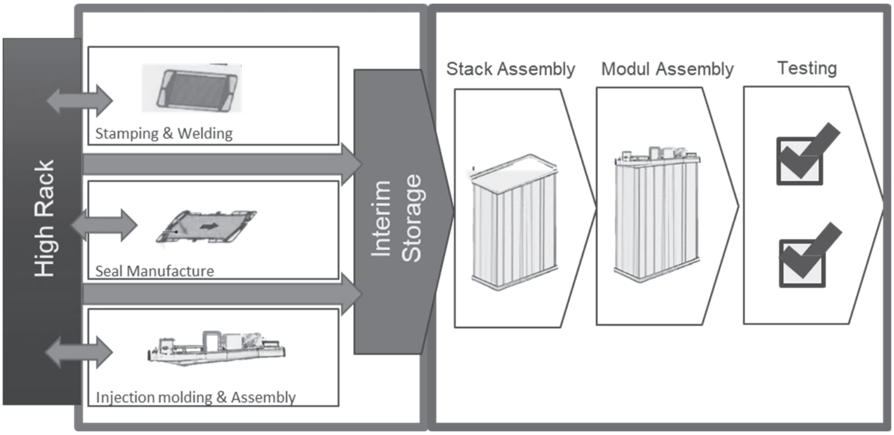

Figure 2: material flow fuel cell production

The own approach is implemented as described above according to the process steps shown in Figure 2. Basic decisions are made in coordination with the industry partner. The interface of production with the customer is to be implemented in the stack assembly. This means that the stack assembly produces the appropriate variant of the fuel cell stack depending on the customer's order. The upstream processes of the stack assembly are controlled according to the pull principle. The downstream processes are controlled according to the push principle. The interface to the customer is simulated by a source that generates production orders. In this practical example, production can view 100 orders in advance. This is modelled by an order warehouse with a capacity of 100. Using an intelligent order control in the outbound control of the order warehouse, the orders are distributed to the stack assemblies. When an order leaves the order warehouse, a new order enters the order warehouse. The order control aims to minimize the waiting times and the accumulated setup times of the stack assemblies. This maximizes the working time and output quantity of the assembly stations. Stack assembly pulls the materials needed for assembly from a supermarket. In this practical example, the intermediate products are stored centrally in a high-rack warehouse. If the stock of an intermediate product falls below the minimum stock level during stack assembly, this intermediate product is ordered from the high rack warehouse. If the stock of a product in the high rack warehouse falls below the minimum stock level, this product is ordered in the corresponding upstream stations. As a result, the intermediate products are produced according to the pull principle.

For the simulation model to simulate the production of multiple variants of fuel cells, the variants must first be generated. In this practical example, three different variants are produced after consultation with the industry partner. These distinctions enable the realistic simulation, the implementation of setup changes and the modelling of assembly and disassembly list changes.

5 Results

In the following of this Chapter, different experiments are analysed and their results are presented. The experiments were carried out in cooperation with the industry partner. The practical example includes the optimization of concrete production. The focus of the optimization was the creation of an intelligent automated order allocation. The goal here was to minimize the accumulated setup times and maximize the output quantity. The presented intelligent automated controls are optimized and applied in simulation in the following. The developed methods are tested for their robustness to changing levels. In addition, the comparison of the developed controls to predefined order assignments in Plant Simulation is drawn.

The output control *min. setup time* is used as the present comparison control. With the output control *min. setup time*, the movable elements are distributed to the successor, which station means the shortest setup time for the movable elements to be distributed. This is only possible if several successors are ready to take up a movable element and the output control has the choice between them. If only one successor is ready to pick up a movable element, the movable element that stays the longest in the order warehouse is allocated to this successor, regardless of the setup time. The output control min. setup time operates according to the FIFO principle. The goal is an intelligent automated order allocation, resulting in an optimal distribution of orders, independent of the order situation and levelling. For this reason, the experiments of the different controls were additionally carried out with three different order levellings. First, a *random* levelling was chosen, which is closest to practice. The second-order levelling used corresponds to a *change in every 10* elements. In this order list, ten fuel cells of *variant A*, then ten fuel cells of *variant B*, and then ten fuel cells of *variant C* are ordered consecutively and entered into the system. The third type of levelling, the *change every 1000* elements, is based on the same principle as the *10-cell change*. The difference is that 1000 units of a variant fuel cell are ordered consecutively. The orders are realized in Plant Simulation via a source, which generates the movable elements based on an order list. The following experiment and optimization of the control in the stack assembly were carried out in an extra model. First, the required part of the stack assembly was extracted from the complete model of the factory. The stack assembly was supplied directly from sources in the extra model. This meant that there was no supply bottleneck. The extraction was carried out for performance reasons. Better measurability of the influence of the accumulated setup times on the overall performance could be achieved. The goal of the extracted model was an investigation of the stack assembly. The minimization of influencing factors on the overall result, adds up to a better understanding of which influencing factors affect the result and how. Eliminating all influencing factors of stack assembly delivery improved the knowledge of how different controls affected cumulative setup times and output.

Before the stack assembly experiments could be conducted, a fixed value was assigned to the variable *SetupDiff*. As described in Chapter 3, the fixed value *SetupDiff* determines when a stack assembly should change over. To determine the optimal value, a genetic algorithm was performed.

Figure 3 compares the results of the different experiments in percentage terms. As a standard scenario, the control min. setup time with the levelling random was chosen. The method *order assignment stack assembly* is robust against changes in order levelling. With levelling *change every 1000*, there is hardly any difference in the output of the different order assignment options. This is because this principle of levelling requires hardly any changeover operations. After all, the system is fed with only one variant at a time for a long time. As a result, the type of order assignment is of little importance. For the other two levellings, the output increases strongly as soon as the developed control order assignment stack assembly is used instead of the control *min. setup time*. In the case of *random* levelling, the output quantity increases by 28.31%, and in the case of *change every 10* levelling, the output quantity increases by 31.99%. The increase in output can be explained by two effects. On the one hand, with the order assignment stack assembly, a control system was developed that intelligently distributes the orders and minimizes accumulated setup times. Secondly, the developed order allocation did not use the FIFO principle. This means that orders can be collected and the control has a larger selection of orders that it can distribute intelligently to the free machines.

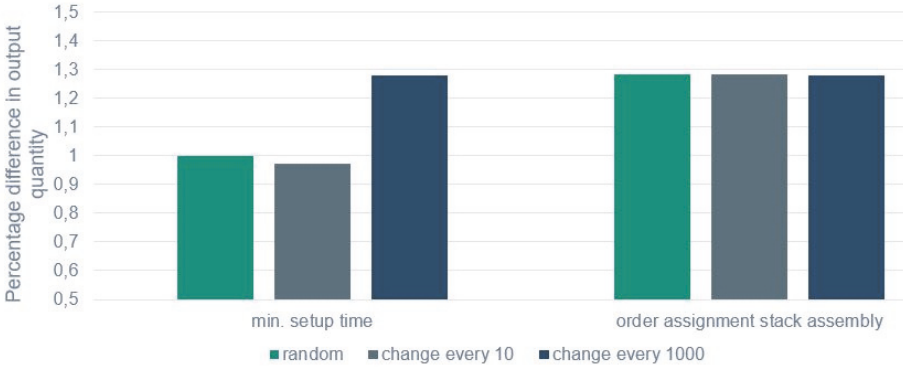

Figure 3: Percentage difference in the stack assembly output

The control of stack assembly was transferred to the overall factory model. This shifted the bottleneck of production to the upstream processes. To optimize the order assignment of the upstream processes, various experiments were carried out in the overall model. In these experiments, the control described in Chapter 3 was also used for upstream stations. The experiments of the following results were carried out in the overall model. The order levelling, which is fed into the stack assembly, and the control of the order assignment of the stamping stations were changed. Figure 4 shows the percentage difference in the output of the overall model with the above changes. Because an upstream process is studied in the experiments, which only produces when needed, the potential for improvement is limited. The fluctuations in the output are therefore not as high as in the experiments with stack assembly.

An increase in output can be seen when changing the *min. setup time* control to the *order assignment stamping* control. This increase in output is independent of the order levelling at about 2%. On the one hand, the increase in output quantity was achieved by reducing the cumulative setup time of the stamping by 0.69%. On the other hand, the output increases when the stack assemblies have less downtime. This is achieved by the *order assignment stamping* control by having the stamping produce the variant that the stack assembly needs.

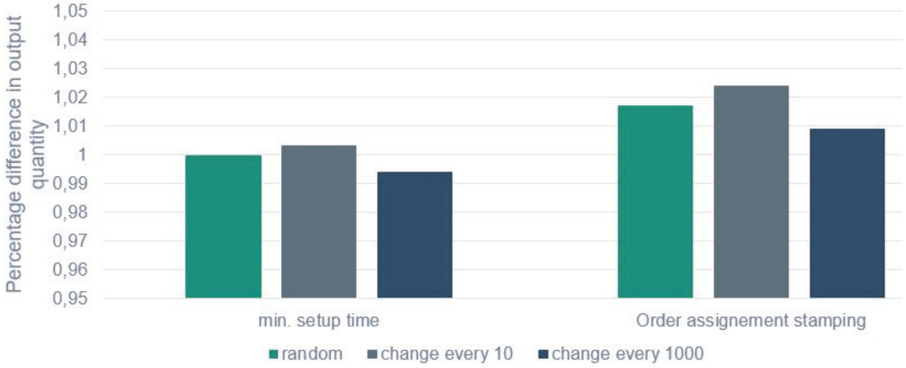

Figure 4: Percentage difference in the output of the overall model

6 Conclusion and Outlook

The task and objective of this research work was to develop an approach for converting an existing model into a realistic operational model of a higher level of detail. The development of the approach was implemented in cooperation with the industrial partner. The implementation of the optimization measures involved the implementation of the pull control and the multi-variant case. Based on this, the setup processes and the output quantity were to be investigated depending on different order levels.

The approach of the present work consisted of implementing pull control by implementing supermarkets. The multi-variant production was implemented by generating multiple variants and embedding methods. In this model, an intelligent automated order assignment could be developed, which is independent of order levelling. The order assignment was created to minimise cumulative setup times and maximise output quantity. In the approach, different order assignments could be developed. When selecting the order assignment, it is important to consider at which point in production the corresponding station is located. Buffer stocks of a downstream station, for example, are important indicators for decision support in the order allocation of an upstream station. The approach was specifically applied to the start-up phase of the industrial partner's series production of fuel cells. This enabled the simulation model to be implemented realistically during operation with a high level of detail. The developed approach could then be tested in practice using experiments. The experiments showed the robustness of the developed order allocation against different order levellings. Optimization of the output quantity as well as the accumulated setup times was achieved.

The following work can build on the presented approach to conduct further experiments. The buffer sizes of production must continue to be optimized. The number of necessary logisticians and their areas of responsibility have not been analysed and optimized in more detail. The influence of different minimum stock levels can be analysed, for example in the buffers and the high rack warehouse, on the output quantity of production.

The above-mentioned possible objectives of subsequent work are specific to the simulation model developed in cooperation with the industry partner. Due to the high level of detail of this specific production, the universal applicability of the simulation model was neglected. The results are therefore not necessarily transferable to other production sites but may provide important approaches to solving similar problems.

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