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Autonomous planning tool for changeable assembly systems

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Abstract

Car manufacturers are expected to start series production of fuel cell vehicles within the next years. Simultaneously, other industries are pushing towards the utilization of fuel cells. Fuel cell manufacturers need to scale up production at the right time and react to changing product requirements with the ideal level and point of changeability. This complex task requires methods and tools for decision support. The authors present SkaliA, an autonomous planning tool, which generates guidelines for the efficient use of change enablers specific to an assembly system. The planning tool is demonstrated on the example of an assembly system for high pressure valves used in fuel cell applications.

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Keywords: Changeability; fuel cells; Scalable Automation

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1. Introduction

Technological research on proton exchange membrane fuel cells (PEMFC) dates back to the 1950s when first patents were issued. A wide application however is still not taking place. In Japan however, the government follows a clear strategy towards the “hydrogen society” and Toyota has become the leading car manufacturer for fuel cell vehicles [1]. Korean car manufacturer Hyundai is also pursuing a strong hydrogen strategy, introducing first fuel cell vehicles in series production [2]. In Europe, car manufacturers are a little more hesitant. Still, Daimler and BMW are planning on the introduction of fuel cell vehicles to a wider public by 2021 [3,4]. Even though, the global market for passenger vehicles is a big opportunity for a successful implementation of PEMFC, other applications, like intralogistics, harbor logistics and many other mobile applications are being explored [5]. Against the high hopes for the fuel cell stands the risk of missing infrastructure, competing technologies and public acceptance [6,7]. As a result, suppliers of hydrogen technology are facing a dilemma. The industry is able to produce fully functional PEMFC in very small numbers. If demand picks up and a supplier did not invest in sufficient production capacities he will be overrun by his competitors. If, on the other hand a supplier invests in expensive facilities for high volume PEMFC production and the demand does not pick up in due time, the cost of unused equipment will lead to dramatic losses.

Subsequently, suppliers of hydrogen components are in need of changeable production systems, which enable them to quickly adapt to a volatile and uncertain market, whilst requiring a minimal investment for production capacities. These systems require a planning of the right amount of changeability at the right place within the production system. The authors propose the planning tool SkaliA for the identification of guidelines supporting the production planner in planning a changeable production system.

In the following section a literature review of approaches to the planning of changeable production systems is presented. Section 3 focuses on the proposed method for the planning of changeable production systems in 4 steps: Scenario analysis, solution space, scaling strategy, guidelines. The methodology is applied to the use case of high pressure valves for PEMFC application, using SkaliA in section 4. The paper concludes with a summary and an outlook on further investigation in section 5.

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2. Planning of changeable production systems

Several approaches for the planning of changeable production systems can be found in the literature. Loferer introduced a software tool which enables a production planner to develop modular assembly stations [8]. The tool applies the VDI 2860 to derive submodules for modular stations from an input of assembly tasks. Based on the approach of Loferer, Kluge developed a methodology which is taking into account a scenario analysis of change drivers as an additional input for the selection of submodules [9]. Just like these approaches, the methodology of Weyand focuses on adaptations to changes in the product [10]. On the example of the production system of a car manufacturer the existing method is adapted to enable product and value changes with a focus on the reuse of production equipment after changes.

The approaches of Loferer, Kluge and Weyand concentrate on establishing a high level of changeability. Pachow-Frauenhofer developed a way to identify the economically ideal level of changeability [11]. In her approach she models the production system as a control loop which tries to optimize a target function with multiple economical KPIs. Change drivers are modelled as disturbances to the control loop. A structured approach of quantifying the impacts of change drivers and their interdependencies is proposed by Moser [12].

Landherr introduces an approach which aims at minimizing the change cost [13]. Based on the works of Loferer and Kluge he focuses on the change cost on the level of assembly station sub modules. The heart of his approach is an integrated hierarchical and functional model of product features and assembly station modules. The described approaches focus on mid to long term changes which require adaptations of the production system. Immediate reactions to short term disruptions of the production system however require special mechanisms. The works of Neumann focus on these short term changes [14]. In his approach Neumann considers short term deviations from the production plan due to machine failures or changes in customer orders. Different reactions to these deviations are simulated in order to estimate the impact on the KPIs of the production system.

Table 1. Applicability of existing approaches to the addressed challenge

Author	Consideration of uncertainty	Scalable level of automation	Consecutive changes	Short term changes
Loferer	no	partially	no	no
Kluge	partially	no	yes	no
Weyand	no	partially	no	no
Pachow-Frauenhofer	partially	no	no	partially
Landherr	partially	no	no	partially
Neumann	partially	no	no	yes
Moser	yes	no	no	no
Eilers	partially	partially	yes	no

A more strategic approach considering the long term impact on a production system due to changes is proposed by Eilers [15]. He developed a method for the planning of scalable and reconfigurable assembly systems. Over a planning horizon of several years he plans several consecutive changes on one scaling path. The performance of a scaling path is measured on static best and worst case scenarios of production volume and product changes.

In order to fulfil the goal of supplying use case specific guidelines for a changeable production system, as described in section 1, four requirements need to be fulfilled:

- Uncertainty of the occurrence and the impact of change drivers must be considered
- The proposed solutions should consider a scalable level of automation
- Consecutive changes of the production system should be considered in order to derive guidelines leading to a long term minimization of production cost
- The solution should allow short term changes to the production system

The approaches of Kluge and Loferer provide important concepts for the construction of modular systems, but due to their technical focus on the station level they are not directly transferable to the planning of complete assembly systems. Weyand's approach is strongly tailored to the final assembly of automotive applications. An adjustment of the degree of automation is only considered marginally. The consideration of the assembly system as a control loop by Pachow-Frauenhofer, Landherr and Neumann offers relevant approaches, especially with regard to short-term adjustments. However, these approaches essentially focus on a reconfiguration of the system. A consideration of the life cycle of the assembly system as well as an explicit consideration of a scalable degree of automation are neglected. Moser focuses on a complex scenario analysis and the consideration of uncertainty. His methodology however focuses on the adaptation of a global production network, rather than a single production system. The approach of Eilers offers an essential basis. The structured representation of the scaling mechanisms and the scenario-based consideration of change drivers on assembly system level are an important prerequisite. However, the approach does not offer the possibility of planning a system with a scalable degree of automation, since essentially rigid system configurations and discrete degrees of automation are assumed.

Table 1 shows the fulfilment of the requirements by the reviewed approaches. Since no existing approach meets all the requirements, the authors propose a new method for the planning of changeable assembly systems.

3. Methodology

In order to meet the requirements introduced in section 2 the methodology is split up in 4 steps. First the uncertainty is quantified in a scenario analysis based on change drivers. Secondly, the solution space of available configurations of the production system is developed. In the third step, the results of step 1 and 2 are combined to the formulation of a Markov Decision Problem (MDP). The solution resulting from the computation of the MDP is a scaling strategy assigning a proposed change to each situation formulated in the original MDP. The fourth step derives guidelines for the construction of assembly stations from the scaling strategy.

3.1. Scenario analysis

A widely used tool in the literature to model uncertainty is the use of change drivers. However, the determination of the impact of change drivers on a production system is not covered by this concept. Cisek introduces the receptor theory, addressing this challenge [16]. The receptors production volume, product, time, quality, technology and cost are considered as the link between volatile environment and a production system. In order to quantify the impact of the receptors, the authors define receptor KPIs whose changes lead to direct consequences within the production system. Basis of the scenario analysis is a scenario model consisting of change drivers and receptor KPIs. Each volatile change driver is mapped to at least one receptor KPI.

Each change driver $x_{n,}$ is described by its occurrence probability and the moment of occurrence. The relation between change driver and receptor KPI is described by the absolute impact ba_{x_n}, the relative impact br_{x_n} and the change of trend m_{x_n}. Based on a distinct realization of the change drivers the value $f_t(x_1, \dots, x_{n,})$ of a receptor KPI at time t can be calculated as defined in equation 1.

$$f_t(x_1, \dots, x_{n,}) = f_{t-1} * m(m_{x_1} * \dots * m_{x_n}) + f_{t-1} * (br_{x_1} + \cdots + br_{x_n}) + ba_{x_1} + \cdots + ba_{x_n} \qquad (1)$$

Using a Monte Carlo Simulation several scenarios of a receptor KPI over the planning horizon can be calculated. The single scenarios are combined to one aggregated scenario for each receptor KPI. These aggregated scenarios consist of probability values for the transition from each discrete value class of a time period to the next.

3.2. Solution space

In order to develop a changeable production system, a modular station concept is a prerequisite. The authors define 4 hierarchical levels of a modular production system (Fig. 1).

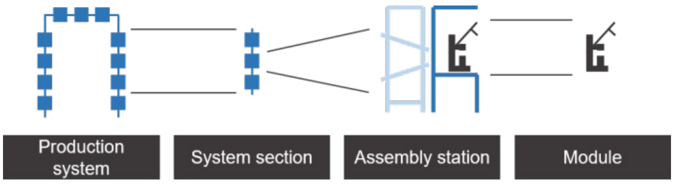

Fig. 1. Modules of the changeable production system.

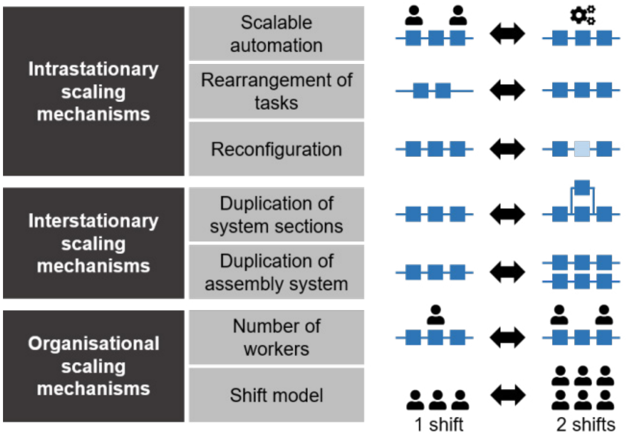

Fig. 2. Scaling Mechanisms

The overall production environment used to produce the product is defined as the production system. This does not include logistics between warehouses of the factory. A system section is a part of the production system which shares no resources with other system sections of the production system. A system section consists of at least one assembly station. The assembly stations within a system section are independent of each other. The only connections are commonly used manipulators like a robot or a human worker. Each assembly station consists of up to three independent modules for transport of the main workpiece, process and the feeding of mounting parts.

In a brown field approach this method starts from an initial state of the production line. Alternative configurations are developed by applying the scaling mechanisms formalized by Eilers [15] (Fig. 2). The authors group the scaling mechanisms reconfiguration, rearrangement of tasks and scalable automation into the intra-stationary scaling mechanisms. Duplication of system sections and duplication of production systems are grouped into the inter-stationary scaling mechanisms. The organizational scaling mechanisms consist of changes in the shift model and the number of workers in the production system (Figure 2). By the application of the scaling mechanisms to the initial production system, additional configurations of the production system are created. These system configurations are being created by applying the scaling mechanisms starting with the inter-stationary scaling mechanisms. After this, the planning software can apply the inter-stationary and organizational scaling mechanisms automatically, using the system sections created by the application of the intra stationary scaling mechanisms as the smallest building blocks.

From the combination of the intra-stationary scaling mechanism results a vast range of possible new station concepts. In order to master this complexity, a *station map* is introduced, visualizing the combination of scalable automation and rearrangement of tasks for the production system. The rows of the map represent the various combinations of assembly tasks in one assembly station. For each field in this station map an analysis of automation potentials and obstacles is carried out. Based on this analysis the fields in the station map with the best relation of automation potential to obstacle are being selected for the development of station concepts. The results of the station concepts are documented in station profiles including all relevant information. In order to make use of common manipulators and to reduce complexity of the algorithm, station concepts are grouped into system section concepts. Based on these system section concepts an algorithm applies first the intra-stationary, then the inter-stationary and finally the organizational scaling mechanisms in order to create the various system configurations.

3.3. Scaling strategy

The aggregated scenarios created in step 1 are combined with the solution space developed in step 2. The goal of this step is to calculate a scaling strategy which defines a cost optimal action for each situation within the planning horizon. Since, this is a decision problem under uncertainty, it can be modelled as a Markovian Decision Problem (MDP) [17]. The state of the production system is modelled as the combination of a deterministic state, consisting of the different configurations of the assembly system and a stochastic state, consisting of the values of the receptor KPIs. The transition between these states over the planning horizon is defined by the actions triggering the change from one deterministic state to the next and the stochastic values of the receptor KPIs. After the MDP has been fully modelled, the scaling strategy can be calculated by solving the MDP with a backward induction algorithm.

3.4. Construction guidelines

In order to detect the right point and level of changeability it is necessary to identify the areas of the production system which require the highest level of changeability. The scaling strategy calculated in step 3 holds valuable information about the expected volatility of the production system. Since each state of the production system has been assigned a cost optimal action as well as a probability of occurrence it is possible to calculate an expected value for the number of changes for each change between configurations of the production system. Based on these expected values the expected values for the number of changes between system sections is being calculated.

After the completion of the scaling strategy analysis the changes on assembly station level with the highest expected values are being categorized in a morphological box. The morphological box consists of six categories:

- Change Type, is the assembly station being added, removed or exchanged
- Change frequency
- Purchase cost of the assembly station
- Existence of a counter event
- Affected module
- Level of automation of old and new assembly station

An initial catalogue of construction guidelines has been created and linked to distinct configurations of the morphological box. During the use of the methodology these guidelines should be expanded to fit specific production systems. The implementation of the selected guidelines should support the design engineers in constructing an assembly system with a cost optimal changeability.

4. Case study

Within the research project Inline [18] the methodology has been applied to a manufacturer of high pressure valves dedicated to the use in mobile fuel cells. In order to carry out the calculations required for the Monte Carlo Simulation of the aggregated scenarios and to solve the MDP, SkaliA was developed by the authors. The software tool supports the user throughout all four steps of the planning process.

4.1. Scenario analysis

During a series of expert interviews with employees of the valve manufacturer a total of nine change drivers could be documented. The receptors influenced by the documented change drivers were product, production volume and lead time. These receptors were translated into the receptor KPIs production volume, lead time and maximum pressure required. Based on certain constellations of the change drivers, it was considered possible that the current requirement of a maximum pressure of 700 bar on the tank could be extended up to 1000 bar, which would require stainless steel valve bodies instead of aluminium valve bodies. Figure 3 shows the impacts of the nine change drivers to the receptor KPIs.

The change drivers were entered into SkaliA including name, description, probability of occurrence as well as the earliest, latest and most probabale period of occurrence. The receptor KPIs were entered including name, initial value, initial trend and change driver impacts. A change driver

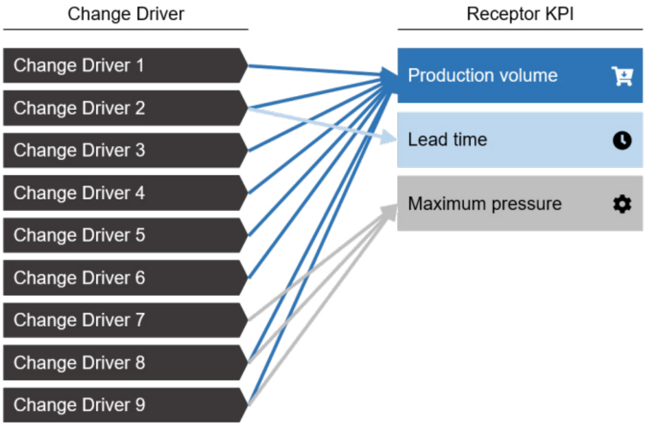

Fig. 3. Change drivers and receptor KPIs.

impact consists of three factors. The trend impact, relative impact and absolute impact. With this information SkaliA carries out the Monte Carlo Simulation in order to calculate an aggregated scenario for each receptor KPI, which are being stored in the SkaliA database. The values of the receptor KPI production volume were grouped into 10 classes. Lead time and maximum pressure could be grouped into two classes each, based on the results of the Monte Carlo Simulation.

4.2. Solution space

The initial production system of the use case consists of four manual assembly stations and a semi-automated tightness test. The assembly consists of complex handling tasks, with a high variety of different parts which have to be mounted to the valve body. Due to this reason the scaling mechanism rearrangement of tasks has been applied to the assembly stations in order to reduce the complexity per station and enable automation of certain tasks. The station map in figure 4 shows the initial state of the production system as well as the new concepts for station concepts after the analysis of automation potential and obstacles.

Based on the final station map 9 system section concepts have been developed, documented in system section profiles and entered into SkaliA. The application of the inter-stationary and organisational scaling mechanisms lead to a total of 864 system configurations.

4.3. Scaling strategy

The planning horizon was defined as 8 years, with planning periods of 3 months, resulting in a total of 32 planning periods. With a total of 864 deterministic states, 40 stochastic states and 32 planning periods the final scaling strategy consists of 1.105.920 data entries. Accordingly, 1.071.360 actions have been defined, since for the last planning period no actions have to be defined. SkaliA calculated the scaling strategy solely based on the results of steps 1 and 2 without additional user input. The scaling strategy is stored in the SkaliA data base and can be accessed by entering a combination of system configuration, class values of the aggregated scenarios and planning period. Figure 5 shows an example of a situation in which the scaling strategy proposes a change to a new system configuration for the following period.

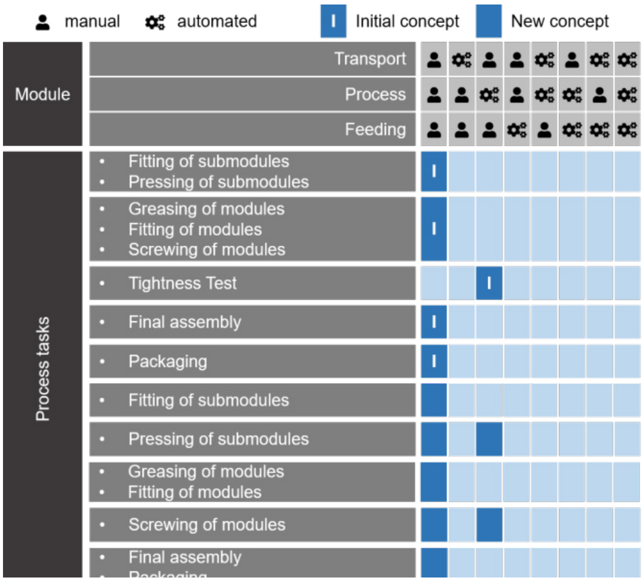

Fig. 4. Station map after analysis of automation potential and obstacles.

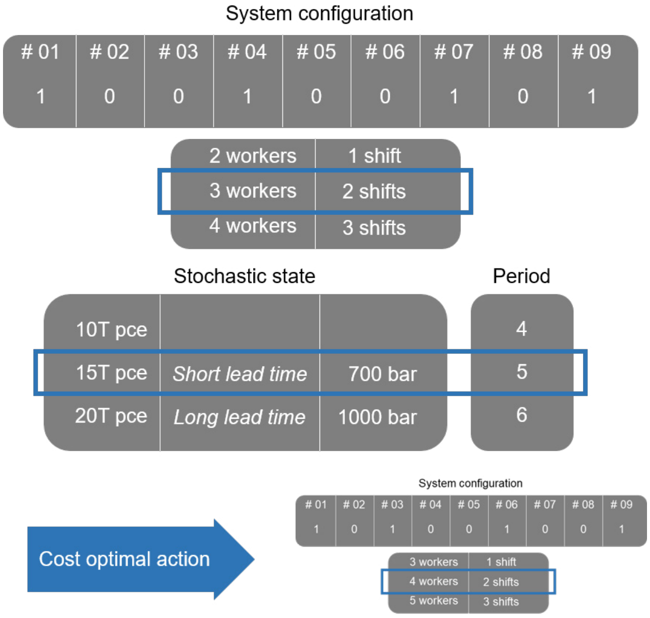

Fig. 5. Excerpt of the scaling strategy.

4.4. Construction guidelines

SkaliA automatically calculates the occurrence probabilities of the changes on the level of system sections based on the scaling strategy. Based on the results in the case study fine planning of the semi-automated sub module assembly and the semi-automated module assembly have been initiated. Skalia supposed 13 construction guidelines for the design of these two stations, based on the classification of changes into the morphological box. For example it was supposed to align the tooling for manual and automated processes for screwing and pressing operations in order to minimize the change cost.

5. Summary & Outlook

A new method for the planning of changeable production systems has been proposed. The method consists of four steps. In step 1 the change drivers impacting the production system are collected and mapped to the receptor KPIs channelling the impact on the production system. A Monte Carlo Simulation is applied in order to generate aggregated scenarios of the trend of each volatile receptor KPI. Step 2 generates the solution space of changeable configurations for the production system. Scenario analysis and solution space are being combined in step 3 in order to model a Markov Decision Problem of the planning situation. In the final step 4 concrete construction guidelines are derived from the scaling strategy advising the station design to develop stations with an optimized level of changeability. The method has been applied to the case of a manufacturer of high pressure valves. For the successful implementation, SkaliA, an interactive software tool has been developed. All manual planning results can be entered into SkaliA through a graphical user interface. The results are being calculated within the SkaliA server and stored in the SkaliA data base. Finally the results are being displayed in the graphical user interface.

In future works, the method will be expanded to consider waiting times for the implementation of new system sections. Furthermore SkaliA will be improved to offer a more comprehensive visualization of planning results and an extended data base of construction guidelines linked to the morphological box.

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