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Impact and risk analysis in the integrated development of product and production system

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Abstract

The assessment of risks and influences of engineering changes of a product or production system on affected technical (sub-) systems of the same or a different domain are of great importance in order to evaluate possible alternatives and to select solutions. The increasing complexity of mechatronic products and production systems with Industry 4.0 technology reinforces the demand for a method that supports engineers in decision making in both technical and strategic issues. By using the method presented in this contribution, interdependencies between product functions, product features and the corresponding production processes and machines can be modelled and used to estimate the impact and risks of changes in one of those domains. Using the method, the change propagation of variations in and between the domains can be evaluated. The objective of the method is to support decision making in different use-cases like integrated product- and production system development, product variations while carrying over most of the production system or varying production processes while carrying over the product to improve production key performance indicators (KPI). Based on the model of PGE – Product Generation Engineering, the information of the reference system is used to identify the interdependencies. The inclusion of strategic factors like know-how and costs is implemented in the model, as well as the quantity and type of variations. The method consists of a representative model for a quick, holistic overview about the interdependencies and of a tool based model by using Model-Based Systems Engineering (MBSE) for an automatic connection and evaluation of the data. The contribution is part of the project I4TP - Sino German Industry 4.0 Factory Automation Platform (i4tp.org), in which a platform is developed to automatically configure a turnkey production system for a product in development.

Keywords: risk analysis; integrated product development; production system; Industry 4.0

1. Introduction

Simultaneous engineering is a well-known approach in product engineering to reduce development time and product costs and to increase product quality [1,2]. The implementation and operationalization has many requirements and challenges for the involved people, like a holistic thinking, acceptance and methodical know-how [3]. In this contribution, a method is developed to support engineers in the holistic thinking by linking product functions and product features with the associated production processes and machines. Especially the increasing complexity of mechatronic products and production systems with Industry 4.0 (I4.0) functions (see definition in [4]) strengthens the demand for a method that helps to identify and model the interdependencies between the different domains. By modelling the interdependencies, the engineer can estimate the impacts and risks of engineering activities more easily and thus have a support in decision making. Examples for different engineering situations are:

- The demand for new product functions which results in a design change in the next product generation and a change of production processes
- Production process changes or optimizations while carrying over the product design
- Development of a new product with the setup of a new production system

The first of these examples serves as a use-case in this contribution. Two main functions of a valve are modelled and interconnected with the belonging domains. The impact of a change of one of the product features is shown clearly by reducing the contemplated features and processes. A SysML model links the information and automatically shows the interdependencies between the domains. This allows the consideration of complex products and production systems.

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2. State of the Art

In this chapter the authors describe the state of the art which is necessary to understand the context and basic models of this contribution.

2.1 The model of PGE – Product Generation Engineering

The model of PGE – Product Generation Engineering describes that most products are developed in generations [5]. Therefore, new product generations – which can also be production systems – are based on elements or the entirety of one or more existing socio-technical systems, the so called reference system [6]. The next product generation G_n always consists of carryover, embodiment or principle variations from the reference system.

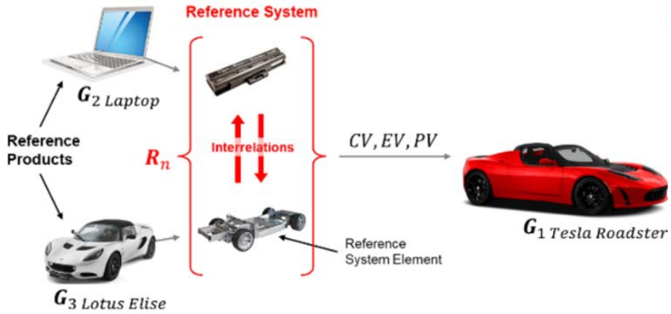

Fig. 1.PGE model with the reference system on the example of a Tesla Roadster [6]

Embodiment and principle variations are new developments [7]. A high share of new developments leads to increased complexity and thus to a higher risk [8]. According to ALBERS ET AL. [7] the variation shares can be calculated by considering the share of the number of characteristics to be changed and their variation type divided by the total number of characteristics of the system.

2.2 Risk analysis in product and production system engineering

Due to the increasing complexity of products and production systems, it becomes harder for engineers to gain an overview of the functionality and the interdependencies within and between the domains of the systems. Due to this high degree of uncertainty it becomes difficult to predict the effect of a change in a subsystem on the overall system. At the same time, development cycles are becoming shorter due to strong competitive pressure [9].

In a complex product in which all parts and systems are closely linked, adjustments to one element of a system are likely to result in a change to another element. The focus must be on the early stage of product generation development. Later corrections to the product lead to significant additional effort and high costs [10]. The "Rule of Ten" describes the increase of the change costs by a factor of 10 in each development stage [11]. This shows the need to identify weaknesses and risks in the early stages of the product development to eliminate them. The early stage of the product generation development is characterized by many uncertainties. A useful method for the impact and risk analysis enables the product developer to identify risks at an early stage and thus errors can be avoided. In order to determine the development risk, the effects and change propagation of an occurring change must be considered [12,13]. A visual representation of all propagation paths can therefore be very useful for a holistic view and can help to predict the risk associated with decisions [14].

The variety and complexity of the functions and properties that are in constant interaction with elements from other domains is a major challenge for the technical risk management process and can only be mastered through a systematic and structured methodology. A good management of technical changes during product development allows the company to reduce development costs and time while improving product quality [15].

2.3 Modelling of interdependencies between product and production system

According to EHRLENSPIEL, Simultaneous Engineering is an interdisciplinary collaboration and parallelization of product, production and sales development [16]. In the approach CONSENS - "CONceptual design Specification technique for the ENgineering of complex Systems" [17], GAUSEMEIER ET AL. model various aspects of products and production systems which intersect in their requirements. In the research project mecPro² [18,19], a model-based integrated development process for cybertronic products and production systems is established. The interdependencies between the domains are modelled using MBSE.

ALBERS ET AL. developed an approach to identify potentials and interdependencies in product and production system development [4] which is shown in *Fig. 2*. This contribution ties in by focussing on a method for an impact and risk analysis of product and production system changes.

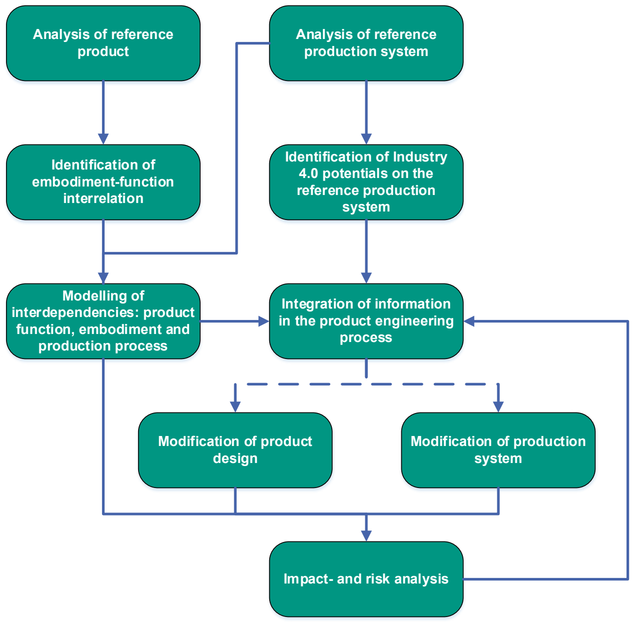

Fig. 2. Approach for the integrated development of product and production system [4]

MANDEL ET AL. describe an approach to model relevant information in the context of integrated product- and production system development with the help of the MBSE language SysML [20]. The approach encompasses the model-based representation of product functions, product design including features relevant for manufacturing as well as suitable manufacturing processes and machines. The dependencies between these model elements are simultaneously modelled using appropriate SysML relations. In this manner, information about the modelled elements and their relations can unambiguously be stored in an interdisciplinary system models. Using built in functionalities of SysML modelling tools, direct and indirect relations of a system model element that have been independently modelled by a multitude of engineers can be displayed automatically. The identified dependencies can than serve as a starting point for impact and risk analyses.

3. Development of a method for the holistic impact and risk analysis

The introduced preliminary work shows that there are several methods for the combined modelling of product and production systems. However, there is no approach to include information of the reference systems in the early stage of the product generation development and how to evaluate modeled, alternative solutions by comparing the impact of changes and the share of new development.

For efficient decision making, product developers need a balance between detailed information and a global overview [14]. Therefore, this paper expands a method to identify and model the interdependencies between product functions, product embodiment with its features, production processes and machines and the correlation of these domains (cf. [4]) with strategic factors like costs or know-how in the early stages of the product generation engineering to support the engineers and product developers in evaluating impacts and risks due to changes or new elements. Especially the technical impacts between the domains can be evaluated with this method by using information of the reference system.

The following sections describe the method and procedure and the advantages that follow from the method.

3.1 Description of the method

The values in the cells represent the strength of the interdependency of the two elements linked to the cell.

According to the model of the PGE, most designs are created by modifying existing products. Therefore the reference system can be considered for the development of the model.

For a holistic overview, the interacting functions, features and production processes and machines and the correlation of these domains with strategic factors are displayed in a matrix-based representation (see *Fig. 3*). The left column shows the product functions, product features and the corresponding production processes. On top, the machines are linked to the processes. The lower part shows the influence of the elements on the strategic factors.

3.2 Procedure

Fig. 3 shows a simple example where the procedure can be explained.

Initial system of objective

When developing a new product generation or changing the production system for example, the focus of the examination of the change propagation must be determined and a system boundary must be defined. It is possible to focus the analysis on a specific part or to analyse the whole system.

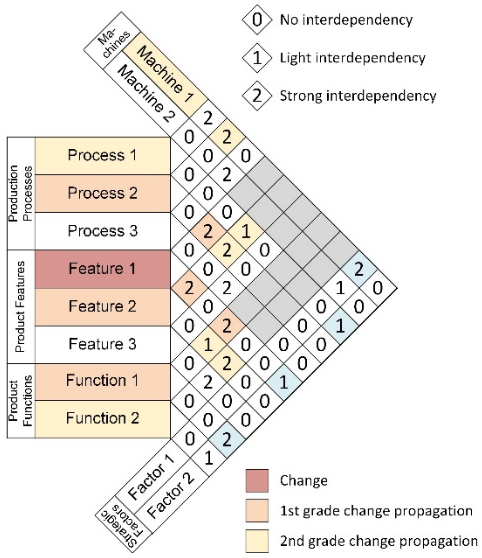

Fig. 3. Example of the correlation matrix with change propagation

Decomposing the system into its elements

The product functions, product features and the corresponding production processes and machines of the reference system are recorded and modeled in a SysML model. To decompose the product features the C&C^2-approach (Contact and Channel Approach) can be used, which helps to analyse the relationship between the function and embodiment of technical systems [21]. Depending on how detailed the system should be viewed, the system can also be broken down into its individual parts or all features can be viewed.

Modelling of interdependencies between product and production system

The method considers the interdependencies shown in *Fig. 4*.

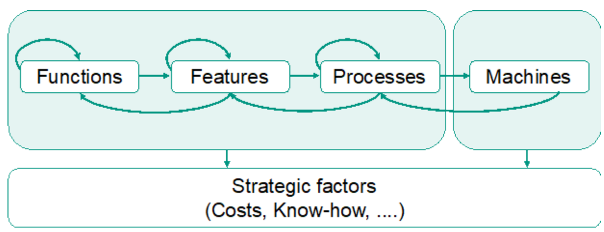

Fig. 4. Considered interdependencies

Based on the model of PGE, the identification of the interdependencies of the elements is supported by elements from the reference system. Following the approach described by MANDEL ET AL. [20], those interdependencies are modelled in a SysML model and can be drawn from there. This description of the interdependencies between the elements captures the current state of knowledge. Thus, as knowledge about element interdependencies progresses in the current development process, the interactions must be revised and updated. The data quality is of great importance and influences all further steps of the approach presented here. Errors in data collection that remain undetected can become critical due to incorrect interpretations. Even a system with few elements requires many decisions. In order to systematically identify and evaluate the interactions, various criteria can be defined. In the application of a use-case in chapter 4, possible criteria are proposed. The number and definition of interaction types depends on the context of the respective design problem. The criteria proposed here are therefore not generally valid. The rating scale for the interdependencies can differ for each specific use-case, in the following a rating from zero to two is used, where zero stands for no interdependency, one for a light interdependency and two for a strong interdependency. Cells that connect elements where the evaluation of the interactions is meaningless can be grayed out.

Prediction of change propagation

The prediction of change propagation is explained by the example shown in *Fig. 3*.

In the example, the red highlighted feature 1 is changed. Cells that represent an interdependency of this element with other elements that are affected by this change and the affected elements are highlighted orange. In the simple example the change of feature 1 probably has four further effects. These effects can also be called first grade change propagation. Subsequently, the changes of second grade are examined in the same way and highlighted yellow. The result is that there may be six more possible impacts. Depending on how detailed the change propagation is to be examined, further degrees of change propagation can also be considered the same way. After focusing the technological factors, the effects on the strategic factors of the elements to be adjusted can also be considered for the impact and risk analysis. This impact is highlighted blue in the figure.

The simple example clearly shows that a change of one element can lead to many more adjustments in different domains that are difficult to manage and can have an impact on strategic factors.

Since this is a model, it is important to question the predicted change propagation with background knowledge. This may exclude a part of the change propagation. Only elements that are likely to be affected need further consideration. The assessment from zero to two can already help in the estimation, but the existence of the change propagation can also depend on the type of changed characteristics.

3.3 Advantages

The method offers possibilities for a holistic analysis, control and optimization of complex products, while the amount of data remains manageable. The small example shows that changing an element can lead to many other changes that occur in different domains. Due to the complex networking, it is hardly possible for the product developer to keep track of the effects of his decisions and to take them into account appropriately. The matrix-based solution described here is designed to help to systematically determine the change propagation and to provide practical support for the impact and risk analysis in product development and in changing products. The method supports impact and risk assessment by drawing the engineers' attention to elements that are strongly networked with other elements, that can also be within another domain. A change to one of these elements can lead to major rework on other elements that are not necessarily directly connected to the element.

The matrix representation allows developers to evaluate whether planned adjustments are recommended or whether they lead to an unmanageable change propagation with a high expected adjustment effort, which requires high adjustment time and costs.

With the help of the matrix, strategic factors can also be taken into account. For example, it can be shown that a change may be easy to implement from a technological point of view, but when considering the strategic factors it becomes clear that the change will have a big impact on the costs and therefore alternative solutions should be considered.

The entire network, a subset or a combination of subsets can be investigated. It is possible to focus on a particular function, if the product developer is interested in determining problematic change propagations in the system that result from the change of function, or to select elements that cause restrictions for the system because they cannot be adjusted, for example. Other system elements connected with the restrictive ones are of interest, since their changeability of the design is also limited. By modelling the information in SysML, the change propagation can be automatically shown to cope with the complexity.

The method also offers the possibility of weighing up alternatives, assuming there are different change paths possible for changed boundary conditions in the created matrix of the reference system. The best solution can be selected by evaluating and analysing the impact and the associated risk on other elements and strategic factors of the alternatives. The procedure supports the product developer in developing product variants and making changes to the product by estimating the required scope of change. The following chapter illustrates this procedure.

4. Application in an industrial use-case and linkage with the model of PGE

The proposed method is evaluated on the use case of a valve (see *Fig. 5*) that is produced at the Advanced Manufacturing Technology Center (AMTC) by the Institute of Production Science (wbk) in Shanghai, China. In a breakdown, some of the functions, features and production processes are displayed and a possible design change due to increased design space boundary conditions is executed.

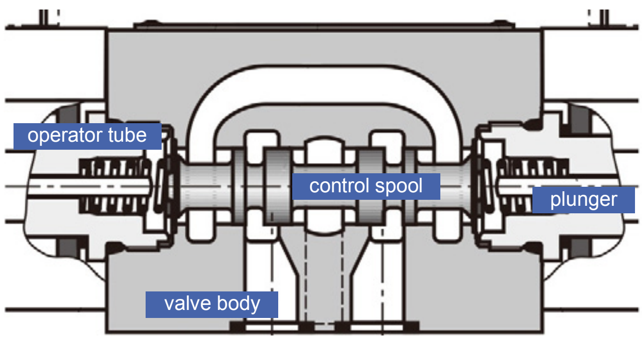

Fig. 5. Reference product - three way valve

4.1 Evaluating alternative solutions with the developed method

Two possible alternatives to create the valve with the new boundary conditions are considered in this example. The reduction in design space can be achieved at different positions, therefore different system boundaries are also selected. At the beginning, the correlation matrix of the reference system is created. With this diagram, the designers can easily identify critical elements and the change propagation of the solutions which have to be considered in the early stage of the development process. For the assessment of the interdependency to create the correlation matrix a scale from zero to two was used, meaning zero for no correlation and two for high correlation. An impact and risk analysis of the two alternatives is provided in the following.

Fig. 6 shows **alternative 1** to realize the reduction of design space with the relevant working surface pairs (WSP) according to the C&C^2-approach (cf. [22]). The design space of the valve can be minimized by minimizing the length of the valve through shortening the WSP XII and IX. *Fig. 7* shows an excerpt of the relevant parts of the correlation matrix. The shaded cells represent the affected elements as described before. The created correlation matrix helps for estimating the impact.

It shows that a change of the WSP XII and IX has a direct influence on other WSP and other domains. With background knowledge and the help of the assessment of the strength of the interdependencies it can be estimated whether the change propagation is relevant.

The matrix shows that the change is easy to implement from the technological point of view. Affected working surfaces have to be changed and thus the affected function of "Store and conduct liquids" can still be fulfilled. Although many of the production processes have to be adjusted, they can still be carried out on the same machines and only the parameters have to be changed. But considering the strategic factors, it becomes clear that the casting process, or to be more precise, the casting tool is very expensive. By changing the embodiment of the valve housing, a new casting mould is needed, which involves very high costs. This can result that the solution is not feasible.

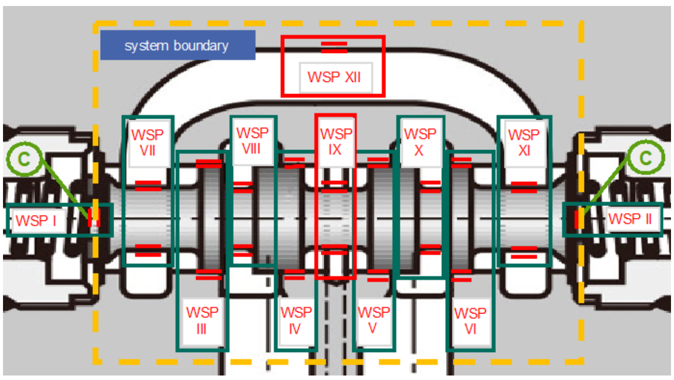

Fig. 6. Alternative 1 – Shortening of control spool and housing

Fig. 8 shows the left part of **alternative 2** for the increased design space boundary by looking at the features. In comparison to *Fig. 6*, the left and the right end of the valve is shortened. The affected features are highlighted red. *Fig. 9* shows the correlation matrix of the reference system with the outlined change propagation and the impact on the strategic factors. As seen, many features must be changed for this alternative solution, which then have further impacts. The plunger and the operator tube are purchased parts. For these parts, the adjustments must be communicated to the supplier. The length of the spring is also shortened, so the spring force changes and probably a different spring has to be selected. In addition, the correlation matrix shows that a change in the spring has an effect on the electromagnet. The force of the magnet may be adjusted.

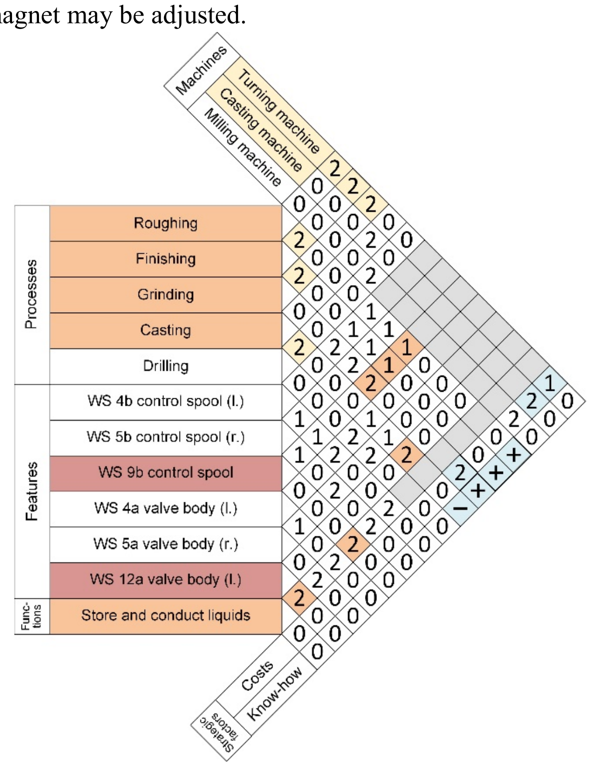

Fig. 7. Correlation matrix for alternative 1

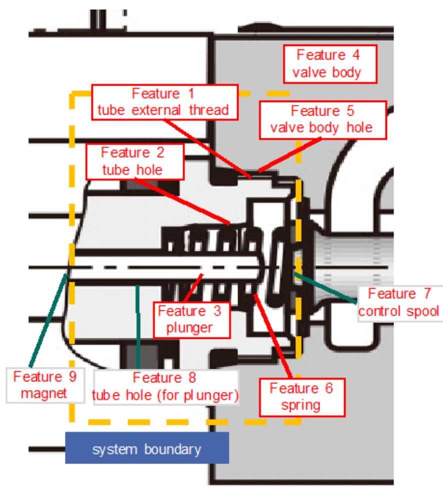

Fig. 8. Alternative 2 – Shortening of tube and housing hole

The body of the valve is also shortened. The matrix shows that this change does not have an effect on any elements other than processes. The body is cast and then milled. A closer look reveals that in this case a new casting mould is not necessarily required, since the subsequent milling process of the contours has a great influence on the final shape, only this could be changed by adjusting the parameters and the casting process does not have to be adapted, since this process can only be adapted in combination with high costs.

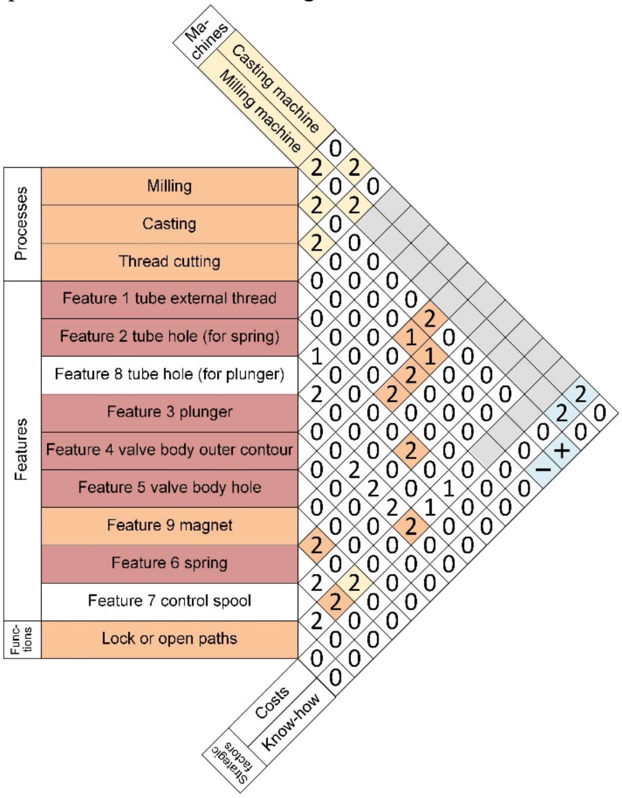

Fig. 9. Correlation matrix for alternative 2

4.2 Linkage with the model of PGE

In the following, the derivation of the variation shares in the context of the model of PGE is described on the example.

The variation shares can be used as values to support variant selection as the ratios of the variation shares give information about the risk, the constructive effort and the potential for the concrete execution. It is only applicable for the product, not for production machines or processes.

As stated in *Table 1* there is a carryover variation (CV) share of 97,6% and an embodiment variation (EV) share of 2,4%. There is no principle variation (PV) to the new product generation in the alternative 1.

Table 1. Variation shares for alternative 1

WS	Part	Number of parameters	CV	EV	PV	CV (%)	EV (%)	PV (%)
	all carryover parts	76	76	0	0	100%	0%	0%
XIIa	valve body	3	2	1	0	66,7%	33,3%	0%
IXb	control spool	3	2	1	0	66,7%	33,3%	0%
	total system	**82**	**80**	**2**	**0**	**97,6%**	**2,4%**	**0%**

For alternative 2 there is a carryover variation share of 85,4% and a embodiment variation share of 14,6% (Table 2).

Table 2. Variation shares for alternative 2

Fea-ture	Part	Number of parameters	CV	EV	PV	CV (%)	EV (%)	PV (%)
	all carryover parts	48	48	0	0	100%	0%	0%
1	tube external thread (l.)	3	2	1	0	66,7%	33,3%	0%
2	tube hole (l.)	2	1	1	0	50%	50%	0%
3	plunger (l.)	4	3	1	0	75%	25%	0%
4	valve body (l.)	2	1	1	0	50%	50%	0%
5	valve body hole (l.)	3	2	1	0	66,7%	33,3%	0%
6	spring (l.)	3	2	1	0	66,7%	33,3%	0%
10	tube external thread (r.)	3	2	1	0	66,7%	33,3%	0%
11	tube hole (r.)	2	1	1	0	50%	50%	0%
12	plunger (r.)	4	3	1	0	75%	25%	0%
13	valve body (r.)	2	1	1	0	50%	50%	0%
14	valve body hole (r.)	3	2	1	0	66,7%	33,3%	0%
15	spring (r.)	3	2	1	0	66,7%	33,3%	0%
	total system	**82**	**70**	**12**	**0**	**85,4%**	**14,6%**	**0%**

According to the PGE alternative 1 indicates a lower risk due to a lower share of new development. The correlation matrix showed that alternative 1 is easy to implement with only a few adjustments, but including strategic factors and the production processes shows that the possible solution is associated with high costs and should therefore be reconsidered.

5. Summary and Outlook

In this contribution, the authors enhance a method for the modelling of interdependencies between product function, embodiment and the belonging production system with an impact and risk analysis of possible changes including strategic factors. The main difference to the approaches described in the state of the art is the use of information of the model of the PGE in the early stages and the evaluation of alternative design solutions by looking at the change propagation and new development shares. The method is applied on an industrial use-case, where two different alternative solutions are compared by the interdependencies between the (sub-)systems and domains and by the variation shares using the model of PGE. The described method is also linked to a SysML model to automate the identification of change propagation. The method contributes to a better understanding of interrelations between product and production systems and is an operative approach for simultaneous engineering. Thus, engineers of different domains can get a better understanding and overview in complex product and production system development processes. The more information is available in early stages, the more detailed the interrelations can be modelled. A high new development share means a high uncertainty in modelling, a high carry over share means a more certain and detailed model. The model can also grow during the development process from a rough system analysis to a detailed analysis of the single elements. Regarding the planning and development engineer of the production system, the method supports the evaluation of impacts and risks of production system changes, like the inclusion of Industry 4.0 technologies (e.g. RFID-chips), that directly interact with the product features. Furthermore, their impact on production KPIs and other production processes modelled.

Regarding the design of products and production systems, the method supports engineers in decision making regarding the risks, change propagation and new development shares. The introduced application shows that the consideration of change propagation and new development shares gives indicators for the product developer which alternative solution brings a higher effort and risk in the development and realization. However, the interdependencies must be checked by the developer carefully. Even a small number of effects can have a huge risk, because e.g. a certain production step is very crucial. This cannot be identified by the method but from the engineer using it. The influence on the risk of strategic factors and production KPIs will be considered in future research more in detail to complement the proposed method.

Acknowledgements

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References

[1] Frankenberger E, Badke-Schaub P, Birkhofer H (1998) Designers: The Key to Successful Product Development. Springer London, London.
[2] Albers A (1994) Simultaneous Engineering, Projektmanagement und Konstruktionsmethodik – Werkzeuge zur Effizienzsteigerung.
[3] Bochtler W, Laufenberg L (1995) Simultaneous Engineering: Erfahrungen aus der Industrie für die Industrie. Springer Berlin Heidelberg, Berlin, Heidelberg.
[4] Albers A, Stürmlinger T, Mandel C, Wang J, Baneres M, Behrendt M (2019) Identification of potentials in the context of Design for Industry 4.0 and modelling of interdependencies between product and production processes. 29th CIRP Design 2019.
[5] Albers A, Bursac N, Urbanec J, Lüdcke R, Rachenkova G (2014) Knowledge Management in Product Generation Development – an empirical study. Beiträge zum 25. DfX-Symposium, p. 13–24.
[6] Albers A, Rapp S, Spadinger M, Richter T, Birk C, Marthaler F, Heimicke J, Kurtz V, Wessels H (2019) The Reference System in the Model of PGE: Proposing a Generalized Description of Reference Products and their Interrelations. Proceedings of the 22nd International Conference on Engineering Design (ICED19), p. 1693–702.
[7] Albers A, Walch M, Bursac N (2016) Entscheidungsunterstützung durch die Variationsanteile der Produktgenerationsentwicklung. Konstruktion - Zeitschrift für Produktentwicklung und Ingenieur-Werktstoffe 1.
[8] Specht G, Beckmann C, Amelingmeyer J (2002) F- & -E-Management: Kompetenz im Innovationsmanagement. 2nd ed. Schäffer-Poeschel, Stuttgart.
[9] Ehrlenspiel K, Meerkamm H (2017) Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit. 6th ed., München, Wien.
[10] Wißler FE (2006) Ein Verfahren zur Bewertung technischer Risiken in der Phase der Entwicklung komplexer Serienprodukte. Zugl.: Stuttgart, Univ., Diss., 2006. Univ; Jost-Jetter, Stuttgart, Heimsheim.
[11] Reinhart G, Lindemann U, Heinzl J (1996) Qualitätsmanagement: Ein Kurs für Studium und Praxis. Springer Berlin Heidelberg, Berlin, Heidelberg.
[12] Eckert C, Clarkson PJ, Zanker W (2004) Change and customisation in complex engineering domains. Research in Engineering Design 15, p. 1–21.
[13] Klingler S (2017) Eine Methode zur effizienten und effektiven Unterstützung der kontinuierlichen Validierung im Kontext der PGE - Produktgenerationsentwicklung, Karlsruhe.
[14] Keller R, Eger T, Eckert C, Clarkson P (2005) Visualising change propagation. Proceedings ICED 05, the 15th International Conference on Engineering Design.
[15] Rouibah K, Caskey KR (2003) Change management in concurrent engineering from a parameter perspective. Computers in Industry 50, p. 15–34.
[16] Ehrlenspiel K (1995) Integrierte Produktentwicklung: Methoden für Prozeßorganisation Produkterstellung und Konstruktion. Hanser, München and Wien.
[17] Gausemeier J, Lanza G, Lindemann U, Gausemeier (2012) Produkte und Produktionssysteme integrativ konzipieren: Modellbildung und Analyse in der frühen Phase der Produktentstehung. Carl Hanser Verlag, München.
[18] Eigner M, Dickopf T, Schulte T, Schneider M, (Eds.) (2015) mecPro^2-Entwurf einer Beschreibungssystematik zur Entwicklung cybertronischer Systeme mit SysML: Tag des Systems Engineering. Carl Hanser.
[19] Steimer C, Fischer J, Cadet M, Meissner h, Aurich JC, Stephan N (2016) SysML-basierte Planung cybertronischer Produktionssysteme in frühen Entwicklungsphasen. in Schulze S-O, Tschirner C, Kaffenberger R, Ackva S, GfSE Gesellschaft für Systems Engineering e.V., TdSE 25.-27.10.2016, (Eds.). Tag des Systems Engineering. Carl Hanser, p. 365–374.
[20] Mandel C, Stürmlinger T, Yue C, Behrendt M, Albers A (2020) Model-Based Systems Engineering Approaches for the integrated development of product and production systems in the context of Industry 4.0. IEEE International Systems Conference (SysCon).
[21] Albers A, Wintergerst E (2014) The Contact and Channel Approach (C&C2-A): Relating a System's Physical Structure to Its Functionality. in Chakrabarti A, Blessing LTM, (Eds.). An Anthology of Theories and Models of Design. Springer London. London, p. 151–172.
[22] Matthiesen S, Ruckpaul A (2012) New insights on the contact & channel-approach – modeling of systems with several logical states: International Design Conference. In International Design Conference – Design 2012.