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A Model-Based Approach to Analyze Change Propagation and Impact in Product-Production-CoDesign

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Abstract

Engineering changes are omnipresent in the product development process and take up an enormous amount of resources. One reason that makes engineering changes resource-intensive is the high system complexity. The interface between product development and production system development is particularly complex. Although model-based systems engineering (MBSE) is considered a promising approach to address these challenges, there is a lack of methods that support the analysis of engineering changes in integrated product-production system development. This paper presents a further developed methodology that supports a holistic analysis and modeling of engineering changes using the example of a production system of an automotive-supplier.

Keywords: Model-Based Systems Engineering; Engineering Change Management; Production System Planning; Product-Production-CoDesign;

1. Introduction

Nowadays, manufacturing companies need more than just the technical product-related improvement of an existing idea to ensure their business success. Since the global market is very competitive and dynamic, manufacturers need to deliver high-quality, customer-individual products in minimal time while maintaining cost efficiency and operational excellence [1]. The latter explicitly deals with the handling of increasing complexity in planning and control of future production systems. Here, a integrated product and production system development is necessary. Unfortunately, it is still the case with some companies that product development and production planning are siloed functions in a complex organization [2]. This mostly leads to inefficient processes causing unnecessary high costs and time-to-market. This gap between product design and production planning frequently leads to inefficiencies, duplicated efforts, and lost opportunities for innovation. To address this issue, Albers et al. introduced the concept of Product-Production-CoDesign (PPCD) [3]. This concept considers the parallel and collaborative planning, development and realization of product production systems over the entire life cycle and across several generations. Their study also underlines the increasing complexity and uncertainty of development processes in the PPCD sector.

However, increasing system complexity also creates great challenges in technical change management (Schuh 2014). For example, greater complexity increases the likelihood of a change spreading to other subsystems in an unforeseen way (Eckert 2004). Engineering changes also take up a large

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proportion of resources in the product development process and are classified as critical in a third of all cases (Langer 2012). One way of dealing with high complexity in the development of technical systems is the Model-Based Systems Engineering (MBSE) approach. With the help of a central system model, relevant information from product development is consistently recorded and made available to relevant stakeholders (source Weilkiens). In addition to many methods for Engineering Change Management, the model-based methodology AECIA - Advanced Engineering Change Impact Approach in particular promises a holistic approach for dealing with Engineering changes by addressing the analysis and modeling of change propagation and change impacts, as well as checking the validity of change requests and communicating change information in an agile development environment [4].

Although initial applications of the methodology to real change cases show initial indications of the added value of the methodology [5, 6], the methodology has not yet been applied to the example of a change case in a product production system. In order to close this research gap, the AECIA methodology is to be further developed, applied and implemented in a case study of a production system of the automotive supplier BENTELER Automobiltechnik GmbH. BENTELER serves as a development partner for leading car manufacturers worldwide, offering tailored solutions across various automotive sectors including chassis, body-in-white, engine and exhaust components as well as electromobility solutions. In the case study of this article, the production system of a Rear Twist Beam (RTB), see Fig. 1., is used as an application case.

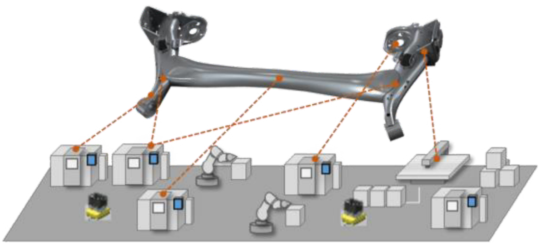

Fig. 1. Schematic representation of a rear twist beam and the links to the production system

This paper is structured as follows. Section 2 introduces relevant fundamentals in the context of model-based systems engineering and engineering change management. Subsequently, in section 3, research questions are posed with reference to the identified research gap. In Section 4, a model-based approach for dealing with Engineering changes in PPCD is presented and in Section 5, this approach is implemented and applied using the example of a real change case in a production system.

2. Field of Action

2.1. Model of SGE - System Generation Engineering

Technical systems are always developed in generations and are based on references [7]. According to Albers, the model of SGE - System Generation Engineering makes it possible to describe this fact in system development [8]. Here, elements of a reference system form the foundation for the development of new system generations and can be divided into different types depending on their origin [9]. A new system is developed by varying elements of the reference system [8]. A distinction is made between the following three types of variation: "carryover variation (CV)", "attribute variation (AV)" and "principle variation (PV)" [10]. Using the variation proportions and the origin of the reference system elements, a statement can be made about the development risk of individual subsystems [9].

2.2. Model-Based Systems Engineering

The model-based systems engineering (MBSE) approach refers to the systematic and formalized application of modelling techniques to support activities in the areas of requirements management, the design process, analysis, verification and validation [11]. Model-based systems engineering, in contrast to document-based systems engineering, uses a central system model that links relevant information from the product development process across disciplines and makes it available through needs-based views [12]. The MBSE approach can be applied across all phases of the product development process and aims to promote a holistic understanding of the system and thus improve efficiency in various product development phases [11].

2.3. Engineering Change Management Methods for the Product-Production-CoDesign

There are a large number of methods for technical change management [13]. In addition to engineering change management methods that deal with the propagation of changes at product level [14–16], there are also approaches that include organizational structures [17] or predict the effort and risk of an Engineering change [18, 19]. There are also MBSE-supported approaches that consider change propagation or change impacts at product [20, 21] or production [22] level.

In contrast to approaches that focus specifically on individual aspects of engineering change management, Martin et. al. present the MBSE-supported methodology "Advanced Engineering Change Impact Approach" (AECIA) for holistic support of engineering change management [4]. This methodology is based on an activity-based framework that is already used in a similar way in other work and provides initial indications of added value for users in the areas of intuitive applicability, adaptability, user-friendliness and teachability and learnability [23, 24]. The AECIA framework contains four main activities that can be divided into relevant analysis and modeling activities for engineering change management and can be carried out iteratively. The main activities address checking the validity of change requests, the propagation and impact analysis of changes and the targeted communication of change-related information in an agile development environment. Initial implementations and applications of the methodology to real change cases show first indications of the added value of the methodology with respect to the model-based handling of engineering changes [6]. Change propagation is modeled using the element types "Change Request", "Change Issue" and "Alternative Solution", see Fig. 2. The initial "Change Request" is linked to one or more system model elements, such as use cases, logical element, requirement or other element types, using the relationship types "changed", "replaced", "removed" or "created". The "Change Issue" element type is used to model potential problems, knowledge gaps or definition gaps that arise as a result of the change request. The "Alternative Solution" element type is used to model a solution for the resulting "Change Issue". Just like a "Change Request", an "Alternative Solution" can be linked to system model elements via the same relationship types and in turn cause new "Change Issues". This means that change propagation can be modeled in a nested manner and the relationships between change requests, knowledge and definition gaps and subsequent changes can be systematically represented.

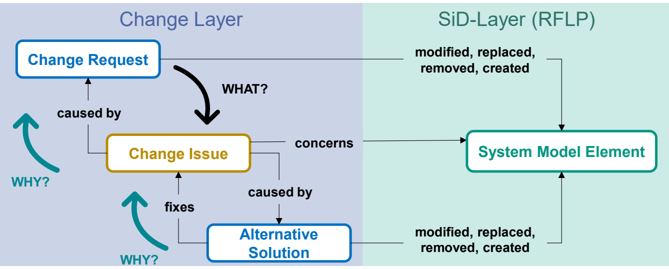

Fig. 2. Element types and relations for modeling change propagation [4]

The AECIA methodology uses a two-part assessment to model the impact of change [4, 6]. The first part of the impact assessment is based on a Pugh matrix. Here, evaluation criteria such as the costs or time required to implement a change are identified, typified and weighted. The evaluation result of an engineering change is calculated from the weightings of the evaluation criteria and the associated evaluation values [4]. The second part of the assessment involves evaluating the engineering risk of an engineering change. The engineering risk can be calculated using three factors [25]. The factors novelty level and prior knowledge of a reference system element can be determined with the help of the SGE model. The complexity of the change can be determined using a suitable metric, see section 2.4.

2.4. Complexity Assessment

As the complexity of a technical system to be developed has a major influence on engineering change management [26, 27], it can be useful to capture it. To measure complexity, structural complexity can be utilized. This allows the architecture of a technical system to be characterized by examining the number, type and arrangement of the elements and the interactions between the elements. There are many metrics for determining structural complexity, but Sinha and Weck's metric [28] in particular fulfills all nine Weyukers criteria [29] for a valid complexity metric. This topological complexity metric consists of the three terms C1, C2 and C3 and can be represented as equation (1).

$$C = C_1 + C_2 C_3 = \sum_{i=1}^{n} \alpha_i + \left(\sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{i,j} A_{i,j}\right) \gamma E(A) \qquad (1)$$

The term C1 represents the sum of the complexities of individual system components. C2 represents the complexity of the connections between the components and C3 the topological complexity resulting from the arrangement of the connections [28].

3. Research Questions

In the last section, the model-based methodology AECIA was presented as a holistic approach for dealing with engineering changes. Although the methodology has already been applied to real change cases at the product level, the question arises if the methodology can also be applied in product-production co-design. In order to close this knowledge gap, the following research questions will be answered in this paper:

- What could a model-based approach look like that supports the analysis and modeling of the propagation and impact of changes in the integrated product-production co-design?
- How can the developed approach be implemented using the example of a production system for a rear twist beam?

To answer the first research question, the model-based methodology AECIA is adapted in section 4 to support the analysis and modeling of change propagation and change effects in Product-Production-CoDesign. The second research question is addressed in section 5 by applying and implementing the adapted approach using the example of a change in the production system of a rear twist beam.

4. Integration of the AECIA methodology in Product-Production-CoDesign

In order to verify the applicability of the AECIA methodology to an integrated product production system, the first step is to analyze the ontology of such a system. For this purpose, relevant element and relation types for the description of a product-production system are examined on the basis of previous work [30, 31]. In addition to elements of the problem space: "System Context Elements", "Stakeholders", "Target Cycle Time", "Stakeholder Needs" and "Boundary Conditions", elements of the solution space: "Operation Resources", "Production System Requirements", "Product Features" and "Production Processes" are also used to describe a production system.

As shown in Fig. 3, the change propagation can also be transferred to a production system based on the preliminary work from [4, 6]. Here, all element types of the production system can be linked to the elements of the change management layer in both the problem and solution spaces. The "Change Request" can be used to create a change request and link it to the affected elements at the production system level. As a result of this change request, "Change Issues" and "Alternative Solutions" can be created in a nested manner and linked to relevant elements of the production system model. This creates a clear traceability of a specific change request.

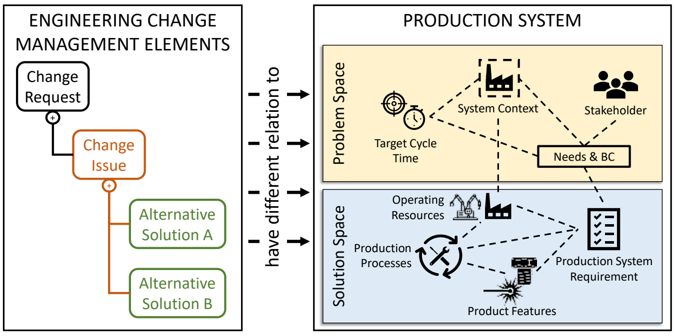

Fig. 3. Modeling the change propagation on a production system

The evaluation of changes and alternative solutions can also be transferred to a production system on the basis of preliminary work from [4–6]. For the two-part evaluation, see section 2.3, evaluation criteria can be identified, typified and weighted. In the context of PPCD, these can be criteria relating to cycle time, SOP, operating costs or investment costs, for example. Based on the selected criteria, different solution alternatives can be evaluated and thus prioritized. The evaluation of the engineering risk is also based on three factors, as in existing preliminary work: Degree of novelty, prior knowledge of the reference system element and complexity. The higher the value of these factors, the higher the engineering risk of an alternative solution, see Fig. 4.

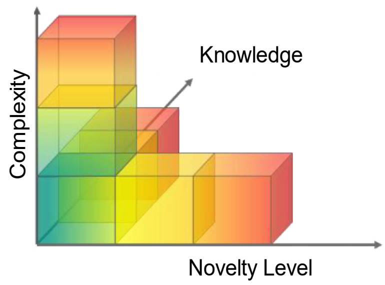

Fig. 4. Three-factor classification of the engineering risk of engineering changes [5]

The characterization of the novelty level and the prior knowledge of the reference system element can also be carried out on the basis of the SGE model for changes in a production system. For the calculation of complexity, the Sinha and Weck [28] metric is used. The network of system model elements for the calculation of complexity results from the elements directly affected by the change and from elements that are linked to the directly affected elements via two levels in the system architecture, see Fig. 5.

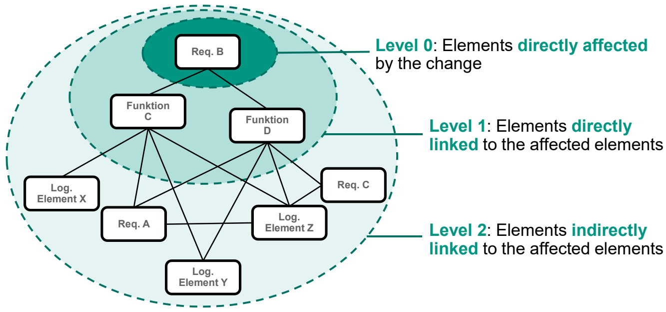

Fig. 5. Exemplary network of system model elements for calculating the structural complexity of an engineering change

5. Implementation of the AECIA methodology on the change case of a rear twist beam production system

The AECIA methodology adapted in section 4 is implemented using the example of a rear twist beam production system at BENTELER Automobiltechnik GmbH. The increase in peak volume is considered as a change case. The nested modeling of the change request, the change issue and the alternative solutions is done using a table, see Fig. 6. The description of the respective change element is shown in the middle column and the elements of the production system linked to the change element are shown in the right-hand column. In our example, the change request is linked to the peak volume requirement. From this, the problem of the excessive actual cycle time is identified and described by a change issue. The three alternative solutions describe potential ways to resolve the change issue. The increase of the welding speed at certain welding cells, the installation of a parallel welding cell or the distribution of weld seams to other welding cells to reduce the cycle time are suggested.

#	Name	Text	Directly affecting
1	⊟ CR Increse output volume to 600000 unitis	The peak volume/year is to be increased to a value of 600,000	45 Requested peak volume
2	⊟ CI Cycle time too high	The increase in volume cannot be compensated by increasing working hours. The cycle time needs to be decreased to 27 sec	Cycle time
3	AS Parallel welding cell	Distribution of the welding process to two identical welding cells	OP30
4	AS Increase welding speed	Increasing the welding speed of the welding cell by 24%	OP30 Welding of Crossbeam + Bulkhead
5	AS Weld seam distribution	Distribution of weld seams to other welding cells	w16 w15 w46 w85 w81 OP30 OP50 OP60

Fig. 6. Table for the nested view of change requests, change issues and alternative solutions as well as the affected elements of the production system

In order to link change elements with the elements of the production system and thus create a clear traceability between the change and production system levels, a matrix is used in this case study, see Fig.7. Various predefined relationships can be created in the matrix. The nested structure in the change level allows change issues and subsequent changes to be assigned to the respective change requests.

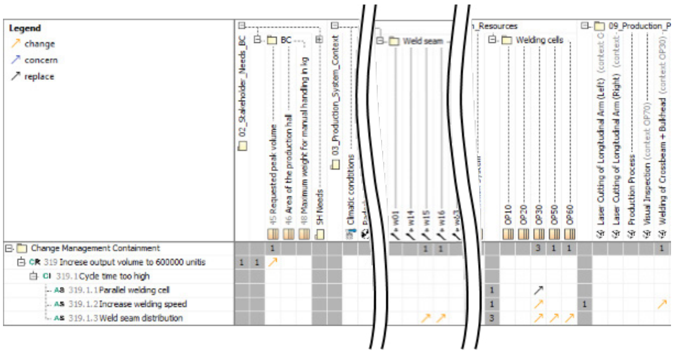

Fig. 7. Matrix for linking change requests, change issues and alternative solutions to the elements of the production system.

Relation maps, as shown in Fig. 8, are used in this case study to analyze possible change issues and alternative solutions. This allows various elements of the production system to be analyzed that are directly or indirectly linked to the production system element affected by the change element. In our case study, it can be analyzed that the peak volume depends on the available production time and the cycle time. While the available production time has already reached a maximum, the cycle time can be further reduced. It also becomes clear which production steps determine the cycle time.

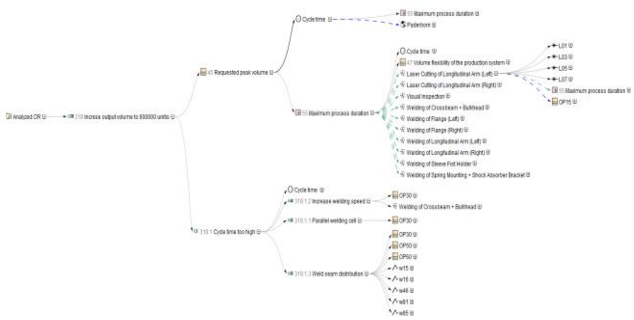

Fig. 8. Relation map for analyzing potentially affected elements of the production system

Once the first alternative solutions have been identified, their impact can be analyzed in the next step. In the first step, relevant evaluation criteria are created, typified and weighted, see Fig. 9. In this case study, the criteria of cost and time for implementing a solution as well as the influence on production quality were considered as examples. The three identified alternative solutions are evaluated with the help of the typified and weighted criteria.

The associated engineering risk for each of the three alternative solutions is then evaluated by identifying the novelty level and prior knowledge of the reference system element of an alternative solution. The complexity of an alternative solution is automatically determined by linking it to the model of the production system, as shown in Fig. 7.

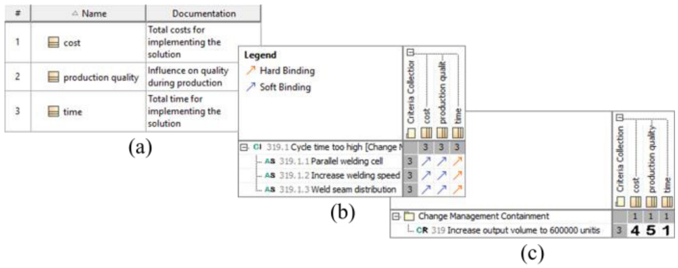

Fig. 9. (a) table for creating and describing evaluation criteria (b) matrix for typification of evaluation criteria; (c) matrix for weighting evaluation criteria

In the case study of this paper, the development risks and the criteria-based evaluation were determined and shown in Fig. 10. Here, a small value stands for particularly good results. The alternative solution, which proposes the distribution of the weld seams to other welding cells, performs best with regard to the selected evaluation criteria from Fig. 9, but this solution is also the riskiest, as the complexity of this solution in particular is significantly higher. Despite the high risk, the developers nevertheless decide in favor of this solution and note this in the right-hand column of the table in Fig. 10.

#	Name	Engineering Risk	Critertia Based Evaluation	Change Status
1	CR Increase output volume to 600000 unitis			proposed
2	CI Cycle time too high			
3	AS Parallel welding cell	0.25	0.63	rejected
4	AS Weld seam distribution	0.52	0.43	approved
5	AS Increase welding speed	0.32	0.6	rejected

Fig. 10. Overview of the evaluation of the engineering risk and the criteria-based evaluation of the three alternative solutions

With this basis, decisions in engineering change management can be analyzed and decided transparently. The aim of the methodology presented is to provide developers with holistic support in the decision-making process by considering not only the spread of a change but also its effects with regard to relevant criteria such as costs, time and quality, as well as the engineering risk. In this way, for example, risky alternative solutions can be consciously selected if the potential outweighs the risk with regard to relevant factors.

6. Discussion and Outlook

This article demonstrates the application of the adapted AECIA methodology using the example of a rear twist beam production system. It can be shown that the change case for increasing the peak volume can be analyzed and modeled in its propagation with the help of the system model. In addition, the impact of the change case can be evaluated transparently by assessing potential solution alternatives with regard to selected criteria and estimating the engineering risk using the model of the SGE and the calculation of the complexity. The results presented have been developed in the context of the case study shown in the article and should not be interpreted as generally applicable. In the next step, further long-term studies with various change cases are required to prove the added value of the methodology in the area of PPCD. In addition, a publication on the main activity "Communication of change information" is planned using the example of a change case in an industrial context.

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