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Creation of configurations for an assembly system with a scalable level of automation

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Abstract

Due to shortened product lifecycles and an increasing number of variants, the need for scalable assembly systems is rising. This trend is even stronger in the production of emerging technologies. An important step in the planning of a scalable assembly system is the creation of system configurations. State of the art is a scaling of the system from a manual, over semi-automated to an automated system during the start of production. This process is very rigid and does not offer the flexibility which is necessary to react to highly volatile influencing factors. The authors have identified the urgent need for a thorough scenario analysis to adequately consider the risk in predicting volatile influencing factors. In this paper, a two-part methodology is proposed considering multiple scaling mechanisms allowing for a swift and cost-effective adaptation to external factors. The first part is concerned with the scenario analysis. In this part, the planner has to identify the volatile receptors that influence their production. For each of the identified receptors, market studies and workshops with internal experts are conducted to develop a detailed scenario analysis, modelled in a modified BPMN logic. In the second part, the planner needs to develop production system configurations according to the results of the scenario analysis. The appropriate scaling mechanisms are chosen based on the volatile receptors. The application of these mechanisms on station level results in various station concepts satisfying the entire range of expected values within the volatile receptors.

Keywords: scalability, changeability, scenario analysis, PEMFC, fuel cell production.

1. Introduction

The market for fuel cells is confronted with many different stresses. New fields of use lead to an increase of product variants [1]. Uncertainty concerning future public funding as well as competing technologies result in a high volatility and uncertainty of customer demand [2,3]. Especially in high wage regions such as Western Europe high cost pressure is exerted to the production of fuel cells due to the high share of manual tasks [4]. One of the new applications of the fuel cell is the use in industrial trucks. Different studies reveal high potential in fuel cell technology winning a great part of the market share in this sector. In comparison to the European market, the USA and Japan are leading the way in this development [5].

A production planner who needs to plan a fuel cell assembly under these circumstances is faced with a dilemma. One can plan an assembly system designed to produce a high volume due to an optimistic sales scenario but at the same time risk planning an overbuilt system that might never be used to capacity. Alternatively, one could plan more conservatively with the risk of not being able to satisfy the customer demand. None of these two outcomes are acceptable, especially considering the high cost pressure in Western Europe. The answer to the dilemma suggested in this article is Scalable Automation (=SA). By planning a production system with a scalable level of automation, the fuel cell producer can seamlessly adapt to changes in the volatile environment of fuel cell production.

The first step to planning a scalable system is the in-depth analysis of the factors impacting the production system which is described in Section 3.1. Based on this analysis, section 3.2 describes a methodology for the creation of alternative system

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configurations within a scalable assembly system. Section 4 applies the theoretical methodology to an exemplary use case of a fuel cell manufacturer.

Nomenclature

CR	Changeability Ratio
DA	Degree of Automation
F	Feeding Module
P	Process Module
Q	Quality Module
RMS	Reconfigurable Manufacturing Systems
S	Setting-Up Module
SA	Scalable Automation
T	Transport Module

2. State of the Art

Cisek et al. [6] describe the environment of a production company with the attribute “turbulent”. Turbulent means an environment of always changing conditions. These conditions are defined as “transition drivers” and can take effect internally from inside the company or externally from other companies, the government or society. The transition drivers have an indirect effect on the production system through the so called “receptors”. Cisek et al. define five receptors of a production system that allow the management to react to changes in the turbulent environment: product characteristics and variety, quantity of produced pieces, production time, production cost and product quality (see [7,8]).

Eilers [9] goes one step further in his evaluation. He focuses on enabling the production system to possible receptor changes. Based on a modular approach to describe the production system (see [10]) he introduces six “scaling mechanisms” to adapt the production system to management requirements. Those scaling mechanisms can further be categorized into personnel, interstationary and intrastationary scaling mechanisms. Scaling the personnel means using different shift models and changing the number of workers. Interstationary scaling can be accomplished by duplicating a bottleneck station or the production system as a whole. When it comes to intrastationary scaling mechanisms the production tasks within an assembly station are analyzed: either the production tasks can be reallocated to additional or fewer assembly stations or the production tasks can be performed using a different degree of automation. The concept of focusing on the latter scaling mechanism when planning the assembly system (hereinafter called SA).

Some approaches can already be found in recent research towards the planning of scalable production systems [11,12,13,14,15,16]. The authors of [17] describe a procedure that consists of six steps – focusing only on the first three. First of all, the process chains are built in form of a production graph. Secondly, the process times need to be collected to characterize the production process chronologically. The third and most crucial step is the definition of scalable process steps in which the actual configurations of the assembly system are created.

In addition, the approach of [18] needs to be mentioned. They introduce the concept of the “reconfigurable manufacturing system” (=RMS) (see [19,20,21]) which possesses six characteristics – scalability being the most important one. These RMSs are developed based on so called “design-for-scalability principles” that can be summarized as requirements to enable the production system of scaling mechanisms. Their method focuses on cost optimal scalability planning to ensure the satisfaction of a surging market demand.

The most recent approach was published by [22]. They introduce a concept for SA consisting of an assembly system for small electric motors in a learning factory. This approach considers all the receptors introduced above by presenting a methodology that focuses on scaling the degree of automation for modular assembly stations.

3. Approach

3.1. Scenario analysis

The first step of the supposed scenario analysis consists in the selection of volatile receptors. Under realistic conditions, not all five receptors described by [6] can be expected to be uncertain and volatile. Accordingly, a team of experts will have to predict which of the five receptors are volatile. The next important information is the frequency of change within the volatile receptors. The experts must decide if they expect short-term changes on a daily basis, mid-term changes on a monthly basis or long-term changes on a yearly basis.

In the second step, a detailed scenario of each volatile receptor has to be created. The time increments considered in each scenario are chosen based on the accordingly predicted frequency of the receptor. In order to adequately model the prediction of process experts, an event-based approach was chosen. The scenario models consist of events and phases. Each phase is indicated by a starting value and a trend of a quantitative value describing the respective volatile receptor.

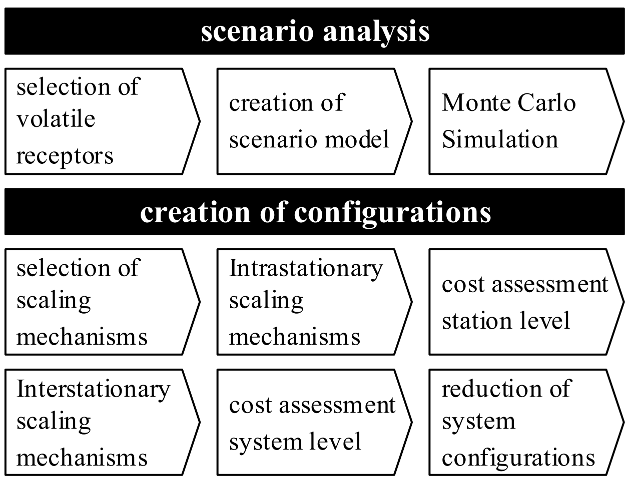

Figure 1. Overview methodology

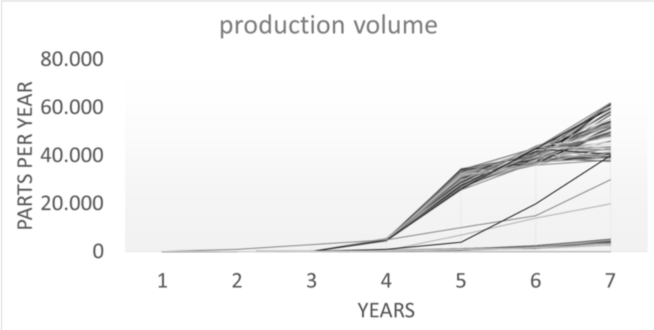

Figure 2. Example of receptor scenario

The events represent change drivers that have an expected effect on the considered receptor. Each event is described by an occurrence probability and a probability function of the time of occurrence. The occurrence of an event leads to a transition from one phase into another.

The final step of the scenario analysis is a Monte Carlo simulation of the possible outcomes in the respective scenario models. During research, a Matlab-based software tool has been created in order to translate the logic defined by the expert team into a matrix which represents the phases and events of a certain receptor. Within the simulation, different realizations of the occurrence probabilities and times of occurrence are simulated. Based on the defined logic within the Matlab matrix, the resulting development of the considered receptor value over time can be calculated. The scenario analysis results is a graph of the probable receptor value over time for each volatile receptor (Figure 2). This information allows to determine a confidence interval of the expected value of a receptor for each time increment within the planning horizon.

3.2. Creation of configurations

Starting with an existing production system or preexisting plans of an assembly system, the six scaling mechanisms of [8] can be applied to the initial configuration of the assembly system. Not all scaling mechanisms are able to react to any receptor. A change in the expected throughput time for example cannot be compensated by a reallocation of assembly tasks to a different number of stations. However, it can be compensated by a duplication of a bottleneck station. A volatility within the receptor production volume, however, can be compensated by a reallocation of assembly tasks. According to this logic, the applicable scaling mechanisms are chosen based on the volatile receptors.

In the following, the selected mechanisms are applied to the initial configuration to create a solution space for future scaling steps. First, the intrastationary mechanisms need to be applied to the assembly system starting with the reallocation of assembly tasks. Using different criteria such as similar processes, mounting parts or process times, the assembly parts are divided or combined, creating new theoretical stations.

Taking into consideration all physical and theoretical stations, an analysis of the automation potential is carried out in the next steps. The authors created a list of automation potentials and a list of automation barriers based on a literature review and several expert interviews. The categories on this list need to be weighted by the management of the company planning the assembly system. A team of process experts checks all the stations and determine a combined automation value using the list of automation potentials and barriers. Only the stations with a positive automation value are selected for the further analysis.

In a next step, the selected stations are analyzed in greater detail. In order to guarantee the changeability of assembly stations, the authors consider the assembly stations to be modular. In total, four modules are considered, namely a process, feeding, quality and change over module. Each module has its own level of automation – except for the process module, which is a prerequisite, the other modules are optional. The described automation value is then estimated for each individual module of the identified stations. For each identified station, a theoretical station with a level of automation according to the automation analysis on the individual modules is planned.

As a result of the two intrastationary scaling mechanisms, the planner receives the full set of possible stations to include in one´s system configuration. In a next step, the interstationary and personnel scaling mechanisms are applied to the set of stations in order to create favorable system configurations. In this step, the cost of the stations needs to be considered, since the planner needs to identify the system configurations resulting in the lowest unit cost in dependence of the volatile receptors. Since the aim of this comparison is to identify the configurations with the lowest cost, it is not necessary to do full-cost accounting. Only the cost drivers resulting in different costs of the configurations are considered. Based on the applied scaling mechanisms, there are for example maintenance cost, energy cost, personnel cost and investment in equipment for the scaling of the degree of automation. Also, the changeability cost for scaling from one system configuration to another has to be considered on module level. The changeability cost include changeability object cost related to the equipment taken out of the configuration, changeability process cost related to the installation of equipment as well as indirect changeability process cost from a standstill of the assembly system [7].

The number of possible system configurations resulting from the combination of the six scaling mechanisms applied to the initial configuration is too large for further planning rounds. Consequently, the choice of permissible configurations needs to be reduced. This choice depends on the volatile receptors. The value of quality, time and variants lead to restrictions due to which part of the configurations can be discarded, since they are not meeting the requirements. A volatility in personnel cost and volume leads to a continuous dependency between the receptor and the unit cost. Thus, it is possible to discard configurations due to high unit cost over the entire expected receptor margin. Due to differences in changeability cost some configurations with high unit cost still need to be considered. Using a software tool developed by the authors, it is possible for the planner to create a set of permissible system configurations which can be used for the planning of a scaling strategy over the lifecycle of the production system.

4. Application

The practical use case of the project is the whole production process of mobile fuel cell systems. These fuel cell systems replace lead acid batteries in forklifts. In addition to providing an alternative for lead acid batteries in smaller forklifts, the fuel cell systems also compete with lithium ion accumulators and combustion engines in bigger trucks. The primary project objective is to offer an affordable fuel cell system for the European forklift market which should be facilitated by a scalable production system that can be adjusted to volatile requirements. The fuel cell system includes three different pre-assembled parts that are manufactured prior to the actual final mounting and testing procedures. So far, all assembly and testing tasks are executed manually.

4.1. Scenario analysis

The scenario analysis was conducted along three parts. Firstly, sales managers were interviewed in the qualitative scenario analysis. Secondly, the quantitative scenario analysis introduced and evaluated a stochastic scenario model via an expert workshop. Thirdly the results of the scenario analysis were communicated to the participants.

First of all, expert interviews were conducted with sales managers from the industry partner. Goal of the interviews was the evaluation of the change drivers on the fuel cell assembly system from both inside and outside the company. It turned out that only the two receptors “quantity of produced pieces” and “product characteristics and variety” are relevant in the context of fuel cell production for the industry partner. As a result, the other receptors were not pursued any further. The changes were expected to occur on a mid-term level resulting in monthly time increments. All change drivers were rated by their influence and their uncertainty. Those drivers were of special interest that had the highest possible influence as well as the highest uncertainty in the outcome – in the following, those drivers are called “key drivers”. The key drivers turned out to be: the development of fuel cell technology in the international market, the competition outcome with the lithium-ion technology, the collaboration with key costumers, the development of the investment cost structure, the desired variants by the customer. Interviewees were the development project manager for the fuel cells of the industry partner as well as two sales managers that supported the project with in-depth knowledge about the fuel cell technology and its application in forklifts.

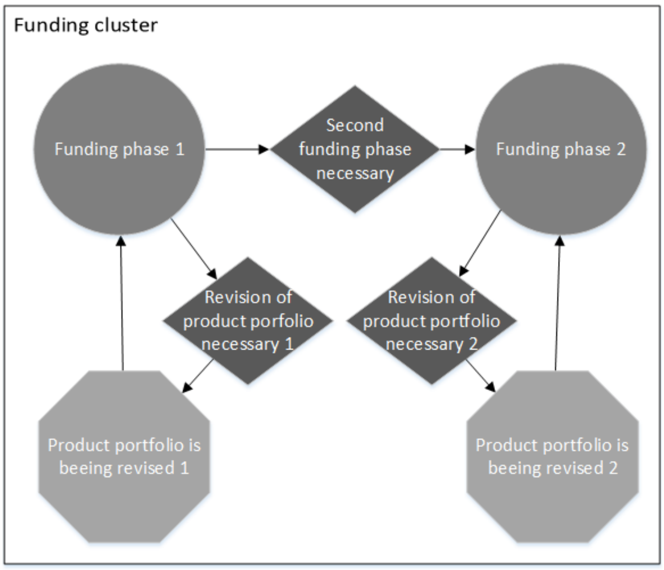

Figure 3. Segment of the stochastic scenario model for the industry partner

After the qualitative scenario analysis was finished, the quantitative stochastic scenario model can be built as the second part of the scenario analysis. The BPMN logic developed consists of three elements: stochastic events, project phases and waiting states. All the key drivers were introduced into the model as stochastic events. Those events could occur coincidently along the planning horizon and lead to a state transition. The states can be divided into project phases and waiting states. Project phases characterize a state in which the assembly system is running – quantified by a market share and a market growth rate. In a waiting state, the assembly system is not running. It is characterized by the expected waiting time. An example of the application of the symbols is given in Figure 3. It shows a segment of the stochastic scenario model, more precisely the so called funding cluster as the first part of the stochastic scenario model. Starting in “funding phase 1” either the event “revision of product portfolio necessary 1” could occur which leads to a waiting time for the revision of the product portfolio. Or a second funding phase would be needed to prolong the funding period until the fuel cell is ready for the market. If neither of the two events occurs after a certain period of time, the process continues with a different cluster.

For the quantification of the model the experts were invited to a scenario workshop. They were asked to quantify the phases in terms of produced fuel cells. The scenarios were developed for two different fuel cell variants that could approximate the whole fuel cell portfolio of the industry partner. For the different events, the experts were asked about the occurrence probability as well as their expected time of occurrence. Finally, the experts should give an estimation of the waiting time they expect during the project phase.

After having organized all data and having established a first scenario simulation model, the first trajectories could be calculated in the third part of the scenario analysis. It turned out that the experts had differing expectations about the probability of occurrence for the key drivers. This fact contributed alongside the basic structure of the model to a high uncertainty of the prediction for the production volume. While the prediction for the first year of the planning horizon is quiet stable with a margin of 400 units. The prediction at year 4 already varies around 5000 units. At the end of the planning horizon in year 10 there is a margin of almost 80.000 units. These results were presented to an interdisciplinary and crossdepartmental team of mechanics, electronics, quality, development, assembly and purchase.

4.2. Creation of configurations

In the second part of the methodology, the different configurations of the assembly system were created. This part builds on the results from the scenario analysis in the following matter: the scenario analysis describes the top-down view from change drivers to expected receptor trajectories while the creation of configurations works bottom up from possible changes in the assembly system to meet the requirements of the expected receptor trajectories. Consequently, a detailed analysis of the current production process was needed as well as an assessment of possible further technical developments. The creation process can be divided into four parts: analysis and reallocation of assembly tasks, assessment of automation criteria and evaluation of the assembly stations on a modular level, creation of process alternatives following a priority scheme, description and quantification of the configurations to suit the cost optimization method of SA.

First of all, the pre-defined assembly stations where analyzed according to their assembly tasks. An assembly precedence graph was created for all pre-assembled parts as well as the final mounting and testing procedures. Some tasks that were not essential for the precedence flow could be outsourced to modular assembly stations to reduce the actual process flow and decrease takt time for the different groups of assembly tasks. As a result, the actual process flow was designed to be scalable to allow a range from two up to six different reallocation concepts from which can be chosen depending on the desired takt time.

Secondly, in order to focus on the degree of automation in terms of pursued scaling mechanisms, the automation potential had to be evaluated for all the groups of assembly tasks. The objective was to find factors that have an effect on the automation of assembly processes in general and to find possible automation alternatives for the single modules of each assembly station in particular. It turned out that the factors that influence process automation can be divided into four groups: technical factors that hinder the automation of a process step, organizational factors that require certain management actions, human factors that influence the assembly staff directly or change the requirements regarding their qualification and economic factors that have an influence on the cost structure of the assembly system. These factors were weighted according to an independent assessment by the top management of the industry partner. It turned out that the most important factors were the economic factors: reduction of takt time, saving cost for personnel, increase of product quality. But also several technical issues with automation could be stated including complex alignment processes, handling issues with special product design and transport of parts with a high variety in terms of dimensions and weight.

Based on these criteria 7 stations of the existing assembly line were evaluated. Two stations were rated with a clearly negative automation value of -1.3 and -0.94. In the first case the negative result stems from a very low potential of 0.52. In the second case high barriers stemming from high variance in handling operations and safety restrictions led to the negative automation value. One of the stations were rated with a moderately negative automation value. Four stations were rated with positive automation values of up to 0.44 mostly due to high economical potentials and reasonably low barriers for the automation of screwing operations.

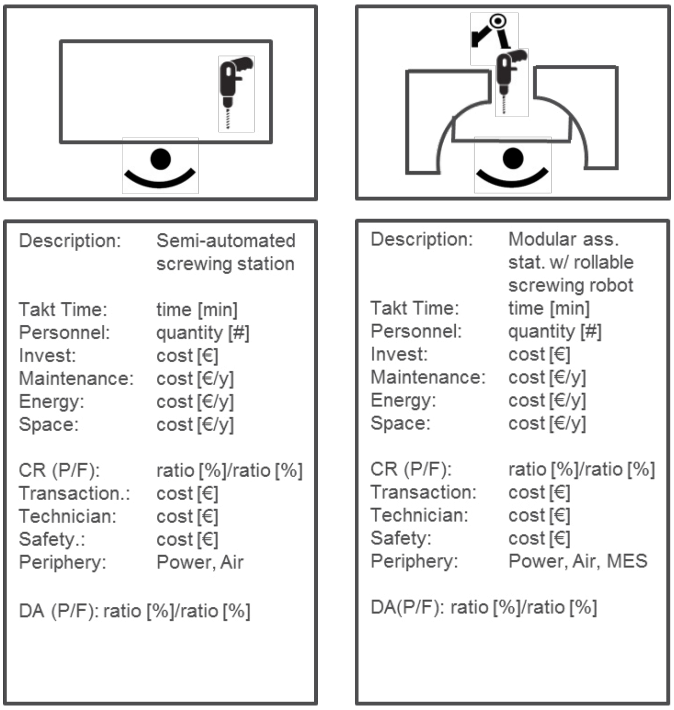

Figure 4. Examples of process characteristics

After having evaluated the automation criteria for all assembly stations, the configurations could be created in the second step. For the four stations with a positive potential-barrier ratio, automated solutions were planned in collaboration with the production development department. The most relevant results can be stated in the automation of the screwing process of the powerbox station, assisted assembly of the battery pack and automation procedures in the end of line test.

The assessment of the automation criteria and the conception of the automated solutions showed that quantified information about the possible configurations was needed. Therefore, so called “process characteristics” were developed that contain all the information needed to describe the process alternatives. These process characteristics can be used in connection with the scenario simulation outcome to find the cost optimal configuration of the assembly system for the whole examination period. Examples of process characteristics can be seen in Figure 4. They show the general structure of the assembly station – in that case the station for the so called “powerbox”. It is a modular station which consists of an assembly desk, two lateral sections for the material and a rollable dolly for the screwing system. The station can be quantitatively described by its takt time, the average amount of workers needed and different costs that either arise only once or on a regular basis. The fix cost that is only paid once consists of the investment cost, the cost for setting up or stripping down the station – these two values are assumed to be equal – and the related conduction cost for the technician as well as the cost for re-establishing process capability. The running costs that are paid regularly are composed of the cost for maintenance, energy and space. Furthermore, the changeability ratio (=CR) is assessed in order to be able to compare the station to others considering the exchange of single modules. In this context, the process modules (=P) and feeding modules (=F) are rated separately.

Within a discrete event simulation using the six scaling mechanisms, the non-dominated system configurations were calculated and characterized by a cost function depending on the produced volume of fuel cells. The simulation showed that the expected moderate increase in volume could be handled with the initial manual line and an increase in the number of assigned workers. The higher volumes need a configuration with all mentioned automation solutions plus a duplication of the EOL test station.

5. Conclusion and Outlook

In the present paper, a new methodology for the conception of scalable assembly systems was introduced. The methodology consists of two parts of which the first part is the scenario analysis used to identify the relevant change drivers and to quantify their effect on the receptors. The second part is the creation of configurations to build modular concepts for a scalable assembly system focusing on scaling up the degree of automation to meet management requirements.

The results of the use case show that the supposed method can be applied to an actual industry use case and support the scalability of production systems. It also became clear that in order to reach a true scalability of a production line it is essential to consider automation barriers already during product development. Early changes to the product can result in lower automation barriers and hence a higher scalability of the level of automation.

Further research is needed to support the creation of a scaling strategy. In order to benefit from the scalability of the production system, the planner will need a strategy that allows to define which system configuration should be installed at which moment in time. Once this strategy is established, the planner disposes of valuable information about which system configurations are likely to be installed. Further research is needed for exploring the possibilities to make use of this knowledge.

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