53rd CIRP Conference on Manufacturing Systems

Identification of Unintended Effects Caused by Adaptations of Manufacturing Process Sequences for Safety-Critical Components

T. Bergs\textsuperscript{a}, L. Hermann\textsuperscript{a*}, J. Rey\textsuperscript{a}, S. Barth\textsuperscript{a}

\textit{Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Campus-Boulevard 30, 52074 Aachen, Germany}

\* Corresponding author. Tel.: +49-241-80-27365; fax: +49-241-80-22293. E-mail address: l.hermann@wzl.rwth-aachen.de

Abstract

Changes of components are inevitable for companies to maintain competitiveness. To implement component changes, the manufacturing has to be adapted as well. For safety-critical components, unintended effects caused by adaptations pose a challenge due to the required reliability to ensure the component’s functionality. Therefore, a methodology to identify unintended effects of manufacturing adaptations is introduced and applied to a case study. Interdependencies within manufacturing are modeled through a multiple domain matrix and the model is extended by unintended effects within single manufacturing processes. Graph theory is further used to analyze the propagation of the instigating change within the manufacturing system.

© 2020 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

Peer-review under responsibility of the scientific committee of the 53rd CIRP Conference on Manufacturing Systems

Keywords: Manufacturing Change Management; Technology Planning; Manufacturing Adaptation; Change Propagation

1. Introduction

For a variety of reasons such as optimizations and changing requirements, product components are subject to change [1]. In order to implement component changes, the established manufacturing has to be adapted. Adaptations of the manufacturing are defined as Manufactures Changes (MCs) [2]. For the manufacturing of safety-critical components in medical technology [3] and aerospace [4], MCs pose a particular challenge due to legally required recertification processes after a conducted MC. The duration and costs of these recertifications depend on the chosen MC to implement a required component change. Changing the edge geometry of a cutting tool in the manufacturing of a jet engine component costs approximately €135k only for the recertification of the changed manufacturing process [5]. In addition, prototypes and field tests of safety-critical components are highly expensive. Therefore, a high planning reliability regarding the capability of an MC to implement a component change is required to avoid costs for non-functional prototypes and inefficient field tests. In addition, information regarding unintended effects (UE) MCs can have on components before manufacturing prototypes and conducting field tests are essential to save cost and time. Only by taking unintended effects of MCs into account, prototypes and the recertification can be designed cost-efficiently. In the following, safety-critical components are characterized by required certification processes they have to undergo after a change of their design or their manufacturing as well as by the fact that malfunctions can critically harm humans or the environment.

To support technology planners in identifying unintended effects MCs can have on the component, a generic methodology is introduced. The reference frame of the methodology comprises of process sequences and components. Process sequences are referred to as sequences of directly value adding manufacturing processes carried out on defined means of production [6]. Manufacturing Changes describe adaptations to one manufacturing process within the considered process sequence, such as changing process parameters, tools or supplies [7]. Quantitative changes of component characteristics like
roughness or length are referred to as component changes. Unintended effects of MCs are referred to as unintended changes of component characteristics which are caused by an MC.

To identify such unintended effects of MCs, the starting point of the hereby introduced methodology is a specific MC. Through the application of the methodology, technology planners are supported in identifying unintended effects of an MC. This leads to cost reductions for the process of implementing a change of a safety-critical component. On the one hand, the cost savings are achieved by reducing the expenses for defectively manufactured prototypes and ineffective field tests. On the other hand, cost savings are achieved by providing technology planners with a procedure to verify the changed manufacturing meets the prescribed requirements to a legal agency, which reduces time and cost efforts of the recertification.

The introduction of the developed is accompanied by a case study to assess the methodology’s applicability. For the case study, a change of the lower pump housing (component) of a Left Ventricular Assist Device (LVAD, product) is examined. The lower pump housing is manufactured by a process sequence of milling, drilling, lapping and drag grinding. The required component change (CC) is a reduction of the surface roughness within the pump housing’s blood channel (cf. Fig. 1). The examined MC to implement the component change is an increase of the drag grinding’s process time, which is given as an input for the developed methodology. The methodology’s scope of application and the case study are depicted in Fig. 1.

Fig. 1: Scope of the methodology and case study

In the following, the state of research regarding the identification of unintended effects caused by MCs is analyzed. The state of research is followed by the presentation of the developed methodology as well as by a conclusion and an outlook on future research activities.

2. State of research

The state of research for the identification of unintended effects caused by MCs can be separated into two different types of approaches. Approaches of the first type focus on identifying direct unintended effects within a single manufacturing process caused by a change to this single process. An example is a change in the cutting speed of a milling process to decrease the surface roughness unintendedly leading to thermal structural changes in the component’s near surface zone. Existing approaches of the second type focus on indirect unintended effects, which describe effects within manufacturing processes caused by an initial change to another manufacturing process of the process sequence. An example is the intended increase of the hardening time of a hardening process (MC) leading to a higher hardness of the component, which causes indirect unintended effects in subsequent machining processes. Therefore, an adaptation of the machining processes is required as well. Indirect unintended effects are described as elements of change propagation in the literature [8]. In the following, the existing approaches of both types are analyzed for their potential to identify unintended effects of MCs on component characteristics within process sequences.

2.1. Approaches identifying direct unintended effects

Karl and Reinhart developed a methodology to identify reconfiguration needs of manufacturing machines [9]. Within the methodology, the impact of reconfigurations on costs are determined. Interdependencies between elements of a manufacturing machine are modeled within a design structure matrix. Based on this matrix, the impact of a reconfiguration of one element on other elements is determined. Since the interdependencies between the manufacturing machine and the manufactured component are not considered, the effects a reconfiguration of the machine has on the manufactured component cannot be analyzed. Another approach analyzing the impact of adaptations of manufacturing machines was developed by Hoang et al. [10]. The approach also includes the use of a matrix to model interdependencies between processes, resources and products. Although Hoang et al. considered the effects of adaptations to a manufacturing machine on the component, the approach is not suitable to identify unintended effects. Potentially occurring unintended effects are assumed to be already known by the technology planner during the modeling and therefore the model is only used to analyze the impact of the effects on a component. For the manufacturing of safety-critical components, identifying these potentially unintended effects poses a challenge on its own that has to be solved before analyzing the impact of the effects. Klocke at al. addressed this challenge by developing a methodology to consider undesired effects within the generation of new process sequences [11]. Although the methodology represents a promising basis to solve the challenge stated in the introduction, further research is required. The methodology supports technology planners to identify unintended effects that potentially occur within manufacturing processes, but it does not reveal the link between a specific MC and the actual unintended effects caused by the specific MC.

In addition to the deficits of the approaches, the identification of direct unintended effects within a specific manufacturing process cannot solely ensure a component’s full functionality after a conducted MC. To ensure a component’s full functionality, effects of adaptations to one manufacturing process on other manufacturing processes within the process sequence
(change propagation) have to be considered as well. This poses a general deficit of the approaches discussed above. The introduced methodology contributes to solving the stated deficits by analyzing the link between a specific MC and unintended effects on component characteristics as well as by considering the change propagation of MCs within this reference frame.

2.2. Approaches identifying indirect unintended effects

An approach considering the propagation of changes within technical systems is the Change Prediction Method (CPM) developed by Clarkson et al. [12]. CPM is widely applied to analyze the risk of change propagation in technical systems such as manufacturing process sequences. By determining the propagation probability and the impact a change in one element of a system has on other system elements, the overall risk of a change is calculated. Although CPM is a cross-process approach to analyze the propagation of changes, it cannot be applied to identify indirect unintended effects of MCs. CPM is applied without referring to a specific change and only analyzes general propagation paths within technical systems. Which indirect unintended effects really occur when conducting MCs cannot be identified by applying CPM. Plehn extended the CPM and transferred its application from technical systems to manufacturing [8]. He developed a methodology to analyze the change propagation within a manufacturing plant. However, the methodology, like CPM, is not considering specific changes within a manufacturing plant, which poses a deficit for its application for safety-critical components. Unintended effects have to be analyzed in a level of detail enabling technology planners to state if an unintended effect of a specific MC is occurring or not. CPM based approaches only allows for the analysis of a system, not of a specific change. Further approaches revealing the same deficit were developed by Cichos and Aurich [13] as well as Malak and Aurich [14].

Apart from the presented methodologies, further approaches to identify indirect unintended effects in manufacturing exist. These approaches and the introduced ones are characterized by a superior deficit for their application to identify unintendedly changed component characteristics. This deficit results from their extensive reference frame comprising whole factories and socio-technical systems. Such reference frames are too extensive for the identification of unintended effects in a level of detail like a qualitative change to the surface roughness of a manufactured component as shown in Fig. 1. The novel contribution of the introduced methodology originates from the analysis of the change propagation in reference to a specific MC rather than the general connectivity within a manufacturing system as well as the close consideration of component characteristics.

3. Methodology for the identification of unintended effects

Based on the deficits of the existing approaches, a methodology to identify unintended effects caused by MCs for the manufacturing of safety-critical components was developed. The methodology consists of three steps. In the first step, the interdependencies within the existing process sequence are modeled. In the second step, potential direct unintended effects of all manufacturing processes of the process sequence are added to the model. The extended model is further used to identify potential propagation paths of indirect unintended effects in the third step. Finally, the potential propagation paths are investigated to specify existing indirect unintended effects.

3.1. Modeling of the process sequence

To model the established process sequence and its interactions with the manufactured component, a multiple domain matrix (MDM) according to Eppinger (cf. [15]) is used. As proven in [8] and [16], an MDM is a suitable tool to model complex interdependencies in manufacturing. The MDM model of the established process sequence is composed of four separate matrices modeling different types of interdependencies. An extract of the MDM model for the manufacturing of the LVAD’s lower pump housing is shown in Fig. 2. The novelty of the MDM’s application in the methodology is represented by the definition of a modeling process and specific interdependencies to model manufacturing process sequences through MDMs.

![Fig. 2: MDM Model of the established process sequence](image)

The first matrix of the MDM is a Domain Mapping Matrix (PC-DMM) describing the effects process steps (P) have on component characteristics (C). Process steps are different manufacturing tasks carried out in a single manufacturing process of the process sequence (e.g. *roughing* and *finishing* during *milling*) [17]. For the case study, the process steps *roughing* (RO), *finishing* (FI), *drilling* (DR) and *drag grinding* (DG) are considered as an excerpt from the entire process sequence. Every process step is assigned to a row in the PC-DMM (cf. Fig. 2). Correspondingly, the component characteristics *blood channel surface roughness* (BR), *joining area edge radius* (ER), *joining area surface roughness* (JR) and *boreshole diameter* (DI) are considered for the lower pump housing and assigned to a column in the PC-DMM each. After setting up the PC-DMM, the effects of process steps on component characteristics are modeled. For this, the process steps (rows) and the component characteristics (columns) are compared pairwise. If a process step does change the state of a component characteristic during the manufacturing, an “x” is assigned to the cell
connecting the process step and the component characteristic. As an example, roughing is changing the states of the component characteristics blood channel surface roughness and joining area surface roughness during manufacturing. Therefore, an “x” is assigned to the corresponding cells (cf. Fig. 2).

The next interdependencies to model exist between process steps and are modeled through a Design Structure Matrix (PP-DSM) in the upper right quadrant of the MDM. Process steps are assigned to rows as well as to columns to form the matrix and compared pairwise again. An interdependency exists if a change in the row’s process step inherently causes a change in the column’s process step due to a functional or materialistic dependence. For example, changing the lubricant for roughing also causes the same change for finishing, since both process steps are carried out on the same machine. If an interdependency exists between two process steps, an “x” is assigned to the corresponding cell in the PP-DSM.

The third type of interdependencies describes relations between component characteristics and is modeled in a CC-DSM in the lower left quadrant (cf. Fig. 2). An interdependency exists if a change in the state of the row’s characteristic can lead to a change in the state of the column’s characteristic. An exemplary interdependency exists between a part’s surface hardness and surface roughness. Since roughness peaks have a lower resistance against plastic deformation than solid material, a change in the surface roughness can lead to alternating results measuring the surface hardness [18]. For the case study, interdependencies between characteristics are not existent.

The last type of interdependencies is modeled through a CP-DMM in the lower right quadrant with rows for component characteristics and columns for process steps (Fig. 2). The interdependencies describe effects single component characteristics have on process steps. If a change in a component characteristic’s state prior to an unaltered process steps leads to a change of any component characteristic after the unaltered process step, an interdependency exists and an “x” is assigned to the cell connecting the component characteristic with the process step. For the case study, interdependencies exist between BR, JR, ER and the process step DG. As an example, increasing the blood channel surface roughness prior to drag grinding leads to an increase of the blood channel surface roughness after drag grinding if the process step remains unaltered.

Since the process sequence to be modeled through the MDM in the first step of the introduced methodology is already established, required information regarding existing interdependencies can be acquired through analyzing available data from a quality management system, additional measurements of component characteristics or expert interviews. Although the MDM model represents a basis to analyze how MCs propagate through the existing manufacturing (indirect unintended changes), direct unintended changes of single process steps are not considered within the model so far. Therefore, the MDM model will be extended with direct unintended effects in the next step of the methodology.

3.2. Identifying direct unintended effects

For the identification of direct unintended effects, the approach by Klocke et al (cf. [11]) is used as a basis. Within the approach, direct unintended effects are traced back to effects process steps have on sections of the component which are not intendedly affected through the process step’s operating principle. As an example, through the operating principle of a milling process, only the sections of a component which are in physical contact with the milling tool are intended to be affected. However, hot chips being removed from the cutting zone can damage nearby surfaces, which are not in contact with the tool and therefore not intendedly affected by the process step’s operating principle. Klocke et al. state that the occurrence of direct unintended effects is specific to each process and therefore needs to be investigated individually [11]. Nevertheless, to further support technology planners identifying direct unintended effects, five general causes for direct unintended effects are utilized. The five causes were constructed by Müller (cf. [19]) as an extension of the approach by Klocke et al. To utilize the five causes for direct unintended effects, a novel method to systematically identify unintended effects and extended the established matrix model was developed as a sub method of the introduced methodology. Every process step of the PC-DMM (cf. Fig. 2) is analyzed regarding the existence of each cause under the given conditions. Fig. 3 illustrates how the five causes for direct unintended effects are utilized to extend the generated MDM model.

Müller identified five causes that potentially lead to direct unintended effects (cf. [19]).

- C1: Surface damages through removed material
- C2: Material structure changes through thermal conduction or mechanical force
- C3: Plastic deformation and material removal through mechanical force
- C4: Induction of residual stresses
- C5: Plastic deformation through releasing residual stresses

Every process step from the PC-DMM is analyzed for the existence of the causes and the characteristics of the component each cause may affect unintendedly. If a cause exists for a process step and potentially affects a component characteristic, an “UE” is assigned to the cell connecting the process step (row) with the affected component characteristic (column).
For the manufacturing of the lower pump housing, five direct unintended effects were identified. The process steps roughening and finishing potentially affect the characteristic joining area surface roughness through removed material (C₁). The same effect exists for the process step drilling, which additionally affects the blood channel surface roughness. Furthermore, the process step drag grinding directly affects the characteristic joining area edge radius through unintended material removal caused by mechanical force (C₃).

Although direct unintended effects have to be identified individually for every process step, the developed procedure serves as a tool supporting technology planners in identifying direct unintended effects for their specific case. After subsequently analyzing the process steps for the five introduced causes for direct unintended effects and extending the MDM model, the second step of the methodology is completed. In the final step, the extended model is used to identify potential propagation paths and specify occurring indirect unintended effects.

### 3.3. Identifying indirect unintended effects

For the identification of indirect unintended effects which result from direct unintended effects, the established matrix model of the existing process sequence is transferred into a directed graph model according to graph theory (cf. [20]). The representation of the matrix model through a graph is used as visual support to systematically analyze the occurrence of indirect unintended effects. A directed graph is used, since the interdependencies within the matrix model are directed as well (from row to column). The directed graph model for the process sequence of the lower pump housing is depicted in Fig. 4. The novelty of the introduced methodology is represented by the newly developed method to analyze the constructed graph, which is described in the following.

![Graph Model](image)

**Legend**

| RO:Roughing | DR:Drilling | ER:Joining Area Edge Radius |
| DG:Blood Channel Surface Roughness | DR:Finishing | DI:Borehole Diameter |
| BR:Joining Area Surface Roughness | : Comp. characteristic |
| aᵢⱼ: Cell of row i and column j in the matrix model |
| : Intended effect | : Unintended effect |

Fig. 4: Direct graph model of the existing process sequence

A node is constructed for every process step and component characteristic of the model. To connect the nodes, the rows of the process steps and component characteristics are examined. If a cell contains an “x” or an “UE”, an edge is directed from the row’s nodes to the column’s node. An intended interdependency (“x”) is represented by a full edge, while an unintended interdependency (“UE”) is depicted by a dotted edge. As the graph model can get complex as a function of the matrix’s complexity, the use of software to generate model is recommended. To analyze the directed graph, a systematic procedure was developed and structured into 4 steps. Through the procedure, the general graph of the process sequence is reduced by deleting nodes and edges with missing interdependencies for the analyzed MC until only the truly occurring direct and indirect unintended effects are represented by the graph.

First, the node of the process step, which is subject of the initial MC (cf. Fig. 1) is analyzed. For the case study, the drag grinding process step (DG) is analyzed (step 0). If an edge is directed from the process step’s node to another node, which is not affected by the MC, the edge connecting the nodes is deleted (step 1). The deletion is carried out due to the missing interdependencies of the nodes for the analyzed MC. Since the MC of the drag grinding process step influences all connected nodes (BR, JR, ER), none of them are deleted.

If a connected node is affected but the influence is intended or acceptable, every edge directed to the affected node is deleted unless it is the instigating edge or an edge of an unintended effect (step 2). The deletion of the incoming edges is carried out to further reduce the graph. The change of the node is acceptable and no countermeasures, which are potentially represented by the incoming edges, are required. Since the blood channel surface roughness (BR) is intendedly affected by the instigating change, the edges a₁₃ and a₂₃ are deleted. The joining area surface roughness is affected as well. However, the surface roughness is decreased and therefore, the influence of the instigating change is assumed to be acceptable. For the affected but indirectly or acceptably changed nodes (BR, JR), the procedure is repeated from step 0. Consequently, the edges a₅₄ and a₇₄ are deleted in step 1, since the node DG is not affected by the changes of the nodes BR and JR.

If a node is unintentionally affected and the influence is not acceptable, outgoing edges are deleted (step 3). The edges are deleted since countermeasures have to be conducted to set the node back to its initial state. No change of the node is present and therefore none of the other nodes connected to the node by outgoing edges are affected. This is the case for the node (ER), representing the component characteristic joining area edge radius, which is increased by the MC conducted for the drag grinding process step. Therefore, edge a₆₄ is deleted.

For the unacceptable change, countermeasures have to be identified. Process steps with the potential to counteract the changes are connected to the affected node by edges directed from the potential process steps to the changed component characteristic. For the case study, the process steps roughening and finishing comprise potential countermeasures for the unacceptable change of the component characteristic joining area edge radius. The specific identification of countermeasures is not in the focus of this publication. For the case study, the process step roughing is assumed to be adapted through a change of its NC-Code to decrease the ER as a countermeasure for its unacceptable increase. The adaptation of the process step roughing is considered as a new MC and therefore, the procedure is repeated from step 0 for the new MC. In step 1, the
edges $a_{1,3}$ and $a_{1,7}$ are deleted due to missing influences. In step 2, $a_{2,2}$ is deleted and an adaptation of the process step finishing is found out to be required since a change in the roughing’s NC-Code is only effective if the finishing’s NC-Code is adapted as well. Step 1 is repeated for the changed process step finishing leading to the edges $a_{2,3}, a_{2,1}$ and $a_{2,5}$ being deleted.

If there are no changed nodes to analyze left, unchanged process steps, component characteristics and their incoming and outgoing edges are deleted from the graph model as a final reduction of the graph (step 4). For the case study, the process step drilling (DR) and the component characteristic borehole diameter (DI) remain unchanged and are therefore deleted including their incoming and outgoing edges $a_{3,8}, a_{3,1}, a_{3,5}$ and $a_{3,7}$.

As a result of the procedure, the directed graph model is reduced to the actually occurring direct and indirect unintended effects. The results of the procedure’s application for the case study are depicted in Fig. 5. Since the procedure to reduce the general graph model to the truly occurring direct and indirect unintended effects can get highly complex for systems with a high number of nodes and edges, it has to be transferred into an algorithm. This algorithm can be executed by software to automatically reduce the graph model and increase the presented methodology’s practical applicability. The objective of this paper is to introduce the concept of the methodology. Therefore, a detailed description of the procedure as an algorithm will be presented in an additionally publication.

**Fig. 5:** Direct and indirect unintended effects for the given

### 4. Conclusion and Outlook

A methodology supporting technology planners identifying unintended effects of changes in manufacturing was introduced. The methodology is structured in the three steps system modeling, identification of direct unintended effects and identification of indirect unintended effects. Its practical applicability was assessed by applying the methodology to a Manufacturing Change for the lower pump housing of the LVAD.

Current limitations of the introduced methodology are its dependency on expert knowledge and the manual application effort, if a high number of MCs is analyzed. To transfer the methodology from research to an industrially applicable solution, these limitations need to be addressed in future research.

Future research will also focus on detailing the interdependencies within the matrix model to improve the planning reliability of the methodology and its application efficiency.

### Acknowledgements

The authors thank the German Research Foundation DFG for research support in the project BE 2542/63-1 “Kostenoptimierte Planung von Änderungen in der Fertigung sicherheitskritischer Bauteile durch systematisches Manufacturing Change Management”.

### References


