Industrial Application of a MDM-based Approach for Generation and Impact Analysis of Adaptation Options - a Case Study

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***Abstract*— Global trends in manufacturing urge existing machines to become more flexible, as the production environment becomes increasingly dynamic. In order to attain this "flexibilization", existing machines have to be adapted during their operational phase, i.e. mechanical changes, changes of sensors and actuators, software changes, or a combination thereof have to be performed. The adaptation of existing machines is a complicated and time-consuming process, as various interdependencies have to be considered. Therefore, a systematic approach for generating adaptation options is crucial for a successful adaptation of machines. State-of-the-art approaches primarily focus on the adaptation of products and, thus, are not appropriate for manufacturing machines. Accordingly, this paper presents an approach for the generation of adaptation options to support the adaptation of manufacturing machines. Furthermore, a use case study is presented and discussed, where the approach is applied to an industrial manufacturing machine. Here, the results demonstrated that the approach is applicable for an industrial manufacturing machine and can automatically generate valid adaptation options.**

Keywords—adaptation options, change impact analysis, manufacturing machines, modernization, flexibility

I. Introduction

Although automated manufacturing machines are usually developed for a static production environment and mostly do not offer the required flexibility to automatically comply with nowadays frequently changing environmental conditions, these systems are expected to stay in operation for multiple decades. These changing environmental conditions such as shorter product (variant) lifecycles, volatile customer demand and variable product variants and portfolios [1, 2] force the machine to evolve in order to cope with the changing production requirements [3].

In cases when the foreseen flexibility is not sufficient to comply with the changing requirements, an adaptation of the manufacturing machine is required. In the literature, the term adaptation is primarily used for describing the evolution of a system with regard to changing environmental conditions in different domains [4]. In the field of automated manufacturing machines, adaptation comprises of changes in the physical structure of a system and/or its automation software. Since automated manufacturing machines are mechatronic systems, multiple disciplines are involved in the adaptation process. According to [5], adaptations of automated manufacturing systems can be classified into three categories, namely (1) Integration of manufacturing operations; (2) Adaptation of operation parameter ranges; (3) Adaptation of material flow. Depending on the changed requirements, adaptation actions of one or more categories need to be implemented to satisfy the new requirements.

Although a common understanding of the term "adaptation" exists, no consistent definition of the adaptation process of manufacturing machines can be found in the literature [6]. While mostly the adaptation process is performed individually and without methodological support, which is error-prone and time-consuming [5], some approaches can be found in the literature that propose modelling techniques that aim at supporting the generation and impact analysis of adaptation options (e.g. [7, 8, 9]). Using these modelling techniques and a subsequent generation and impact analysis of adaptation options, the adaptation process can be methodologically supported.

An important aspect of this methodological support is the industrial application and evaluation of these approaches. Thus, this paper presents and discusses the results of a case study where the approach based on the methodology suggested in [10] and [11] was applied to a manufacturing machine in the tobacco industry.

The remainder of this paper is structured as follows: Section II gives an overview about related works that are suitable for the generation and impact analysis of adaptation options. Section III briefly summarizes the approach that is applied in the case study. Section IV describes the results of the case study. Finally, the paper closes with conclusions and an outlook on future works in Section V.

II. Related Works

In this section, existing approaches that are suitable for the generation and impact analysis of adaptation options are described. Applicable approaches have been introduced in the field of engineering change management where many works address the modeling of interdependencies between product elements and the analysis of change propagation. These approaches can be roughly classified into two categories: (1) approaches that model interdependencies between components of the system and (2) approaches that model interdependencies between system parameters.

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Approaches of the first category model interdependencies between the components of the system usually by using probabilities or binary values. To display the interdependencies, most approaches use a matrix-based representation form [12, 13, 14] (Design Structure Matrix (DSM) or Multiple Domain Matrix (MDM)). Although the modeled information is at least partly sufficient to identify possible impacts of component changes on other components, the automatic generation of adaptation options is not supported. It is also not considered that the change of a component can be performed in different ways and thus, can result in different propagation paths [15].

Approaches in the second category focus on the modelling of interdependencies between parameters of the system. Ollinger and Stahovich [7] describe interdependencies between product parameters by quantity constraints and causal influences between quantities. The modeled information is used to generate adaptation options to achieve defined redesign goals of the product. Based on that work, Yang and Duan [8] classify interdependencies between product parameters into physical links, which cannot be changed, and design links, which are regarded as modifiable. The interdependencies are modeled as algebraic functions which can be used to generate different change propagation paths for given initial changes. Ahmad et al. [9] present an approach which comprises four different layers. On the top layer, requirements representing changes are contained. These requirements can be tracked down to detail design layers where linkages between parameters can be analyzed. The results of this analysis can be used to generate adaptation options for the given requirements.

A frequently used concept in this field is modularization. By identification of adaptive modules [16], the modules can be reused in future projects [17]. A good modularization enables to limit the impact of changes to a specific module and thus, simplifies to determine the change propagation.

To sum up, the approaches of the second category provide an appropriate basis for the generation of adaptation options and the corresponding impact analysis. However, a disadvantage of most existing approaches in this category is the quantity and level of detail of the required data which can have an impact on the industrial applicability. Moreover, since the works are rooted in the engineering change or product design community, the approaches cannot be applied to automated manufacturing machines directly. With regard to the adaptations of manufacturing resources in mechatronic systems, interrelations between product, process and resource elements have to be considered in the generation of adaptation options. To overcome these limitations, an approach was developed by the authors which is described in section III.

III. APPROACH FOR THE GENERATION AND IMPACT ANALYSIS OF ADAPTATION OPTIONS FOR AUTOMATED MANUFACTURING MACHINES

The proposed approach for the generation and impact analysis of adaptation options consists of three steps overall. In the first step, the technical process of a machine is modelled with the formalised process description. This process description was developed for the modelling of technical processes and is introduced in the guideline VDI/VDE 3682 [18]. According to the guideline, a technical process has one or multiple input products, information and energies that are transformed during the process and result in one or multiple

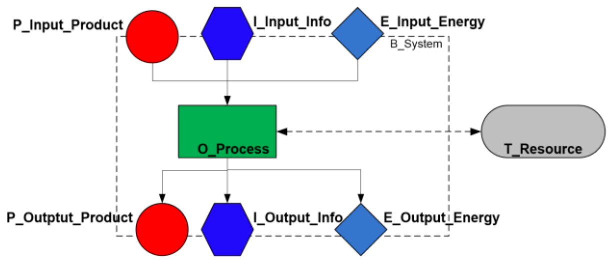

Figure 1: Example of the formalised process description

output products, information and energies. For the transformation, the technical process utilizes a technical resource. Moreover, a technical process can be decomposed into further technical processes. An example of the formalised process description is depicted in Figure 1.

In the second step, for each technical process, the interdependencies between the process and its technical resource as well as its input and output elements are analyzed and modelled on a parameter level in a Multiple-Domain-Matrix (MDM), which is a frequently used description technique for the modelling of interdependencies of complex products in the domain of engineering change management. In the MDM, the interdependencies are described qualitatively as correlation relations or constraints. Here, correlations are noted by the symbol '+', in case of a positive correlation between two parameters, or by the symbol '-', if a negative correlation between parameters exists. Interdependencies between two parameters where no clear statement about the correlation can be made are noted by the symbol '0'. Regarding the notation of constraints, the symbols '<', '>', and '=' are used, which describes a "less than", "greater than" and "equal" constraint, respectively. For a more detailed description of the MDM, the reader is referred to [10].

In the third step, the processes including their MDMs are analyzed regarding adaptation options and their impact on further elements of the system. For the impact analysis and adaptation option generation, a rooted tree graph is constructed and used. The nodes of the tree represent system parameters, whereas the edges depict interdependencies between parameters. In the first level of the tree (level 0), the nodes can represent the product parameter that is initially supposed to be adapted and the process parameters that have to be adapted because of the product parameter adaptation. Nodes on level 1 or higher denote resource, product, or other process parameters that have a direct influence on the adaptation of the parameters of the preceding level. Note here that parameters which restrict or are affected by an adaptation of a node are located in the same tree level as the restricted parameters. In the rooted tree, dashed edges denote "less than" or "greater than" constraints and continuous edges "equal to" constraints. Correlation relations are depicted by the edges by the same symbols as in the MDM. Furthermore, in the rooted tree graph each parameter is denoted with a type of change, which describes the direction of an adaptation. Here, a parameter can be increased, which is denoted by the symbol '↑', or decreased, which then is denoted by the symbol '↓'. If no statement about the adaptation direction can be made, the type of change is denoted by the symbol '→'. A detailed description of the rooted tree graph as well as the algorithm for the impact analysis and option generation can be found in [11].

IV. CASE STUDY

The developed approach has been applied to a cigarette-manufacturing machine in the tobacco industry. Due to restrictions on the disclosure of information, certain parts of the case study are only discussed on an abstract level in this section. In the initial situation of the case study, a customer requested a material change of one of the input products of the machine. Thus, the company had to analyze if the current setup of the machine could run with the new material. For this purpose, the presented approach has been utilized.

In the first step, the technical process of the machine is modelled according to the VDI/VDE 3682, which results in 19 processes in total after decomposition. Note here that in the process model solely products have been considered as input and output elements. Based on the process model, a pre-analysis has been conducted where six processes have been selected, which were most likely to be affected by the material change. The further analysis steps were focused on these six processes to reduce the effort of modelling. For these processes, MDMs and adaptation options have been generated. Due to space restrictions, only the simplest process is discussed in detail in the following.

The considered process is a handling process, where the produced cigarette sticks are transferred to a catcher drum. In this process, a double accelerator with two accelerator disks accelerates the sticks that come from a garniture tape into the catcher drum. Because of the requested change of the initial input product, the input product parameters of this process have also changed. Here, the weight of the input product has increased. Based on this knowledge, the MDM was modelled by taking all process and resource parameters into account that are related to the weight increase of the input product. The MDM has been constructed by interviewing the engineers of the company. Note here that it is not efficient and expedient to modell all existing interdependencies. The MDM of the handling process is depicted in Figure 2. Here, for instance, by analyzing the row "PdI_Weight", it can be concluded that the increase of the input product's weight is constrained by the acceleration force of the process, and because of the correlation relation, this constraint can be relaxed by increasing the acceleration force. Note here that process and resource parameters in the MDM are noted with a "P" or an "R" at the beginning, respectively. Whereas, input product parameters start with "PdI" and output product parameters with "PdO".

For the third step, the algorithm presented in [11] has been implemented as a java application, to automatically analyze the MDMs and generate adaptation options including an impact analysis. Based on the depicted MDM in Figure 2, the algorithm generated seven adaptation options to adjust to the increased weight of the input product. The algorithm identified that the increase of the input product's weight can result in a violation of the parameter "allowed weight" of the process. Therefore, in the adaptation option 1, the algorithm suggested an increase of the acceleration force, to increase the allowed weight of the process by increasing the transmission of the double accelerator (resource). However, the increase of this resource parameter would also result in an increase of the acceleration velocity of the process and thus, also in an increase of the velocity of the output product. The outlined interdependencies are depicted by the tree graph in Figure 3. In the second suggested option, the process' acceleration force should also be increased. But in this case, by increasing the normal force of the process. This normal force increase should be achieved by the decrease of the distances between the two disks. However, the algorithm identified that this adaptation would result in a decrease of the process parameter "allowed width", which then could require a decrease of the diameter of the input and output product to fit between the disks. The tree graph of option 2 is depicted in Figure 4. Option 3 suggested an increase of the double accelerator's torque to increase the acceleration force, which can be accomplished without further implications. Option 4 included the reduction of the disks' radii without changing their distance to increase the acceleration force. This adaptation would result in the increase of the process' acceleration velocity and hence, result in an increase of the output product's velocity. Option 5 proposed to increase the accelerator's friction, e.g. by roughening the surface of the disks, to increase the normal force, which would also increase the acceleration force. As the option 6 the algorithm suggested to increase the input product's diameter to increase the process' normal force. Option 7 included the increase of the roughness of the input product. Note here that the options are not ranked or ordered by any criteria. Also, combinations of the options could be created to generate further options. Moreover, it should be mentioned that the adaptation options are on a qualitative level, i.e. it has to be further analyzed whether the options can achieve the desired adaptation on a quantitative level.

Accelerating	P_allowWeight	P_allowWidth	P_NormalForce	P_AccellerationForce	P_AccellerationVelocity	R_Accelerator.Torque	R_Accelerator.NoR	R_Accelerator.Transmission	R_Accelator.Radii	R_Accelerator.Friction	R_Accelerator.Distance	PdI_xDiameter	PdI_Velocity	PdI_Weight	PdI_Elasticity	PdI_RollingFriction	PdO_xDiameter	PdO_Velocity
P_allowWeight				+										>+				
P_allowWidth											+	=+			+		=+	
P_NormalForce										+	-	+				+		
P_AccellerationForce			+			+		+	-									
P_AccellerationVelocity							+	+	+				>+					=+
R_Accelerator.Torque																		
R_Accelerator.NoR																		
R_Accelerator.Transmission																		
R_Accelator.Radii																		
R_Accelerator.Friction																		
R_Accelerator.Distance																		
PdI_xDiameter		=+	+															
PdI_Velocity					<+													
PdI_Weight	<+																	
PdI_Elasticity		+																
PdI_RollingFriction			+															
PdO_xDiameter		=+																
PdO_Velocity					=+													

Figure 2: Multiple-Domain-Matrix of the considered handling process

The generated adaptation options have been discussed with the engineers of the company. The engineers adjudged

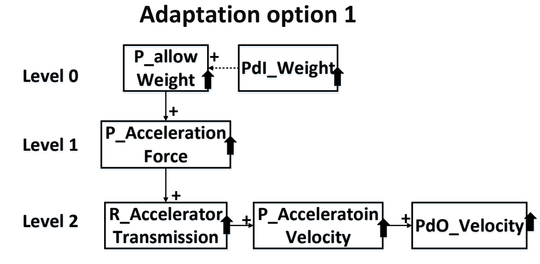

Figure 3: Tree graph of adaptation option 1

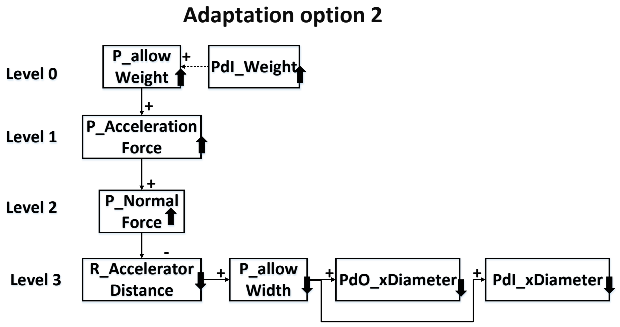

Figure 4: Tree graph of generated adaptation option 2

the options 1-5 as valid, but commented that some of the options would be costly and, thus not the best choice. Since the company is not allowed to change the specification of the customer's product, option 6 and 7 are no real adaptation options for the company. Furthermore, the engineers stated that the effort to create the MDMs is relatively high, if they cannot be re-used. Here, the creation of the process description required roughly four hours. Whereas, the creation time of one MDM varied between four hours, for the simplest process, and eight hours, depending on the complexity of the process step. However, the engineers also remarked that the approach generated more options than they had considered. The implemented solution regarding the increased weight was equivalent to option 1, as the change of the double accelerator's transmission could be accomplished by a simple software change and was the option with the least effort and cost. The increase of the output product's velocity did not have a negative impact on the subsequent process. Note here that the change impact on preceding or subsequent processes can also be traced by the analysis of product parameters, as changes of the input/output product of one process are used as the output/input product of the preceding or subsequent process.

V. CONCLUSION AND OUTLOOK

This contribution presented an approach for the generation and impact analysis of adaptation options for manufacturing machines. The approach consists of three steps, where in the first step the process of the machine is modeled with the formalised process description. In the second step, the approach models information about interdependencies between product, process, and resource parameters in a MDM. In the last step, the approach constructs a rooted tree graph by retrieving the stored information in the MDM and generates potential adaptation options by the analysis of tree paths. Furthermore, this contribution presented the results of a case study, where the presented approach has been applied to a cigarette-manufacturing machine. The study demonstrated that the approach is applicable for an industrial manufacturing machine and can automatically generate valid adaptation options for parametrical changes. However, the study also showed that the generated options are not equal regarding their implementation effort and, thus, should be ordered by certain criteria. Furthermore, it has been revealed that the modelling effort of the required information basis is relatively high, especially if the models are solely used for a single time.

Hence, future work will research a method for the evaluation of the generated adaptation options to provide the user with more information for decision making. Furthermore, the support for an automatic or semi-automatic generation of the Multiple-Domain-Matrix is also subject of ongoing work to decrease the modelling effort and, thus, to increase the practicality of the presented approach.

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