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CLASSIFICATION OF METHODS FOR THE INDICATION OF CHANGE PROPAGATION – A LITERATURE REVIEW

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1. Introduction

In today's globalized and competitive world, product development processes need to be innovative, effective and efficient. Engineering changes (EC) are an unavoidable part of product development and are both source of innovation and costs. Every innovation derives from a change, but at the same time unnecessary and late changes can be the reason for sky-rocketing costs [Fricke 2000]. Therefore, companies have to find a balance between having too many changes which are costly and time-consuming, and having too few which might lead to missed opportunities with regards to improving quality and being innovative. One particular aspect of changes in engineering design is their risk of propagating further through the product. Engineering change propagation (ECP) can occur wherever there are dependencies within the product and thus a change to one part of the system will trigger subsequent changes in other parts [Yang 2011]. To tackle the problem of unwanted ECP, various methods that aim at supporting designers with the assessment of alternative change options have been developed in recent years. These methods, however, often apply to different scopes and intend at answering different questions. There are academic papers that include a listing and discussion of the various methods that are out in literature such as the one from Jaratt et al. [2011]. Moreover, authors that introduce their own method in their paper often refer to other already existing methods. However, most of these papers not exclusively consider the methods that are able to deal with ECP but rather consider the broader field of EC. Also, there is no classified overview in literature that provides deeper insights into what aspects of the various methods differ or are similar. Having such a classified overview at hand with methods that can handle ECP a quicker comparison and assessment of those methods can take place and can therefore save precious time. Hence, this work's objective is to find methods that can indicate change propagation and to analyse how these differ to each. Therefore, the research questions to be answered are; (RQ 1) what methods in literature to EC propagation do already exist and (RQ 2) based on the findings from RQ 1, how do the so found methods differ to each other?

Based on the definitions from Jarratt et al. [2011] and Conrat [1998], ECs are in this work defined as modifications in forms, fits, materials, dimensions, functions, drawings or software of a product or component that has already been released during the production design process. ECs include the connected process changes and can be of any size or type, can involve any people, and can take any length of time. EC propagation, based on Tang et al.'s [2008] and Koh et al.'s [2012] definition, originates from the relationships or dependencies between items, such as between components, parameters, functions, etc., and describes the process by which a change to one part or element of an existing system configuration or design results in one or more additional changes to the system, when those changes would not have otherwise been required.

2. Research methodology

To answer the RQ 1 and 2, a literature review was conducted to find ECP methods, which were analysed in order to compare them and find out their differences. Thereby, the review covers journals and conference contributions in the field of engineering design. Methods conducted in the literature search had to fulfil certain requirements to be included; (1) Methods have to predict, track or indicate ECP. (2) The papers must be written less than 15 years ago to provide sufficient pertinence. (3) Methods must relate to product development of engineering products, i.e. methods that deal with e.g. ECP in the software industry were not included as it is not focused by this paper. (4) Methods must consider ECP within a company, not across companies. Especially the first requirement depicts a major difference between contributions in the depicted field of research, like Eckert et al. [2003] that focuses more on characteristics of ECP featuring a generic classification of ECs than on methods for ECP. In total eleven methods could be found that fulfil those requirements.

3. Methods for the indication of ECP

In total eleven methods are found that fulfilled the above requirements and which will be shortly introduced in the following, clustered into matrix-based methods, methods requiring a database and methods based on other underlying concepts according to their requirements and approach.

3.1 Matrix-based methods

Five methods are matrix-based. The first step breaks down the product into its subsystems and mapping their dependencies in a matrix such as the Design Structure Matrix (DSM).

Clarkson et al. [2004] developed a **Change Prediction Model (CPM)** that uses the DSM to map the dependencies between a product's components and then uses risk management techniques to predict the risk of an EC propagating further through the product. For calculating the risk of a change propagating, the likelihood value and the impact value first need to be generated and then to be multiplied with each other. For each initiated change the predicted risk for propagation can be computed and then plotted on risk scatter graphs for easy comparison.

Koh et al. [2012] recently developed a **change modelling method (CMM)** which is based on the CPM and on the House of Quality (HoQ) by Hauser and Clausing [1988]. With the help of the CMM, potential change propagation paths that are possibly triggered by different change options can be gained which are then assessed on their effect on product attributes so that the optimal change option can be chosen by the designer.

Tang et al. [2008] developed a **DSM-based EC management system (ECMS)** that not only maps whether or not a relation between two items exists, but that also has an additional information field next to the DSM where details to the property of dependency can be noted, such as type of dependencies (e.g. material or geometry), and dependency strength. Besides a DSM for the product domain, two additional DSM representations are built, one for the process and one for the organization domain. That way, a more holistic and comprehensive view on EC propagation shall be obtained.

Flanagan et al. [2003] introduced a method for a **functional analysis of change propagation (FACP)** which is based on the DSM and which shall help designers in finding possible change propagation paths, evaluating those and then enabling selecting the optimal one. Whereas some methods, such as the CPM, only consider dependencies between components, the FACP also includes functional relations in its analysis. That way, change is not only considered in terms of either function or form but instead is considered as both since 'two components (forms) can only affect each other if there is a functional link between them' [Flanagan 2003].

Chen et al. [2007] suggest a pattern-based decomposition methodology for rapid redesign so that design customization in agile manufacturing can be supported which will be called the **Rapid Redesign Methodology (RRM)** in the following. By applying the method, only the parts of the design model that have to be recomputed in order to meet the redesign requirements shall be quickly located so that recomputing the whole model won't be necessary. The optimal solution which entails the least redesign effort can then be chosen.

3.2 Methods requiring a database

Another approach to deal with ECP is by using a database. Mostly, the authors suggest an approach based on databases to reduce the dependence on expert knowledge, to make the method practicable for also novice/non-technical designers, or to involve many people.
Kocar and Akgunduz [2010] developed the **Active Distributed Virtual Change Environment (ADVICE)** which can be applied during the course of Engineering Change Management (ECM) and shall improve the ECM process by providing textual and graphical information to the designers in a way that also non-technical members of the Engineering Change Board (ECB) can use it. ADVICE aims at providing support to its users by prioritizing ECRs and by predicting possible propagation. By modelling the proposed ECM system in a Virtual Collaborative Design Environments (VCDE) a 'shared, real-time, simulated 3D representation of EC' can be provided [Kocar 2010].
Grantham Lough et al. [2006] developed the **risk in early design method (REDM)** that performs risk assessment before the physical form of a product has been decided, i.e. in the conceptual design phase. The REDM is an extension to the Failure Function Design Method (FFDM) which links product functions to historical failures. By storing past failures in a database and by using those for assessing the risk that a similar failure will occur to the current design, the dependence on individual experts who identify risks based on their own experience shall be reduced and hence biases eliminated.
Ma et al. [2008] developed a method that models associative engineering relations in a unified feature modelling scheme which is why it will be called the **Unified Feature Modelling Scheme (UFMS)** in the following. The authors state that results from earlier design stages are needed in later stages whereas at the same time later design stages influence decisions that were made in the earlier stages. Hence, Ma et al. [2008] propose a way how information consistency control between the different applications of the various product lifecycle stages can be obtained and ECP across the stages can be made more efficient.

3.3 Methods based on other underlying concepts

The following methods do not require populated databases and are based on other approaches than using matrices such as the DSM to break down the product designs mapping their dependencies.
Cohen et al. [2000] developed the **Change Favorable Representation (C-FAR)** methodology that aims at facilitating change representation, propagation as well as qualitative evaluation. Thereby, information is extracted from the Standard for the Exchange of Product (STEP) data model in order to make changes more easily traceable. C-FAR is based on EXPRESS which defines its main artefacts as objects or entities which, in turn, are described by their attributes. Hence, C-FAR considers a product's dependencies on the attribute level.
ReDesignIT (RDIT) is a computer program, developed by Ollinger and Stahovich [2001], that is intended to be used during the first stages of a redesign project and that generates and evaluates different proposals of redesign plans. The program ranks the different redesign proposals concerning their effectiveness and indicates how undesired side effects, i.e. ECP, can be counteracted. The authors admit that the proposed redesign plans are rather abstract as they only show what quantities and in what direction they should be changed, and cannot specify numerical values for these quantities.
Yang et al. [2011] recently developed a method for searching ECP paths by considering parameter linkages in order to help designers in finding optimal change solutions which is why this method will be called the **PLN-based Method (PLN)** throughout this paper. First, the PLN model needs to be created by analysing the linkages between the product's parameters. The authors hereby differ between two types of linkages: constraint linkages, which can be influenced by designers, and fundamental linkages which cannot be influenced. By iterating through an algorithm ECP paths can be searched and evaluated in order to find the optimal path.
By having found eleven methods in literature that come into consideration for indicating ECP during product development, RQ 1 could be answered. Even though the above introduced methods all can be applied for indicating ECP, they do differ to each other as they often apply to different scopes and intend at answering different questions. For instance, some methods aim at indicating potential ECP paths so that product designers can see what other components are to be affected in the course of the initiated change, others, on the contrary, aim at calculating the risk for a change to propagate. Some

methods map physical components, whereas others are able to map functional or parameter linkages in a product, etc. Hence, the next step for accomplishing this paper's purpose is to analyse and classify the eleven methods in a consistent way so that comparison can take place.

4. Classification of methods

For analysing the methods with regards to their content, the Munich methods model (MMM) developed by Lindemann [2009] is utilized (see table 1). The MMM is a scheme that consists of the sections 'purpose', 'situation', 'effect', 'approach', and 'tools and methods'. With the help of these sections, any method can be examined concerning their purpose which they aim to fulfil, the situation in which they can be applied, including marginal conditions that are required to be fulfilled, their expected effects, the general approach, i.e. steps that are made when applying the method, and underlying tools/methods. For this work, the MMM has additionally been modified by adding a process flowchart to provide a quick and visual overview of the main steps of the method's approach. Hence, Lindemann's MMM scheme [2009] provides a way to consistently analyse and prepare methods so that a structured overview can be obtained and be compared.

When mapping the eleven methods in the MMM schemes, close attention to the actual content of the original papers was paid to not accidentally misinterpret and lose information. In a next step, the content in the purpose, situation, effect, and tools and methods section has been generalized in order to enable clustering. Then, for providing comparison, 4 tables are prepared, labelled 'purpose', 'situation', 'effect' and 'tools and methods' which can be seen below in the tables 2 to 5. The criteria in the tables derive by comparing the respective sections in the eleven MMM schemes. That is to say, that, for instance, the criteria listed in the 'purpose' table (table 2) derive from the content of the purpose section of the MMM schemes, the criteria in the 'situation' table (table 3) derive from the situation section, etc. Hence, all the information discussed below with regards to the tables' content is taken from the methods' individual MMM schemes. The 'X' in the tables 2 to 5 indicates that the method fulfils the regarded aspect according to their description in the academic papers. '(X)' indicates that it is not explicitly mentioned in the papers itself; however, due to the regarded paper's context it can be assumed that the method fulfills the regarded aspect.

Table 1. Modified MMM scheme

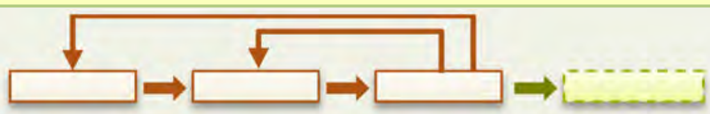
METHOD NAME		
Purpose	**Situation**	**Effect**
• Tasks in the development process that shall be supported by the used method • Functioning of the method	• Areas of application and problems for which the use of the method is reasonable • Marginal conditions that must be fulfilled in order for the method to achieve the intended effect	• Possible effects and side effects of the method • Product models, artifacts, etc. that result from the application of the method
Approach		
• Steps that need to be made during the application of the method • Application notes for the performance of single steps • Rules that need to be considered		
Tools and Methods		
• Underlying tools and/or methods		
Process		
		

Table 2 shows all the criteria regarding the methods' purposes. As can be seen in table 2 all methods can indicate ECP, be it, for instance, by calculating the risk of ECP occurring in the first place, or by searching for possible EC propagation paths. However, not all methods explicitly have the purpose to indicate ECP. RDIT, for example, aims at searching and evaluating redesign plans. The method, however, is able to indicate ECP, even though it might not be the authors' primary aim. The situation is similar with the REDM and the RRM method. Since being able to indicate change propagation was a requirement for the methods being included in the first place, it is not surprising that all of them fulfil this purpose. Besides being able to indicate ECP, table 2 furthermore shows that the purposes most often proposed in the papers are to search and evaluate ECP paths, to support the prediction of ECP, to evaluate the influence of an EC, and to support the prediction of undesired ECP. The remaining columns of table 2 show the less prominent purposes which only one or two of the methods have incorporated.

Table 2. Overview of the methods' purposes

PURPOSE	METHODS										
	CPM	CMM	ECMS	FACP	RRM	ADV	REDM	UFMS	C-FAR	RDIT	PLN
Providing an indication for possible CP	X	X	X	X	(X)	X	X	X	X	(X)	X
Searching for possible CP paths, evaluation and selection of optimal one			X	X							X
Supporting the prediction (and management) of undesired EC propagation	X	X	(X)			X			X		
Providing an evaluation of the change influence		X	X	X					X	X	X
Providing risk assessment (predicting CP/future failures)	X	(X)	(X)				X				
Searching for and evaluation of possible redesign plans					X					X	
Aiming at obtaining a more holistic view on CP			X					X			
Reducing dependence on expert knowledge						X	X				
Improving the ECM process by providing textual and graphical information						X					
Prioritization of ECs						X					
Achieving traceability of design change routes in multi-domains (i.e. product, process, and org. domain)			X								
Maintaining the validity and consistency of product models in collaborative and concurrent engineering								X			
Reducing computing effort and expediting redesign solution process					X						

Table 3 shows the criteria from the situation section of the methods' MMM schemes. As can be seen, all of the methods have at least one marginal condition in order to be able to work: almost every method, except the ADV and the REDM, requires experts or experienced designers who are able to do the initial product model breakdown and dependency mapping. ADV and the REDM, on the contrary, require a populated database. Furthermore, it can be seen in table 3 what kind of change the methods can deal with: changes that result from new requirements, such as changed customer needs, or the ones that become necessary because faults have been made during the design. Six out of the eleven methods can deal with both. The CMM as well as C-FAR are explicitly only designed for changes that result from new requirements whereas the REDM is explicitly suitable for changes resulting from faults. The RRM and RDIT are suitable during redesign projects.

Table 3. Overview of the methods' situations

SITUATION	METHODS										
	CPM	CMM	ECMS	FACP	RRM	ADV	REDM	UFMS	C-FAR	RDIT	PLN
Marginal Conditions											
Expert knowledge	X	X	X	X	X			X	X	X	X
Database						X	X	X			
Changes to a product resulting from ...											
Faults	X		X	X		(X)	X	(X)			(X)
New requirements (e.g. improvements, changed customer needs)	X	X	X	X		(X)		(X)	X		(X)
Redesign project					X					X	
explicitly considering EC	X	X	X	(X)	(X)	X	(X)	(X)	X	(X)	(X)
Suitable...											
...during the course of ECM			X			X					
...during the first stages of a (re-) design project	(X)	X	(X)			(X)	X	X		X	
...throughout the product development process	X		X			X		X			
...for more complex products /systems	X	X			X					X	
...only for small or simple products									X		X

All methods can be applied to engineering products as can be seen in table 3. This shouldn't be surprising since a requirement on the methods was to be applicable to the product development of engineering products. At what point during the product development process the various methods are suitable is varying, as can be seen in table 3. Some methods are only intended for the first stages during the product development life-cycle, whereas others can be applied throughout the whole development process. ECMS as well as ADV are explicitly suitable for supporting the formal ECM process. Also, the complexity level of a product the method can handle varies. Some are explicitly created for being able to deal with ECP in more complex products, whereas other methods' effort would be too large for complex products, which is why they are only suitable for simple products. Some papers, however, neither say when in product development their method can be applied, nor what complexity level of the product they are suitable for. This is why some of the cells are left blank in the table. When preparing these tables, close attention to the actual content of the papers was paid to not accidentally misinterpret and lose information. In future research the methods could be applied on the same case study in order to detect more differences and similarities among them. That way a more thorough and accurate distinction can be obtained and the blank cells could be figured out.
Table 4 shows the criteria from the effect section of the MMM schemes. First of all, this table indicates the various outcomes of the methods. Most methods' outcomes are EC propagation paths,

followed by risk scatter graphs and quantitative ratings. Table 4 furthermore indicates whether or not the methods’ solutions are computerized. Only the PLN does not provide a computerized solution yet. All the other methods do which means that computing the approaches does not have to be done manually. When it comes up to what dependencies of a product are mapped, the methods are almost equally divided into the ones that map component, functional or parameter linkages. Six of the methods can map two kinds of dependencies, such as the FACP which considers relations among components, among functions, but also between components and functions. Last, table 4 shows whether or not non-experts can use the respective methods. Only ADV, REDM and C-FAR are explicitly suitable for non-experts to use.

Table 4. Overview of the methods’ effects

EFFECT	METHODS										
	CPM	CMM	ECMS	FACP	RRM	ADV	REDM	UFMS	C-FAR	RDIT	PLN
Outcome											
Change (propagation) paths	X		X	X				X	X		X
Risk scatter graphs/ risk fever charts	X		X				X				
Redesign plans/patterns					X					X	
Quantitative ratings (e.g. risk)	X	X							X		
Real-time, simulated 3D representation of EC						X					
Computerized solution	X	X	X	X	X	X	X	X	X	X	
Consideration of											
Component linkages	X	X	X	X	X						
Functional linkages				X	X	X	X	X			
Parameter linkages		X	X			X		X	X	X	X
Non-experts can use it						X	X		X		

Table 5 shows the criteria that are derived from the ‘tools/methods’ section of the MMM schemes. It can be seen that six methods are matrix-based. Mostly they are based on DSMs. CPM as well as RED incorporates risk techniques. As the CMM and ECMS use the CPM as part of their approach, it is assumed that they also are based on risk techniques. Other methods are based upon the HoQ (CMM), VCDE and Sequential Pattern Mining (ADV), JTMS (UFMS), and EXPRESS and STEP (C-FAR).
With these four tables for comparison, a quick overview of the various methods is provided, including their intention and situational constraints. This saves time and resources, as prior screening of the literature for ECP methods as well as an identification of similarities and differences among them.

Table 5. Overview of the methods’ underlying tools/methods

TOOLS/METHODS	METHODS										
	CPM	CMM	ECMS	FACP	RRM	ADV	REDM	UFMS	C-FAR	RDIT	PLN
Matrix-based	DSM	DSM, DMM	DSM	DSM	DDM		FFDM				
Risk techniques	X	X (CPM)	X (CPM)				X				
Other		HoQ				VCDE, Sequential Pattern Mining		JTMS	EXPRESS, STEP		

As mentioned above, the original MMM scheme by Lindemann [2009] is extended by a process row where the method's approach was visually mapped in a process flowchart. This is done in order to provide a simplified and hence quicker overview of the various approaches. These process flowcharts are prepared by taking the main steps of the description of the approaches as the components in the flowcharts, and by mapping where iterations are intended. The last component in the flowcharts illustrates the output that is obtained after having completed the method's approach. In order to not only obtain an overview of the methods' characteristics but also of the different steps of the methods' approaches, a generic process of the procedures is generated. Hereby, the individual process flowcharts in the MMM schemes are merged into a generic process flowchart. Figure 1 shows the general layout of a process flowchart in the MMM schemes.

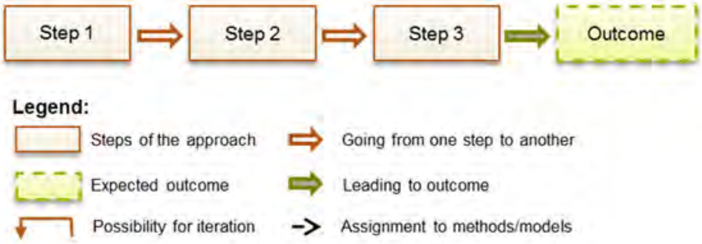


Figure 1. General layout of process flowcharts, including an explaining legend

In order to prepare a generic process flowchart for all the methods, their individual process flowcharts have to be analysed regarding their similarities. Once overlapping components can be identified, generic wording has to be generated for the considered similarity among the methods' approaches. Next, the methods that have the considered component incorporated in their approach are allotted by arrows, assembled in clusters. This gives a quick understanding of the methods that are similar to one another with regards to specific components. Figure 2 summarizes this generic process flowchart.

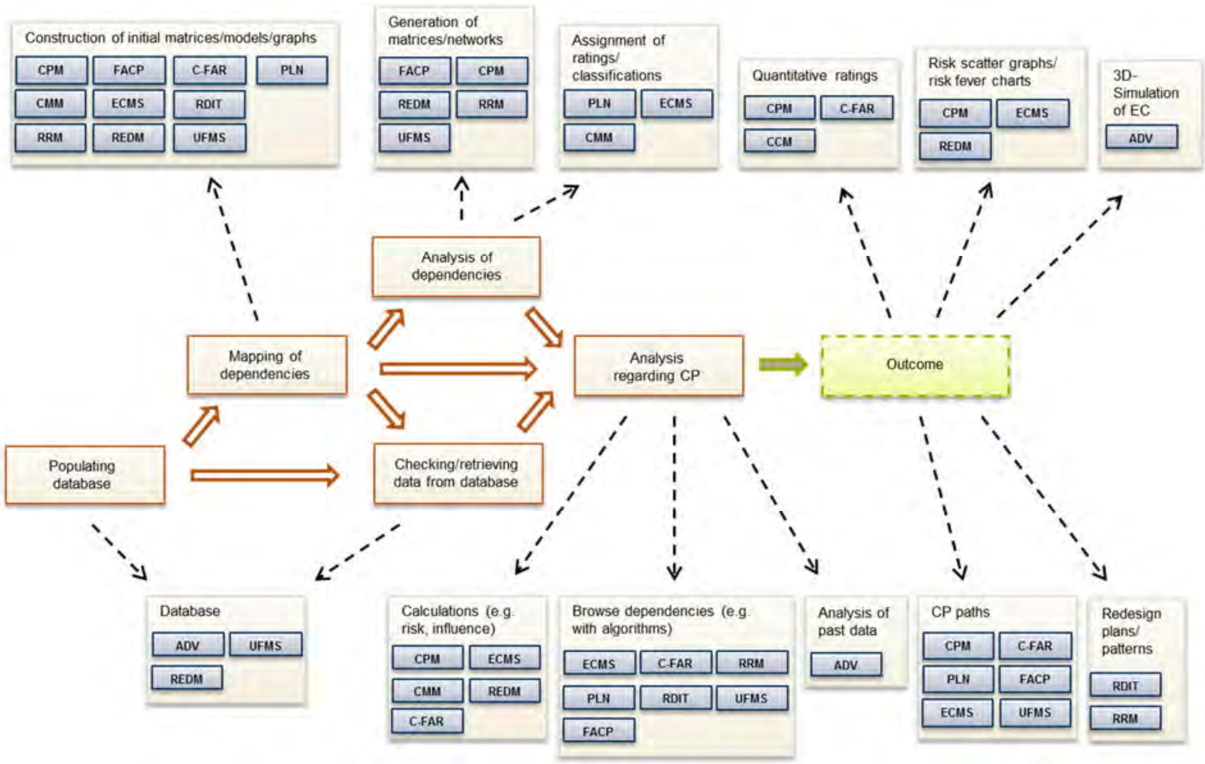


Figure 2. Generic process flowcharts of all the eleven methods

With this generic process flowchart a user can quickly get an idea of what methods have similar steps by simply looking at the clusters allotted to the steps. For instance, the generic process flowchart

shows that three methods need databases in order to work, i.e. ADV, UFMS and REDM. These need to be populated first so that data can be retrieved or checked for the ECP analysis. All the other methods require that the product's dependencies are mapped, either in matrices, models or graphs. Most of these methods then continue with analysing those dependencies, for instance by generating matrices or networks, or by assigning ratings or classifications. With each method an analysis regarding ECP takes place. Some methods do this by carrying out calculations, others browse the product's dependencies with e.g. algorithms, and others analyse historical data. Besides the methods' main steps, their outcome can also be seen in figure 2 which are either quantitative ratings, risk scatter graphs, a 3D-simulation of EC, redesign plans or patterns, or change propagation paths.
With these four tables for comparison and with the general process flowchart at hand a classified overview of the various methods could be gained. The classification of the methods can give an answer to RQ 2, i.e. how the found methods differ to each other.

5. Summary, conclusion and outlook

This paper's objective is to find methods that can indicate ECP and analyse how these differ to each other. The methods conducted in literature search mostly apply to different scopes (e.g. mapping component, functional or parameter linkages among a product) and intend at answering different questions (e.g. what is the risk for an EC triggering change propagation, or what is the scale of potential ECP). For obtaining a classified overview so that comparison can take place, the methods were analysed by means of Lindemann's [2009] Munich Methods Modelling (MMM) schemes. This way in total eleven MMM schemes could be obtained which provide information about the methods' intended purposes, situations they are applicable to, expected outcomes, their approaches, underlying methods/tools, and a graphic process flowchart. Then, four tables were prepared in order to enable drawing comparison of the methods' purpose, situation, etc. Hence, with these tables for comparison a classified overview could be obtained that enables quick assessment what methods are, for instance, matrix-based, which ones require a database, what methods can map component linkages, which ones are applicable throughout the whole product development process, etc. Furthermore, by having prepared a generic process flowchart an overview of the methods' approaches could also be provided which gives further insights into how the methods differ to one another. Since looking for methods that deal with ECP in literature, gaining sufficient knowledge about the method, analyzing their content, and comparing them to each other is very time consuming, the classified overview prepared in this work saves time by allowing a quick and easy comparison and assessment of ECP methods.
When preparing the tables for comparison, close attention to the actual content of the papers was paid to not accidentally misinterpret or lose information. This means that the information in the tables for comparison mostly derive directly from the respective papers, as far as available to the authors. Nevertheless, some assumptions could be drawn out of the context of the papers' content. However, due to the fact, some cells in the situation table are left blank since there was no correspondent information in the papers.
Thus, in future research, the individual methods could be carried out and this way it can be tested what the methods are able to do besides what is indicated in the individual papers. By actually applying the methods, not only the blank cells could be figured out but it could also be found out if some methods can additionally fulfil other criteria which were not explicitly stated in the respective papers. Another aspect of future work is the consideration of different levels of abstraction used in the presented methods (section 3). This aspire an analysis of the time in the design process, when the methods intend to anticipate changes as well as the required set of information for the application of the methods. A last step of future work is the utilisation of the classification to a case study from either a research or an industry project to allow an evaluation of the classification of methods for ECP. Thereby, evaluating the intended benefits of the classification in terms of saving time by allowing a quick and easy comparison and assessment of ECP methods is in the centre of interest as well as improvement potentials.

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