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ASSESSMENT OF CHANGES IN ENGINEERING DESIGN USING CHANGE PROPAGATION COST ANALYSIS

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Abstract

Due to diverse customer demands, volatile markets, and dynamics in technology and innovation, the potential for engineering changes has significantly risen in product development projects as well as over the product lifecycle in recent years. Engineering changes can often lead to undesired change propagation effects. Thus, projects may overrun in both costs and schedule. Therefore, it is desirable to be able to predict the change impact caused by an engineering change and to estimate the cost impact on both product and production. This paper will present a multilayer network model to operationalize the dependencies among product requirements, product elements and production processes. Based on this, a change propagation analysis is presented. Initially, alternative technical solutions are generated to fulfill a specific change request. The change impact on both product and production is determined for each alternative. To identify the most cost-effective solution, the overall change costs of each alternative are calculated. Finally, the method is applied to the example of an asynchronous motor design to demonstrate the model's practical utility.

Keywords: Engineering change management, Change propagation, Design management, Decision making, Simulation

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1 INTRODUCTION

Globalization has transformed the seller's market into a buyer's market. In consequence, companies are facing highly diverse customer demands and are more and more forced to offer customized products. This has resulted in an extending companies' product range and increasing product complexity in recent years (Elmaraghy et al., 2013). Reinforced by highly volatile markets and increasing dynamics in technology and innovation, the number of engineering changes has significantly risen in product development projects as well as over the product lifecycle. Typically, these changes enable an increase in performance or an adaption to market-specific requirements (Schuh et al., 2015). Sometimes changes to a product, especially for complex technical systems, lead to undesired change propagation (Clarkson et al., 2004), leading to projects overrunning in both costs and schedule. An integrative perspective on both product and production is necessary for two principal reasons: First, costs are mainly determined in the product development process but incurred later in production (Ehrlenspiel et al., 2007). Second, economies of scale are realized along the entire value chain (Schuh et al., 2014). Engineering changes are increasingly the rule rather than the exception. They form a substantial part of the product development process (Fricke et al., 2000). Therefore, it is essential to understand and predict the effects of change propagation caused by engineering changes.

For the purpose of cost-effective engineering change management, this paper presents a multilayer network model, consisting of a customer layer, a product layer and a production layer, to evaluate changes in engineering design by using a change propagation cost analysis. Using normally distributed change probabilities, the matrix-based explanatory model investigates and quantifies the effects of engineering changes caused, for example, by a customer's change request on both product and production. The decision model calculates the overall change costs and enables the selection of the most cost-effective solution.

2 FUNDAMENTALS AND CURRENT STATE OF RESEARCH

According to Sjögren (2015) engineering change management (ECM) as an element of product development and project management can be defined as an active process by which an organization documents, communicates, evaluates and implements changes to the design of a product or project. Jarratt et al. (2011) define these engineering changes as an "alteration made to parts, drawings or software that have already been released during the product design process". According to Eckert et al. (2001), engineering changes can arise due to external or internal reasons. External reasons are typically caused by customer's change requests or market trends. Examples of internal reasons are errors in the product design, process improvement or cost reduction measures. Furthermore, according to Lindemann et al. (1998) changes can be subdivided into *local changes*, which involve one component only, and *interface-overlapping changes* (common in highly integrated and complex products), which involve many components. The system's impact on an engineering change depends on the capability of the system's interfaces to resist changing requirements. Consequently, Eckert et al. (2001) categorize components or sub-systems depending on their change properties into three different types: absorbers, carriers and multipliers. As Clarkson et al. (2004) have pointed out, an initial change to a product can lead to additional changes. This phenomenon, by which a change to one part or element of a design requires additional changes throughout the product, is commonly referred to as change propagation (Giffin et al., 2009). In practice, studies have shown that an initial change usually propagates no more than four generations (Eckert et al., 2001).

Over the past decade, the research interest in the phenomenon of change propagation has risen, yielding numerous comprehensive studies as well as a variety of tools and methods to characterize, analyze, predict and manage change propagation. Many of them are network-based models and analyses. To gain an overview of the dependencies between single network nodes such as product components, it is crucial to not only reveal the directly visible connections between them, but also the indirect ones, where their linkage is achieved by the interplay of one or several other network nodes (Keller et al., 2005). For many years, the *Design Structure Matrix (DSM)* has been used as an effective method for both the representation and the analysis of complex systems (Eppinger et al., 1994). A DSM is a single domain matrix representation of network nodes and their mutual dependencies (edges). Based on this, *Domain Mapping Matrices (DMM)* enable an examination of interactions across domains. By combining both DSM and DMM, an expanded view of complex systems can be gained (Bartolomei et al., 2007). For the purpose of predicting change propagation, Clarkson et al. (2004) developed a method called the *Change Prediction Method (CPM)*. The CPM combines methods of component-based DSMs with risk management techniques. For the analysis and prediction of a single component's propagation behavior, Suh et al. (2007) introduced the *Change Propagation Index (CPI)*. According to Eckert et al. (2001), Suh et al. (2007) classify components as absorbers (CPI < 0), carriers (CPI =0) and multipliers (CPI >0) by calculating and comparing the numbers of changes that propagated in and out of a component. Based on the CPI, critical components can be identified and flexibility potentials can be derived. To quantify a network area's propensity for changes and to formalize the idea of change motifs, Giffin et al. (2009) developed both the *Change Acceptance Index (CAI)* and the *Change Reflection Index (CRI)*, and modified the original definition of CPI. For the analysis of the actual change structure of networks over several time periods in the design process, a modified DSM, called the *change DSM*, has been developed. Pasqual et al. (2012) unified above-mentioned research by introducing a multilayer network approach. Adding a *social layer* to the previously common *product layer* and *change layer* has led to an adaption of the CPI on engineers, called the *Engineer CPI*.

Many other researchers are dealing with the phenomenon of change propagation in a wider sense. Especially the approaches by Schuh et al. (2013) and Rebentisch et al. (2016) must be mentioned in this context. Schuh et al. (2013) developed a holistic approach by focusing both on the product and on the production. Using graph theory and sensitivity analysis, interactions between product and production parameters have been analyzed. Based on the analysis, product and production standards can be derived in order to optimize the overall commonality. Rebentisch et al. (2016) have focused on the impact of engineering changes on product cost and project duration. Therefore, change alternatives have been evaluated regarding their effect on structural complexity to enable a prediction of costs and duration.

The cost effect of change propagation on both the product and production has however not been adequately investigated by research so far. Therefore, it is helpful to combine different methods of analysis to enable a comprehensive understanding of change propagation. This shall include a general understanding of all dependencies of components within the product and between components and production processes, their likelihood and the costs they will cause.

3 METHOD FOR THE ASSESSMENT OF CHANGES IN ENGINEERING DESIGN USING CHANGE PROPAGATION COST ANALYSIS

In order to solve the formulated problem, a methodology for the assessment of changes in engineering design will be presented. The aim of the methodology is to calculate the overall change costs caused by change propagation and to figure out the most cost-effective solution.

For this purpose, a description model in terms of a multilayer network model was developed and transferred into a matrix-based model. Using the matrix-based description model and generating alternative technical solutions for the fulfilment of e.g. customer's change requests, the explanatory model simulates for each alternative the expected change propagation for both product and production. Based on the simulation results of the change propagation, the decision model calculates the overall change costs for each alternative and therefore enables a selection of the most cost-effective solution. The partial models and the following sections are shown in Figure 1.

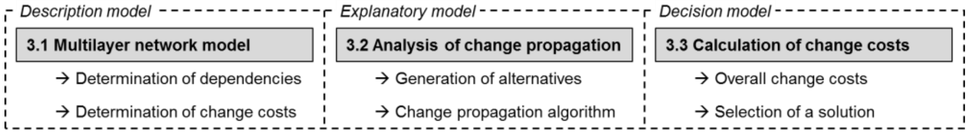
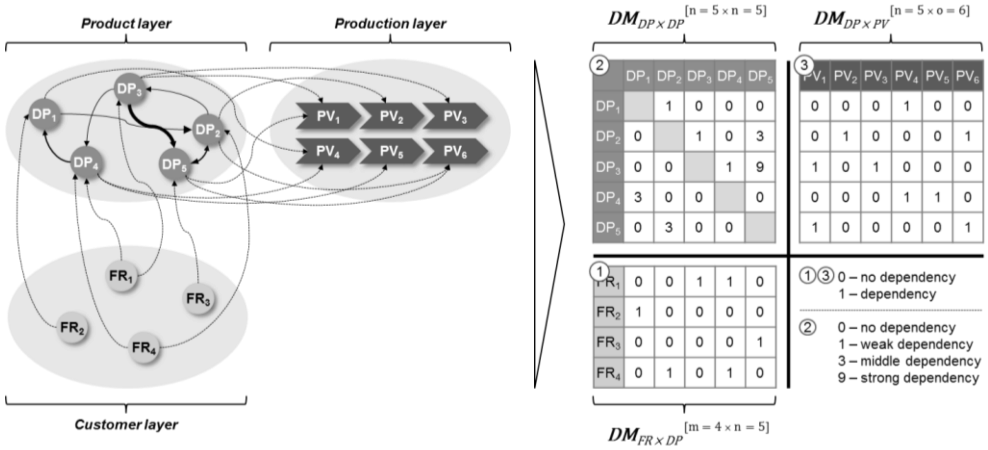


Figure 1. Partial models and the following sections

3.1 Multilayer network model

For the design of the description model, the principles of *Axiomatic Design* according to Suh (1998) have been applied. The multilayer network model is composed of three layers, as shown in Figure 2: the *customer layer*, *product layer* and *production layer*. The customer layer implies all functional requirements of a product caused by customer demands. Each network node represents a specific *functional requirement (FR)*. The product layer is a network representation of the product being designed. The network nodes represent *design parameters (DPs)* at the level of component specifications of the product. The edges represent interdependencies among the DPs. The *intra-layer* *edges* are both directed and weighted, depending on the degree of dependency. A dependency among DPs could be either a physical connection or a channel for the flow of energy, mass and information (Suh et al., 2007). The third layer of the methodology, called the production layer, represents the production process of the product, whereby nodes represent *process variables (PVs)*. A PV is the smallest possible process step of the production process. The directed inter-layer *customer-to-product edges* relate the customer layer to the product layer. Each edge links a FR to the related DP. The directed inter-layer *product-to-production edges* relate the product layer to the production layer. Each edge links a DP to the related PV.

For the purpose of simulation, the multilayer network model is used in form of a matrix model. A binary DMM, called *dependency matrix* $\boldsymbol{DM}_{FR \times DP}{}^{[\mathrm{m \times n}]}$, relates the customer layer to the product layer. A square DSM, called *dependency matrix* $\boldsymbol{DM}_{DP \times DP}{}^{[\mathrm{n \times n}]}$, represents the product layer. Therefore, the dependencies among the DPs are qualitatively weighted depending on their strength. The relation between the product layer and the production layer is also represented by a binary DMM, called the *dependency matrix* $\boldsymbol{DM}_{DP \times PV}{}^{[\mathrm{n \times o}]}$.



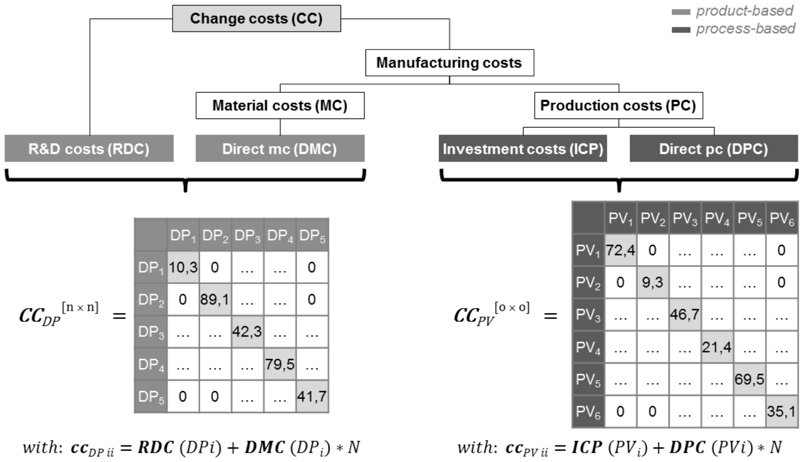
②	DP_1	DP_2	DP_3	DP_4	DP_5
DP_1		1	0	0	0
DP_2	0		1	0	3
DP_3	0	0		1	9
DP_4	3	0	0		0
DP_5	0	3	0	0	

③	PV_1	PV_2	PV_3	PV_4	PV_5	PV_6
DP_1	0	0	0	1	0	0
DP_2	0	1	0	0	0	1
DP_3	1	0	1	0	0	0
DP_4	0	0	0	1	1	0
DP_5	1	0	0	0	0	1

①	DP_1	DP_2	DP_3	DP_4	DP_5
FR_1	0	0	1	1	0
FR_2	1	0	0	0	0
FR_3	0	0	0	0	1
FR_4	0	1	0	1	0

Figure 2. Multilayer network model and matrix-based model

The description model is complemented by the determination of change costs. Change costs are product- or process-based costs incurred by changing a DP or a PV. The R&D costs (RDC) as well as the investment costs (ICP) for machines and equipment are independent of the expected *number of units N*. In contrast, the direct material costs (DMC) as well as the direct production costs (DPC) are dependent on the quantity. The overall change costs of each DP or PV consist of the sum of the associated individual costs resulting in both the product-based *change costs matrix* $\boldsymbol{CC}_{DP}{}^{[\mathrm{n \times n}]}$ and the process-based *change costs matrix* $\boldsymbol{CC}_{PV}{}^{[\mathrm{o \times o}]}$. A detailed decomposition and allocation of change costs is shown in Figure 3.



$\boldsymbol{CC}_{DP}{}^{[\mathrm{n \times n}]} =$

	DP_1	DP_2	DP_3	DP_4	DP_5
DP_1	10,3	0	…	…	0
DP_2	0	89,1	…	…	0
DP_3	…	…	42,3	…	…
DP_4	…	…	…	79,5	…
DP_5	0	0	…	…	41,7

$$with:\ \boldsymbol{cc}_{DP\,ii} = \boldsymbol{RDC}\ (DPi) + \boldsymbol{DMC}\ (DP_i) * N$$

$\boldsymbol{CC}_{PV}{}^{[\mathrm{o \times o}]} =$

	PV_1	PV_2	PV_3	PV_4	PV_5	PV_6
PV_1	72,4	0	…	…	…	0
PV_2	0	9,3	…	…	…	0
PV_3	…	…	46,7	…	…	…
PV_4	…	…	…	21,4	…	…
PV_5	…	…	…	…	69,5	…
PV_6	0	0	…	…	…	35,1

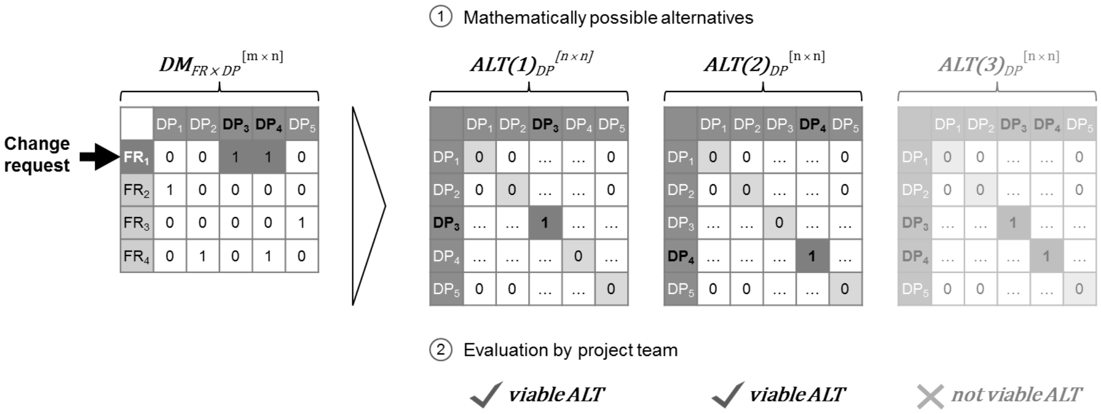
$$with:\ \boldsymbol{cc}_{PV\,ii} = \boldsymbol{ICP}\ (PV_i) + \boldsymbol{DPC}\ (PVi) * N$$

Figure 3. Decomposition and allocation of change costs

3.2 Analysis of change propagation

The purpose of the explanatory model is to predict change propagation caused by engineering changes within the multilayer network model.

The starting point of the change propagation analysis are engineering changes externally or internally caused, for example, by a customer’s change request. These change requests affect one or more FRs in the customer-layer. All DPs that are directly related by customer-to-product edges to the affected FRs represent the solution space to realize the change requests. Out of this solution space, a bundle of alternatives will be generated. Initially, all mathematically possible alternatives based on the dependency matrix $\boldsymbol{DM}_{FR\times DP}{}^{[\mathrm{m}\times\mathrm{n}]}$ will be generated. Subsequently, the product development team would evaluate these alternatives concerning their technical functionality. Each *alternative a* is represented by the *change propagation matrix* $\boldsymbol{CP}^{diag}(a; t = 0)$. $\boldsymbol{CP}^{diag}(a; t = 0)$ is a diagonal matrix with the changed DPs represented by the value 1 on the main diagonal, as shown in Figure 4. The number of DPs that can be changed ranges from 1 to n.



	DP1	DP2	DP3	DP4	DP5
FR1	0	0	1	1	0
FR2	1	0	0	0	0
FR3	0	0	0	0	1
FR4	0	1	0	1	0

	DP1	DP2	DP3	DP4	DP5
DP1	0	0	…	…	0
DP2	0	0	…	…	0
DP3	…	…	1	…	…
DP4	…	…	…	0	…
DP5	0	0	…	…	0

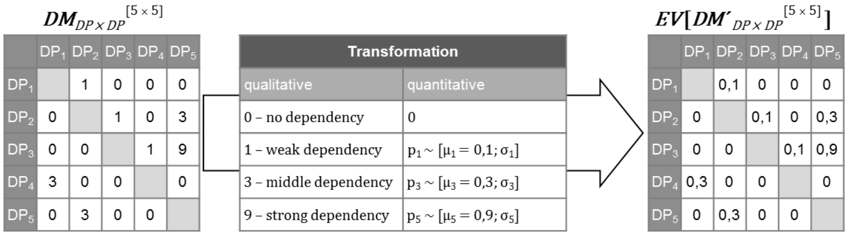
	DP1	DP2	DP3	DP4	DP5
DP1	0	0	…	…	0
DP2	0	0	…	…	0
DP3	…	…	0	…	…
DP4	…	…	…	1	…
DP5	0	0	…	…	0

	DP1	DP2	DP3	DP4	DP5
DP1	0	0	…	…	0
DP2	0	0	…	…	0
DP3	…	…	1	…	…
DP4	…	…	…	1	…
DP5	0	0	…	…	0

Figure 4. Generating alternatives

Each alternative represents an initial engineering change to the product and can lead to change propagation effects. Consequently, the change propagation will be simulated for each alternative. The simulation results are the probabilities that a DP or a PV will change caused by implementing alternative a. In the following section, the change propagation analysis will be conducted.

Besides the set of alternatives, further input data is needed for the change propagation analysis. First, the dependency matrix $\boldsymbol{DM}_{DP\times DP}{}^{[\mathrm{n}\times\mathrm{n}]}$ will be adjusted. The qualitative assessment of dependencies among DPs will be transformed into a probability-based assessment using normally distributed probabilities, shown in Figure 5. The *expected values μ* of the normally distributed probabilities represent the probability of changing a DP in case of changing the related design parameter. These expected change probabilities are assumptions under uncertainty made by the product development team. Therefore, the *standard deviation σ* represents the project-related degree of uncertainty. A further project-related variable is the *learning factor L*. Change propagation can be described as a time-discrete iteration process. After each iteration step of change propagation, the product development team will learn about the behavior of the system being designed, commonly known as learning effect. Consequently, the change probabilities will decrease. Therefore, the learning factor L is a project-related assumption also made by the product development team and determines how much lower the change probabilities will be after each iteration step. This factor is significantly dependent on the communication level within the product development team.



	DP1	DP2	DP3	DP4	DP5
DP1		1	0	0	0
DP2	0		1	0	3
DP3	0	0		1	9
DP4	3	0	0		0
DP5	0	3	0	0	

qualitative	quantitative
0 – no dependency	0
1 – weak dependency	$p_1 \sim [\mu_1 = 0{,}1; \sigma_1]$
3 – middle dependency	$p_3 \sim [\mu_3 = 0{,}3; \sigma_3]$
9 – strong dependency	$p_5 \sim [\mu_5 = 0{,}9; \sigma_5]$

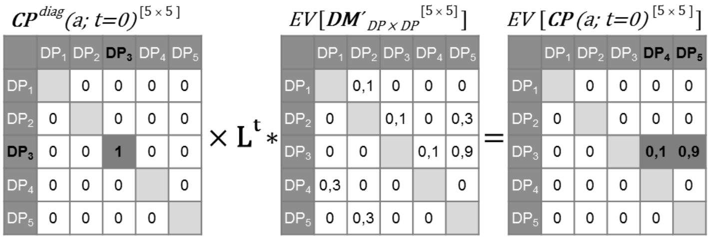
	DP1	DP2	DP3	DP4	DP5
DP1		0,1	0	0	0
DP2	0		0,1	0	0,3
DP3	0	0		0,1	0,9
DP4	0,3	0	0		0
DP5	0	0,3	0	0	

Figure 5. Matrix transformation

As mentioned before, each alternative represents an initial engineering change to the product and forms the starting point of the change propagation analysis. In the first *time step t* of the iterative procedure, the initial change propagation matrix $\boldsymbol{CP}^{diag}(a; t=0)$ will be multiplied by the probability-based dependency matrix $\boldsymbol{DM'}_{DP \times DP}{}^{[\mathrm{n} \times \mathrm{n}]}$ as shown in Equation (1):

$$\boldsymbol{CP}^{diag}(a; t=0) \times \boldsymbol{L}^{t} * \boldsymbol{DM'}_{DP \times DP}{}^{[\mathrm{n} \times \mathrm{n}]} = \boldsymbol{CP}(a; t=0) \tag{1}$$

The *resulting matrix* $\boldsymbol{CP}(a; t=0)$, shown in Figure 6, indicates the changes that are directly caused by changing DPs according to the chosen alternative a. At t = 0, learning effects have not yet been reached. As also mentioned before, the probabilities are normally distributed. Therefore, the change propagation analysis uses a Monte Carlo Simulation. The following figures show notional expected values as matrix elements.



$CP^{diag}(a;\, t=0)^{[5 \times 5]}$

	DP1	DP2	DP3	DP4	DP5
DP1		0	0	0	0
DP2	0		0	0	0
DP3	0	0	1	0	0
DP4	0	0	0		0
DP5	0	0	0	0	

$\times \mathrm{L}^{t} *$

$EV[\boldsymbol{DM'}_{DP \times DP}{}^{[5 \times 5]}]$

	DP1	DP2	DP3	DP4	DP5
DP1		0,1	0	0	0
DP2	0		0,1	0	0,3
DP3	0	0		0,1	0,9
DP4	0,3	0	0		0
DP5	0	0,3	0	0	

$=$

$EV\,[\boldsymbol{CP}(a;\, t=0)^{[5 \times 5]}]$

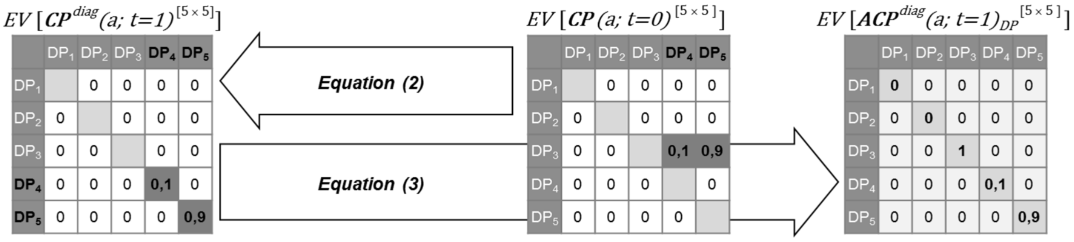
	DP1	DP2	DP3	DP4	DP5
DP1		0	0	0	0
DP2	0		0	0	0
DP3	0	0		0,1	0,9
DP4	0	0	0		0
DP5	0	0	0	0	

Figure 6. First generation of change propagation

The first iteration step ends with three transformations: First, the resulting matrix $\boldsymbol{CP}(a; t=0)$ is transferred into the diagonal matrix $\boldsymbol{CP}^{diag}(a; t=1)$ and the time counter t is set to t = 1. According to Clarkson et al. (2004), the overall change probability of a DP can be aggregated by multiplying the counter values of the probabilities in the corresponding column using Equation (2). Second, the change probabilities for each DP can be accumulated throughout the entire iteration process, resulting in the *diagonal accumulated change propagation matrix* $\boldsymbol{ACP}^{diag}{}_{DP}(a; t)$. The mathematical term of each diagonal element for this matrix is shown in Equation (3). This result matrix represents the overall change impact on each DP caused by implementing alternative a after t iteration steps, shown in Figure 7.

$$\boldsymbol{cp}^{diag}{}_{jj}(a; t+1) = 1 - \prod_{i=1}^{n}\Big(1 - \boldsymbol{cp}_{ij}(a; t)\Big) \tag{2}$$

$$\boldsymbol{acp}^{diag}{}_{DP\, jj}(a; t) = 1 - \prod_{0}^{t}\Big(1 - \boldsymbol{cp}^{diag}{}_{jj}(a; t)\Big) \tag{3}$$



$EV\,[\boldsymbol{CP}^{diag}(a;\, t=1)^{[5 \times 5]}]$

	DP1	DP2	DP3	DP4	DP5
DP1		0	0	0	0
DP2	0		0	0	0
DP3	0	0		0	0
DP4	0	0	0	0,1	0
DP5	0	0	0	0	0,9

$EV\,[\boldsymbol{CP}(a;\, t=0)^{[5 \times 5]}]$

	DP1	DP2	DP3	DP4	DP5
DP1		0	0	0	0
DP2	0		0	0	0
DP3	0	0		0,1	0,9
DP4	0	0	0		0
DP5	0	0	0	0	

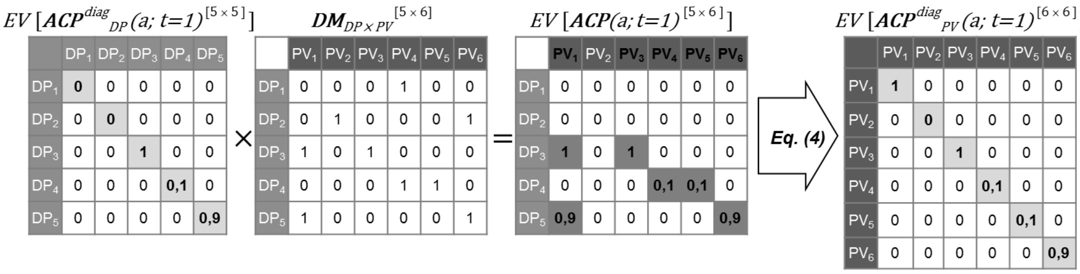
$EV\,[\boldsymbol{ACP}^{diag}(a;\, t=1)_{DP}{}^{[5 \times 5]}]$

	DP1	DP2	DP3	DP4	DP5
DP1	0	0	0	0	0
DP2	0	0	0	0	0
DP3	0	0	1	0	0
DP4	0	0	0	0,1	0
DP5	0	0	0	0	0,9

Figure 7. The first two transformations after each iteration step

Based on the results of the overall change impact on each design parameter, the third transformation calculates the change impact on the production. Therefore, the accumulated change propagation matrix $\boldsymbol{ACP}^{diag}{}_{DP}(a; t)$ will be multiplied by the dependency matrix $\boldsymbol{DM}_{DP \times PV}{}^{[\mathrm{n} \times \mathrm{o}]}$. In analogy to Equation (3), the resulting matrix will be transferred into the *diagonal accumulated change propagation matrix* $\boldsymbol{ACP}^{diag}{}_{PV}(a; t)$ (see Equation 4). This matrix gives the change probabilities for each PV over the time period t, shown in Figure 8.

$$\boldsymbol{acp}^{diag}{}_{PV\, jj}(a; t) = 1 - \prod_{i=1}^{o}\big(1 - \boldsymbol{acp}_{ij}(\mathrm{a}; \mathrm{t})^{PV}\big) \tag{4}$$



$EV[\boldsymbol{ACP^{diag}}_{DP}(a;t=1)^{[5\times5]}]$

	DP1	DP2	DP3	DP4	DP5
DP1	0	0	0	0	0
DP2	0	0	0	0	0
DP3	0	0	1	0	0
DP4	0	0	0	0,1	0
DP5	0	0	0	0	0,9

×

$\boldsymbol{DM}_{DP\times PV}{}^{[5\times6]}$

	PV1	PV2	PV3	PV4	PV5	PV6
DP1	0	0	0	1	0	0
DP2	0	1	0	0	0	1
DP3	1	0	1	0	0	0
DP4	0	0	0	1	1	0
DP5	1	0	0	0	0	1

=

$EV[\boldsymbol{ACP}(a;t=1)^{[5\times6]}]$

	PV1	PV2	PV3	PV4	PV5	PV6
DP1	0	0	0	0	0	0
DP2	0	0	0	0	0	0
DP3	1	0	1	0	0	0
DP4	0	0	0	0,1	0,1	0
DP5	0,9	0	0	0	0	0,9

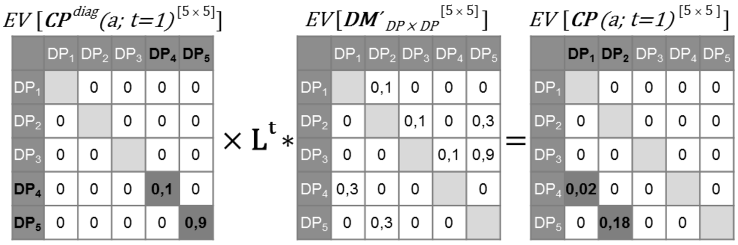
$EV[\boldsymbol{ACP^{diag}}_{PV}(a;t=1)^{[6\times6]}]$

	PV1	PV2	PV3	PV4	PV5	PV6
PV1	1	0	0	0	0	0
PV2	0	0	0	0	0	0
PV3	0	0	1	0	0	0
PV4	0	0	0	0,1	0	0
PV5	0	0	0	0	0,1	0
PV6	0	0	0	0	0	0,9

Figure 8. Third transformation after each iteration step resulting in $\boldsymbol{ACP}^{diag}{}_{PV}(a;t)$

The transformed change propagation matrix $\boldsymbol{CP}^{diag}(a;t=1)$ acts as new input matrix for the second iteration of change propagation. It is once again multiplied by the probability-based dependency matrix $\boldsymbol{DM'}_{DP\times DP}{}^{[\mathrm{n}\times\mathrm{n}]}$ resulting in the change propagation matrix $\boldsymbol{CP}(a;t=1)$ at t = 1 (see Equation 5). Thereby, the change probabilities of the dependency matrix $\boldsymbol{DM'}_{DP\times DP}{}^{[\mathrm{n}\times\mathrm{n}]}$ decrease for the first time as a result of learning effects, shown in Figure 9. For the presented example, the learning factor L = 0,67 was chosen.

$$\boldsymbol{CP}^{diag}(a;t=1)\times\boldsymbol{L}^{t}*\boldsymbol{DM'}_{DP\times DP}{}^{[\mathrm{n}\times\mathrm{n}]}=\boldsymbol{CP}(a;t=1) \qquad (5)$$



$EV[\boldsymbol{CP}^{diag}(a;t=1)^{[5\times5]}]$

	DP1	DP2	DP3	DP4	DP5
DP1		0	0	0	0
DP2	0		0	0	0
DP3	0	0		0	0
DP4	0	0	0	0,1	0
DP5	0	0	0	0	0,9

$\times\,\mathrm{L}^{t}*$

$EV[\boldsymbol{DM'}_{DP\times DP}{}^{[5\times5]}]$

	DP1	DP2	DP3	DP4	DP5
DP1		0,1	0	0	0
DP2	0		0,1	0	0,3
DP3	0	0		0,1	0,9
DP4	0,3	0	0		0
DP5	0	0,3	0	0	

=

$EV[\boldsymbol{CP}(a;t=1)^{[5\times5]}]$

	DP1	DP2	DP3	DP4	DP5
DP1		0	0	0	0
DP2	0		0	0	0
DP3	0	0		0	0
DP4	0,02	0	0		0
DP5	0	0,18	0	0	

Figure 9. Second generation of change propagation

Once again, the resulting matrix $\boldsymbol{CP}(a;t=1)$ is first transferred into a diagonal matrix, the change propagation matrix $\boldsymbol{CP}^{diag}(a;t=2)$ according to the mathematical term as previously shown (see Equation (2)). Based on this, both accumulated change propagation matrices $\boldsymbol{ACP}^{diag}{}_{DP}(a;t=2)$ and $\boldsymbol{ACP}^{diag}{}_{PV}(a;t=2)$ will change as shown before (see Equations (3) and (4)). Subsequently, the resulting matrix $\boldsymbol{CP}^{diag}(a;t=2)$ acts as new input matrix for the next iteration step of change propagation again. This process, shown in Figure 10, can be continued until a defined threshold of a minimum increase is reached resulting in the following algorithm:

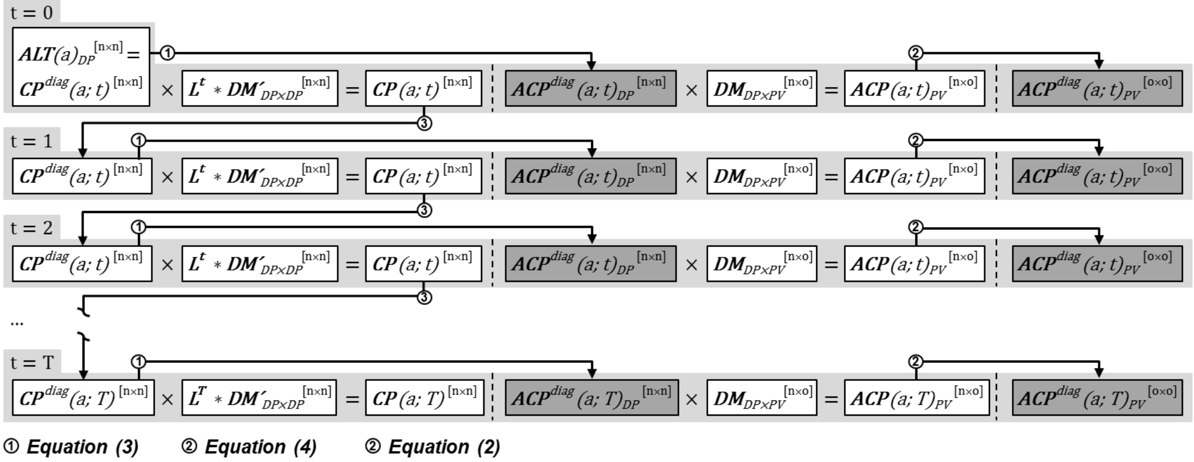


Figure 10: Algorithm of the change propagation analysis

Using this change propagation analysis method, the overall change impact on both product and production caused by an initial engineering change can be simulated. Over time, the accumulated change probabilities of both DPs and PVs converge. Thereby, it can be observed that after 3 or 4 time intervals there is no significant increase in probabilities. This insight concurs with previous research by Clarkson et al. (2004).

3.3 Calculation of change costs

The previously presented change propagation analysis predicts the overall change impact on both product and production caused by implementing an alternative a. Each alternative represents a technical solution to fulfil a change request. To evaluate the performance of each alternative, the overall change costs for each alternative need to be calculated.

For this purpose, the *overall change costs OCC(a)* for a specific alternative for both product and production is calculated as follows: First, the accumulated change propagation matrix ${\boldsymbol{ACP}^{diag}}_{DP}(a;t)$ will be multiplied by the change costs matrix ${\boldsymbol{CC}_{DP}}^{[n \times n]}$, and the accumulated change propagation matrix ${\boldsymbol{ACP}^{diag}}_{PV}(a;t)$ will be multiplied by the change costs matrix ${\boldsymbol{CC}_{PV}}^{[o \times o]}$. Subsequently, the traces of these two result matrices will be calculated and summed as shown in Equation (6):

$$\begin{aligned} \boldsymbol{OCC}(a) &= \boldsymbol{OCC}(a)_{DP} + \boldsymbol{OCC}(a)_{PV} \\ &= \sum_{i=1}^{n} {\boldsymbol{acp}^{diag}}_{DP\,ii}(a;t) * \boldsymbol{cc}_{DP\,ii} + \sum_{i=1}^{o} {\boldsymbol{acp}^{diag}}_{PV\,ii}(a;t) * \boldsymbol{cc}_{PV\,ii} \end{aligned} \tag{6}$$

Since the change probabilities are normally distributed, the overall change costs OCC(a), calculated by using a Monte Carlo Simulation, are normally distributed as well. Figure 11 shows simulation results of the described example (see Figures 3 to 9) for the chosen alternatives 1 and 2. These results enable the selection of the most cost-effective solution. In this case, alternative 2 is more cost-effective than alternative 1.

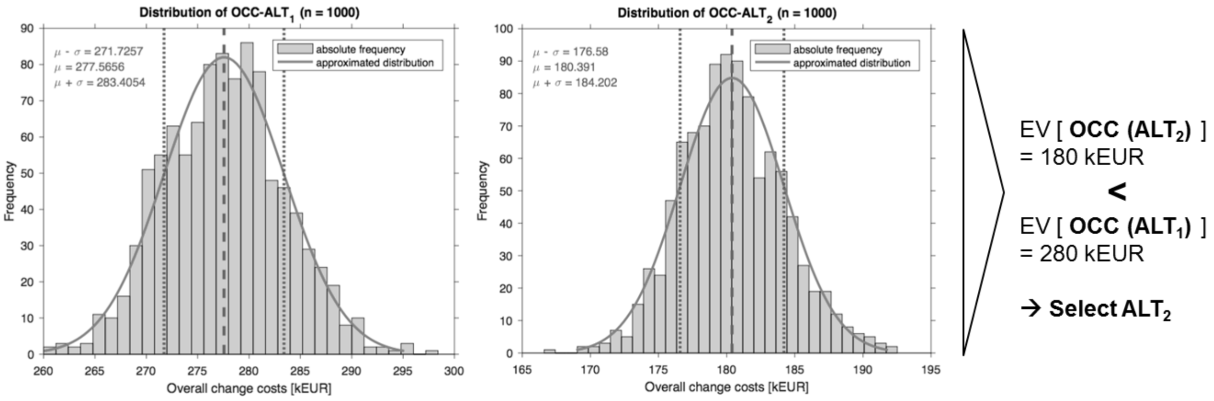


Figure 11. Simulation results of the described example

4 CASE STUDY

This method was applied for the analysis of an asynchronous motor. In cooperation with a medium-sized company, the dependencies and change costs were determined for an existing asynchronous motor, as explained in section 3.1. The simulation results of the change propagation analysis were validated with experts of the chair of Production Engineering for E-Mobility Components (PEM) of RWTH Aachen University.

An electric engine converts electrical energy into mechanical energy. The main components of an asynchronous motor are the rotor and the fixed stator. The stator's laminated core is fastened inside the housing by means of interference fit. The rotation of the rotor is obtained by electromechanical induction from the magnetic field of the stator winding. This torque is transmitted to the motor shaft (Kampker, 2014). Electric engines are usually developed and produced by tier one suppliers, for instance in the automotive industry. Since customer enquiries arise throughout the entire lifecycle, engineering changes occur frequently. Therefore, it is necessary to predict the change costs for both product and production as well as to figure out the most cost-effective solution.

For the case study, an already produced asynchronous motor was analyzed. According to that, changes in requirements over the product lifecycle were considered. The analyzed motor consisting of 31 DPs needs to fulfil a broad range of 27 FRs. The production of that engine can be described by 81 PVs. As a representative change request, a modification of the nominal power was analyzed. Therefore, three possible technical solutions were generated, namely a length change of active parts ($\boldsymbol{ALT}_1$), a diameter change of active parts ($\boldsymbol{ALT}_2$) and a change of the rotor laminations ($\boldsymbol{ALT}_3$). Each alternative represents an initial engineering change to the product to fulfil the change request. Consequently, a change propagation analysis as described before was carried out for each of them. The simulation results are shown in Figure 12. Thereby, only R&D costs as well as investment costs of the production were considered. The product and production change costs of each alternative are set in relation to the change costs if all DPs or all PVs were changed. Additionally, the production change costs are set in relation to the overall costs of the entire production line.

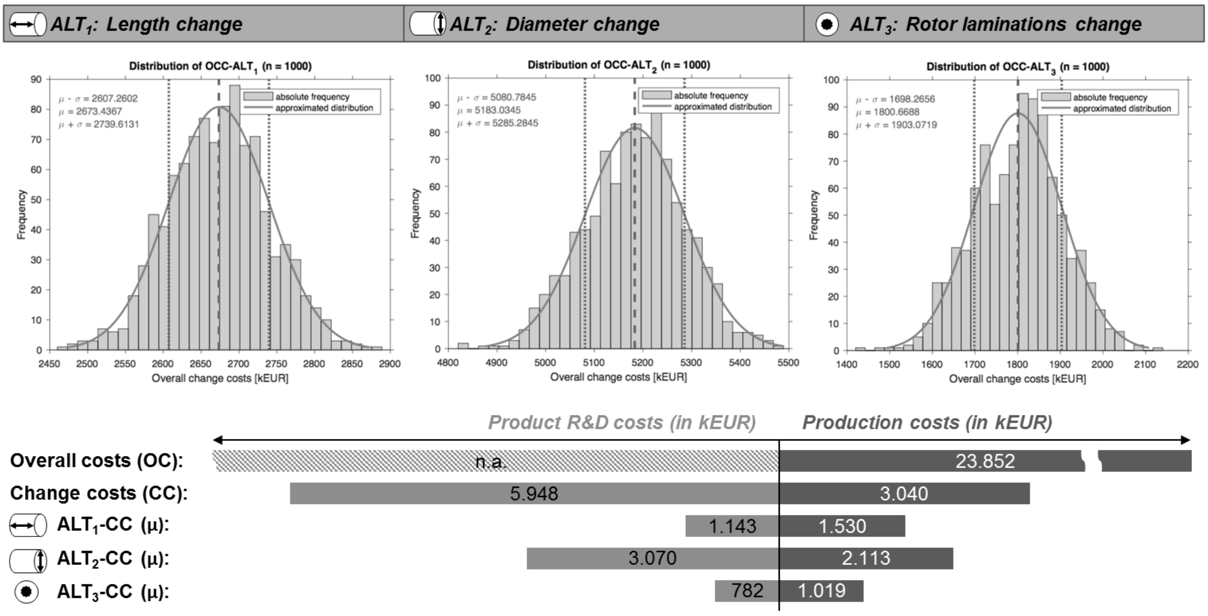


Figure 12. Simulation results of the case study

It was found that a change of the rotor laminations ($\boldsymbol{ALT_3}$) causes the least change propagation and provides the most cost-effective solution to change the nominal power of the asynchronous motor. Although the active part diameter ($\boldsymbol{ALT_2}$) has a high effect on the nominal power (quadratic relationship), a variation of this component specification leads to strong change propagation effects and high overall change costs. The expected overall change costs of this solution are almost twice as high as the expected overall change costs caused by a variation of the active parts length ($\boldsymbol{ALT_1}$) and almost three times as high as the expected overall change costs caused by a variation of the rotor laminations ($\boldsymbol{ALT_3}$). The application of the methodology showed its practicability and using the commercially-available MATLAB tool, the effort for the application is deemed reasonable.

5 CONCLUSION

In this paper an approach for the assessment of changes in engineering design was introduced. Initial engineering changes to the product often lead to undesired change propagation effects on both product and production. Therefore, it is necessary to predict the change impact caused by an engineering change and to estimate the cost impact on both product and production. For this purpose, a change propagation analysis was developed and applied.

To relate FRs derived from customer needs, DPs of the product and PVs of the production, a multilayer network model was designed and operationalized. Based on this, the change propagation analysis was developed. Starting from a change request, alternative technical solutions were generated at first. Each alternative represents an initial change to the product. Consequently, for each alternative the change propagation for both product and production was determined in an iterative multiplication of change propagation matrices with the probability-based interdependency matrix of the product. The resulting matrices can then be used to calculate the overall change costs of each alternative to identify the most cost-effective solution.

The application and validation of the method for design changes to an asynchronous motor demonstrated the value of the method and its usefulness. The application of the method, however, requires a detailed set of input data. Therefore, an efficient integration into existing PDM systems is desirable. Further research could integrate an assessment model to evaluate the function fulfilment of the generated alternatives. Thus, the relative degree of change of each alternative could be considered.

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