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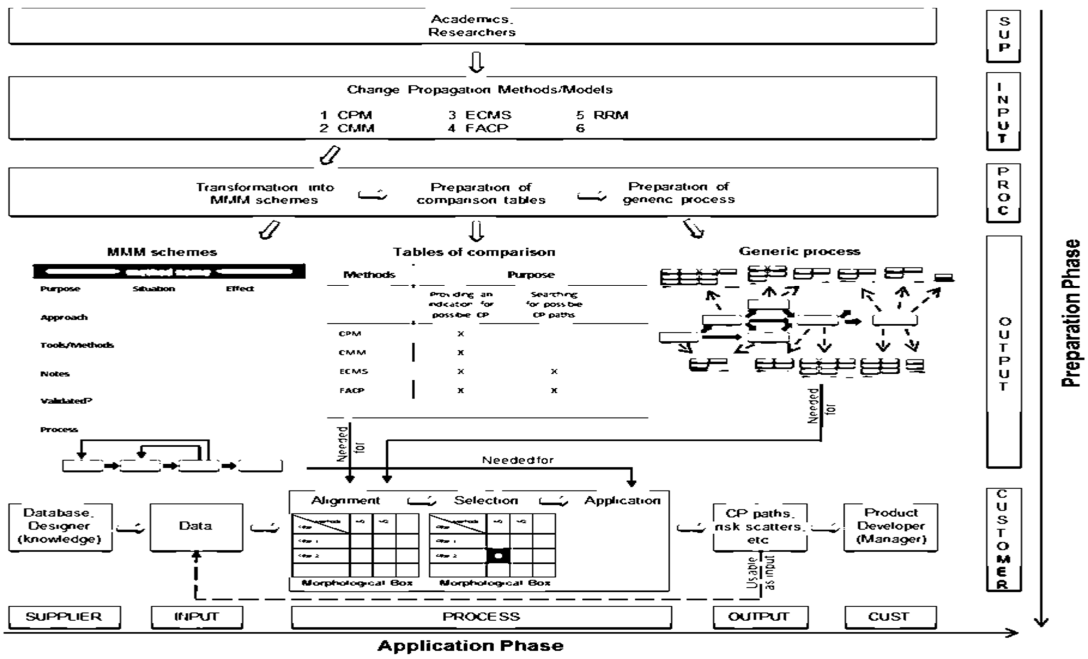

Development of a Procedure Model for the Prediction of Change Propagation in Product Development

Master of Science Thesis
in the Master Degree Program Quality and Operations Management

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Gothenburg, Sweden, 2013
Report No. E2013:096

MASTER'S THESIS E2013:096

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Chalmers Reproservice
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ABSTRACT

This thesis presents a procedure model, the Preparation-Application-SIPOC² (PA-SIPOC²) which is developed to support product developers with choosing the most suitable method for predicting change propagation when engineering changes (ECs) occur. The PA-SIPOC² is based on Six Sigma's SIPOC (**S**upplier, **I**nput, **P**rocess, **O**utput, **C**ustomer) technique in order to provide a quick overview of a process' core elements, i.e. the people involved as suppliers and customers, the required input and resulting output, and the process itself. The PA-SIPOC² consists of two phases, the preparation and the application phase. By means of the Preparation-SIPOC², methods that can deal with change propagation can be analyzed in a consistent manner with regards to their intended purpose, situation they can apply to, expected outcome and proposed approach. That way a classified overview can be obtained which is needed for the application phase of the PA-SIPOC². The Application-SIPOC provides a hands-on guide to product developers when ECs occur on what method to choose that fits the product developer's specific application environment best. Hence, looking for methods that deal with change propagation in literature, gaining sufficient knowledge about the method, analyzing their content, comparing them to each other and assessing their appropriateness for the intended purpose becomes redundant for the product developers to do when using the PA-SIPOC² and precious time during product development can be saved.

Keywords: Engineering change management, engineering change propagation, product development

DEVELOPMENT OF A PROCEDURE MODEL FOR THE PREDICTION OF CHANGE PROPAGATION IN PRODUCT DEVELOPMENT

1 Introduction

In a globalized world where competition becomes more and more fierce and short time-to-market, low costs as well as innovative products are key, product development processes need to be effective and efficient. One driver for costs but also for innovation is changes to parts of a product during product development. Fricke et al. (2000) point out that every innovation derives from a change, but at the same time unnecessary and late changes can be the reason for sky-rocketing costs. 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. Change propagation 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 and Duan, 2011). Especially as product designs become more and more complex and components are increasingly linked to each other, both directly and indirectly, changes to one part are more likely to call for a change in at least one other component. According to Koh et al. (2012), it is possible for even small changes to cause change avalanches as they turn out to propagate uncontrollably.

Many companies today therefore try to reduce component dependencies by designing their products in a modular manner. In fully decoupled modular designs, where interfaces are clearly defined and a functional element can be changed independently by just changing the corresponding part, changes can be done in a more easy and quick manner than in fully integral product designs where more inherent dependencies among the parts exist (Ulrich, 1995). Hence, a modular architecture can reduce the component dependencies and thus the scale of potential change propagation. However, fully modular products are difficult to design, especially when the product is complex as almost always dependencies between at least some parts in the system exist. Eckert et al. (2004) therefore state that it is necessary to implement an efficient change management which aims at predicting the impact of a change so that, according to Ariyo et al. (2006), designers are able to assess potential benefits and drawbacks when there are alternative ways for meeting the new requirements.

1.1 Problem Description

As change propagation is one particular potential drawback of changes, various methods that aim at dealing with change propagation in some way and, hence, at supporting designers with the assessment of alternative change options have been developed in recent years. Jarratt et al. (2011) recently published a paper which gives an overview on the engineering change (EC) subject in literature where the authors also summarize various methods that can deal with change propagation. However, as those methods often apply to different scopes and intend at answering different questions, it is difficult to know which one to choose for one's own specific situation.

So, for instance, some methods aim at indicating potential change propagation 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 are delimited to certain stages during product development such as the conceptual design phase, whereas others can be applied throughout all product development stages. Some methods map physical components, whereas others are able to map functional or parameter linkages in a product, etc.

Hence, the methods developed in recent years differ to each other with regards to various aspects such as purpose or expected outcome. This means that, depending on the situation and intention of the product developer, not all methods are equally suitable. So, product developers who find themselves in a situation where alternative ways of implementing a change in order to meet the new requirement or to correct faults are available might question themselves what methods are out there that can support them and which of them is the most suitable.

As of right now, there are some 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 change propagation but rather consider the broader field of EC. Also, there is neither a classified overview in literature that provides deeper insights into what aspects of the various methods differ or are similar, nor does a support exist which helps product developers in deciding which method fits their specific application environment best.

1.2 Purpose, Research Questions and Delimitations

Looking for methods that deal with change propagation in literature, gaining sufficient knowledge about the method, analyzing their content, comparing them to each other and assessing their appropriateness for the intended purpose is very time consuming. In product development where often tight deadlines exist and time is a scarce resource, this procedure would take too long, especially when unexpected target deviations occur which will require unscheduled engineering changes. Hence, if product developers would already have a classified overview at hand with the methods that can handle and deal with change propagation, and a procedure that will guide them to quickly choosing the method that is the most suitable to their situation, then precious development time can be saved.

Thus, the purpose of this work is first to obtain an overview of the existing methods in literature and then to develop a procedure model for the prediction of change propagation. This procedure model shall be a hands-on guide for product developers when ECs occur on what method to choose in order to fit the user’s specific application environment best. The selected method, in turn, can support the product developers in assessing the degree of potential change propagation for the different change options so that an informed decision can be made with regards to the change propagation effects of a change option.

To achieve this, the following three research questions (RQ) are of interest and shall be answered in the course of this thesis:

1. What methods in literature to EC propagation do already exist?

2. Based on the findings from RQ1, how do the so found methods differ with regards to the requirements of a specific application environment?

3. Based on RQ1 and RQ2, how can a procedure model look like that product developers can use as a guide to decide what method for EC propagation fits best to their specific application environment and shall therefore be chosen?

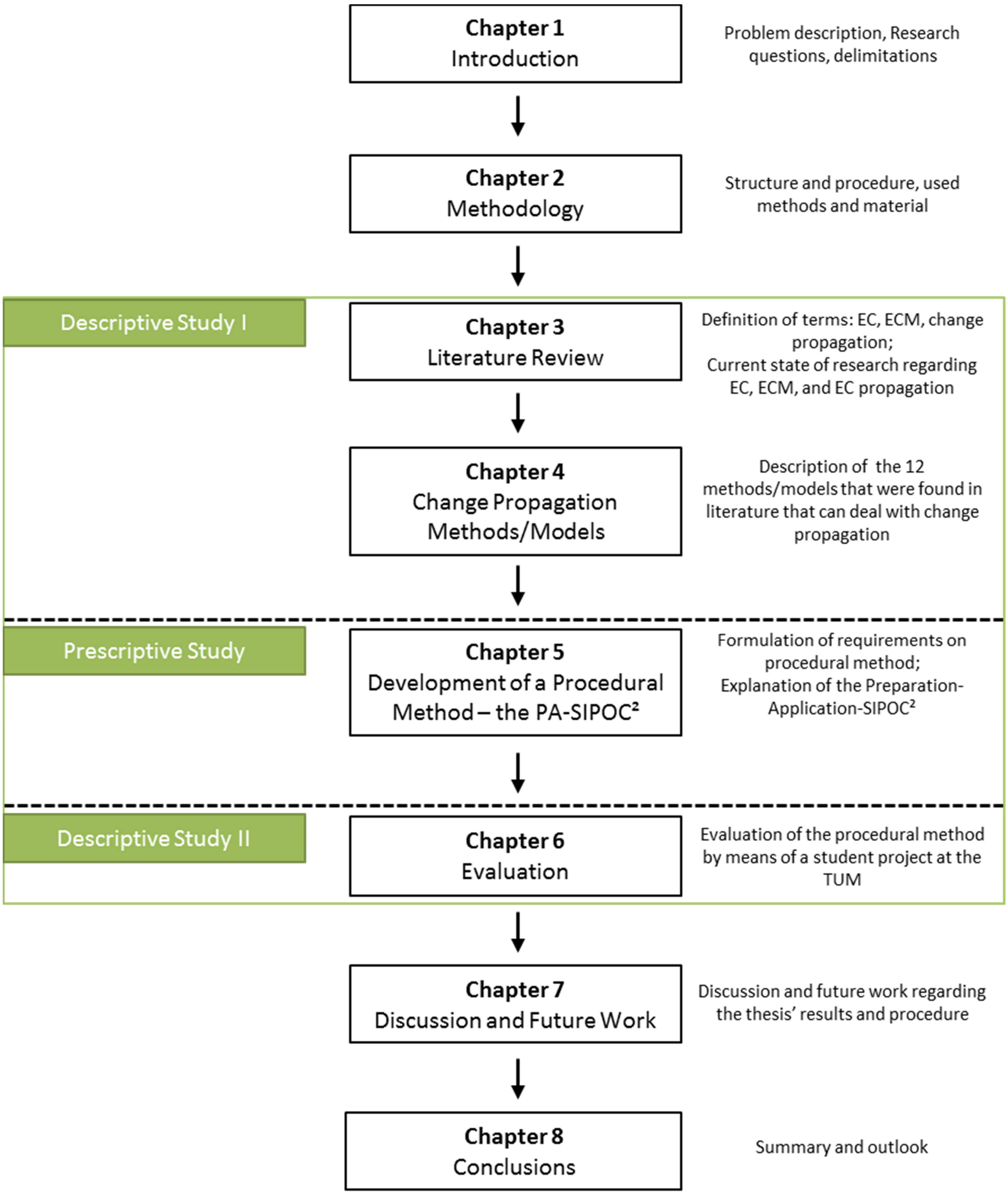
The field of change propagation in literature is broad. But since ECs draw a quarter of companies' R&D capacities, as a study recently conducted in more than 90 German companies found out (Langer et al., 2012), it is fair to say that there is a great need for supporting methods in product development of engineering products. Hence, this thesis' focus is on change propagation in engineering products and the following delimitations will further narrow the scope of this thesis in order to obtain focused results:

- Methods that deal with change propagation in the software industry are excluded.
- Only methods that consider change propagation within a company, not across companies, are included.

The following chapters therefore aim at answering the above mentioned three RQs within the set scope and, hence, aim at fulfilling the purpose of this thesis, namely obtaining an overview of the existing methods and developing a procedure model for the prediction of EC propagation.

2 Methodology

After having clarified the purpose, the three research questions as well as the delimitations, the overall methodology employed during this work will be discussed in the following. Figure 2-1 shows the structure of this thesis and shall therefore give an holistic overview of this thesis' framework.



Figur 2-1: Structure and framework of the thesis

The procedure of this thesis is conducted in the style of the Design Research Methodology (DRM) framework by Blessing and Chakrabarti (2002). According to Blessing and Chakrabarti (2002), using a 'methodology should help realise a better planned and smoother research process, thereby increasing the chances of obtaining valid and useful results'. Since the DRM allows a variety of research approaches and since it aims at supporting systematic planning of research and at helping to develop a solid line of argumentation it was regarded as being suitable to be used as a basic guide to this thesis. Thus, by conducting this work according to the DRM framework it shall be ensured that a holistic view on this thesis can be obtained and that this thesis is conducted in a structured and coherent way.

The DRM contains in total four stages: Research Clarification, Descriptive Study I, Prescriptive Study, and Descriptive Study II. According to Blessing and Chakrabarti (2002) there are seven different types of research which can be seen in figure 2-2. Review-based study means that the study is only based on the review of literature. Comprehensive study means that besides a literature review also a study in which the results are produced by the researcher is included. Initial study means that first steps of showing the consequences of the results and preparing them for use by others are included (Blessing and Chakrabarti, 2002).

Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1. Review-based →	Comprehensive		
2. Review-based →	Comprehensive →	Initial	
3. Review-based →	Review-based →	Comprehensive →	Initial
4. Review-based →	Review-based →	Review-based → Initial/ Comprehensive ←	Comprehensive
5. Review-based →	Comprehensive →	Comprehensive →	Initial
6. Review-based →	Review-based →	Comprehensive →	Comprehensive
7. Review-based →	Comprehensive →	Comprehensive →	Comprehensive

Figur 2-2: Types of research projects and their main focus, Blessing and Chakrabarti (2002)

The research project of this thesis falls under type three (see figure 2-2). This is because both, the **Research Clarification,** where the research purpose and goal shall be clarified, and the **Descriptive Study I,** where literature is being reviewed in order to gain sufficient background understanding on the topic and a better grasp of the existing situation, are review-based. The

Prescriptive Study, on the other hand, is regarded as being a comprehensive study since here an own approach is being developed which is then validated in an initial evaluation during the **Descriptive Study II**.

The **Research Clarification** had to be done in the beginning of the study to this thesis in order to gain a clear purpose and concrete research questions. These were already discussed in chapter 1.2 together with the delimitations to the scope of this work. The remaining three stages constitute the body of this thesis (see figure 2-1) and will therefore be discussed in more detail in the following.

During the **Descriptive Study I**, a thorough literature research is conducted in order to get an understanding of the topic of EC, of the problem of change propagation in general, and more specifically of already existing methods that can deal with change propagation. Therefore, the conducted literature research serves two purposes: first, an understanding on the more general topic of EC and EC propagation had to be gained. These issues will be presented in chapter 3 by discussing first relevant definitions of used terms and by then giving basic backgroung on the subject of EC and EC propagation, e.g. where do ECs occur, what impacts does it have, how does propagation originate, etc. (see figure 2-1). Second, once the background on the subject could be set, the literature research aims at finding methods that can deal with change propagation.

For conducting the literature research, key words such as ‘engineering change’, ‘engineering change propagation’, ‘change propagation’, ‘change propagation method’ and ‘engineering change propagation method’ were used. Search engines from Chalmers University of Technology and the Technische Universität München (TUM) as well as GoogleSearch were used to obtain papers on said key words. Once initial papers that were of interest for this thesis were found, their references additionally served as a research basis and guide for the subsequent literature review. The literature research focused on English written papers, however, a handful of German papers that contained valuable insights were also included. Direct quotations taken from these papers were translated into English while providing the original quotation in footnotes.

During the literature search for change propagation methods, certain requirements had to be fulfilled by the found methods to be further considered in order to make sure that they fit this thesis’ purpose. First of all, the papers introducing change propagation methods must not been written more than 15 years ago in order to provide sufficient pertinence and topicality. Second, the methods must be able to predict, track or indicate EC propagation in some way. Furthermore, the delimitations mentioned in 1.2 imply that the methods have to relate to product development of engineering products. This means that methods that deal with e.g. change propagation in the software industry are not included. Moreover, the methods must consider change propagation within a company, i.e. not across companies.

Hence, the methods that could be found using above mentioned key words or references from other papers were analysed according to said requirements. Only when the methods could withstand the set requirements, they were further considered for this thesis. Thus, after having conducted the literature review, in total 12 different methods could be found which are considered to fit the purpose and scope of this thesis and which will be introduced in chapter

4 (see figure 2-1).

However, it has to be noted that it is possible that there are more methods that are able to indicate change propagation regarding engineering products that could not be found during this thesis' literature research. For instance, papers introducing change propagation methods that don't have the searched key words in their title, could have been missed. The same applies to papers from conferences which could not be obtained due to restricted access.

After having conducted the Descriptive Study I and thus after having found 12 methods on change propagation, the **Prescriptive Study,** i.e. the development of an own approach, was done. As can be seen in figure 2-1, chapter 5 describes the development of the procedure model, called the Preparation-Application-SIPOC² (PA-SIPOC²), in more detail. The PA-SIPOC² is based on Six Sigma's SIPOC (**S**uppler, **I**nput, **P**rocess, **O**utput, **C**ustomer) technique which was originally developed at Motorola as one of the continuous improvement tools concerning an organization's processes. The SIPOC concept was adapted for this thesis for providing a quick overview about the people involved, the individual steps that have to be conducted during the process stage and the needed input as well as resulting output. This shall provide the user with a holistic overview on the value stream inherent in the process.

In chapter 5 the motivation for such a procedure model as well as the requirements it shall fulfill will be clarified in more detail. Also, the idea behind the developed PA-SIPOC² will be discussed, following with a detailed description of the two phases, the preparation phase and the application phase.

The preparation phase of the PA-SIPOC² serves the purpose to analyze the 12 different methods that were found during the literature search, i.e. during Descriptive Study I, in a consistent way in order to make them comparable to each other. In order to conduct the analysis in a structured and consistent way, the Munich methods model[1] (MMM) developed by Lindemann (2009) is used. The MMM scheme was chosen to be used in the course of this thesis as it supports analyzing methods concerning their intended purpose, situation they can be applied to, their expected effects and marginal conditions. Thus, the MMM scheme enable a consistent analysis of the found methods' content so that a structured overview of these can be obtained and a comparison of said methods can take place. In order to fit the purpose of this thesis, the scheme is modified by adding rows and columns. This is necessary in order to extend the scale of comparison so that valuable insights into not only the methods' purposes, situations, effects, and approaches can be gained but also into the methods' maturity and underlying concepts can be gained. Detailed information about how exactly the MMM scheme was modified can be found in chapter 5.

The application phase has the purpose to support product developers or other potential users in selecting the most suitable method according to their specific application environment. Therefore, the application phase uses the output from the preparation phase for aligning the users' application environment with the ones from the various methods so that the one that fits the best can be chosen. Chapter 5 will discuss this procedure in more detail.

[1] Translated from German: Münchener Methodenmodell (MMM)

After having developed an own approach during the Prescriptive Study, the PA-SIPOC², an evaluation of the developed procedure model took place and therefore comprises the **Descriptive Study II**. As can be seen in figure 2-1, chapter 6 illustrates the evaluation which used a student project conducted within the PSSycle project at the Technische Universität München (TUM) as a case study. Within the PSSycle project, an E-bike sharing concept similar to bike or car sharing concepts is developed. The student project dealt with developing an adequate locking system for the E-bike. This student project was chosen to be a suitable case study to evaluate the PA-SIPOC² out of numerous reasosn: first of all, this student project was completed in spring 2013. This was an important factor since this way the data provided by the student project was up-to-date and also available in time to this thesis' evaluation. Second, as the students were developing a locking system for an E-bike their product is regarded as an engineering product and is therefore within the scope of this thesis. Third, the students experienced target deviations during the development process which led to necessary changes in their design. Additionally, the students had always more than one option available for implementing the change. This means that they had to decide on one of the options and in that moment it would have been beneficial for the students to assess the effects of potential change propagation in order to take this information into consideration. And forth, the students had very limited time for the option decision making process which is why it is important that the selection of a method won't be too time consuming. These four issues made this case study suitable for evaluating the developed procedure model in order to assess whether or not it is applicable and useable in a practical setting and whether or not it fulfills the desired purpose of supporting product developers in quickly choosing the method that fits their application environment best.

Changes that occurred during the development of the locking system were recorded and documented by the students. This written documentation, which contains detailed information about the target deviations and the necessary changes was used as input data to validate the procedure model. This documented input for the evaluation can be found in März (2012) and can therefore be used for replicating the evaluation. Chapter 6 describes in more detail how the evaluation was conducted and what results could be gained.

As can be seen in figure 2-1, after having completed the Descriptive Study II, chapter 7 comprises a discussion of the thesis' results and on the thesis' approach as well as a lookout for future work. Finally, the thesis will end with chapter 8 by provding a summary and conclusions of the conducted work.

3 Literature Review

Having clarified this thesis' purpose, research questions, as well as its employed methodology, a literature review on the topic of EC and EC propagation will be provided in the following. Relevant terms that are used throughout this work will be discussed in chapter 3.1 before providing sufficient background knowledge on EC, engineering change management (ECM) and EC propagation in the subsequent chapter 3.2

3.1 Definition of Relevant Terms

Relevant terms for this thesis are EC, EC propagation, and ECM. As this work deals with the subject on EC propagation, it first has to be clarified what an EC is. Table 3-1 shows the various definitions on EC that were found in literature.

Table 3-1: Existing definitions on engineering change (EC)

Source	**Definition**
Wright (1997)	'an engineering change (EC) is a modification to a component of a product, after that product has entered production'
Conrat (1998)	'Engineering changes are all subsequent changes on already released (i.e. bindingly specified) work results within a continuous technical development process. They always comprise a change on technical documentation/database, but also include all connected product and process changes. According to valid standards they are liable to examination, approval and documentation.'[2]
Huang and Mak (1999)	'[engineering changes are] the changes and modifications in forms, fits, materials, dimensions, functions, etc. of a product or a component'
Terwiesch and Loch (1999)	'engineering change orders (ECOs) - changes to parts, drawings or software that have already been released'
Jarratt et al. (2011)	'An engineering change is an alteration made to parts, drawings or software that have already been released during the production design process. The change can be of any size or type; the change can involve any people and take any length of time.'

[2] Translated from: 'Als technische Änderung […] werden alle nachträglichen Änderungen an freigegebenen (d.h. verbindlich festgelegten) Arbeitsergebnissen innerhalb eines zusammenhängenden technischen Entwicklungsprozesses betrachtet. Sie beinhalten immer eine Änderung der technischen Dokumentation bzw. der Datenbasis, schließen aber auch alle damit zusammenhängenden Produkt- und Prozeßänderungen ein. Sie sind nach den gültigen Normen prüfungs-, genehmigungs- und dokumentationspflichtig.'

In the late 1990ies, Wright (1997) defined ECs as ‘a modification to a component of a product, after that product has entered production’. Huang and Mak (1999) specified the term ‘modification’ by clarifying that these can concern forms, fits, materials, dimensions or functions of a product or component. Terwiesch and Loch (1999) also included the aspect of changes to a product’s software. However, the latter two definitions leave out the time issue, i.e. when in product development a change is to be considered as an EC. Conrat (1998) stated that all the changes that emerge after work results have already been released are ECs. Furthermore, he also included various aspects that the other authors haven’t considered such as that changes also concern the connected processes, and that they have to be liable with regards to examination, approval and documentation.

Jarratt et al. (2011) recently comprised the definitions of Huang and Mak (1999), and Terwiesch and Loch (1999) and added the aspect that ECs can be of any size or type, and that they can involve any people, and can take any length of time. The definition valid throughout this specific thesis is based on the one from Jarratt et al. (2011) and will be extended by the process aspect of Conrat’s (1998) definition while leaving out the aspects that are irrelevant for this thesis, such as the liability aspect.

Hence, ECs in this thesis are defined as follows:

ECs are 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.

This thesis furthermore deals with the subject of ECM which has to be distinguished from the term change management. According to Jarratt et al. (2011) the latter refers to the concept of change in a business or organizational context which incorporates the administration and supervision of organizational transformation, e.g. implementing new business processes. ECM, on the contrary, refers to the organizing and controlling of EC.

The definition that will be used throughout this thesis is the one from Huang and Mak (1999) as this one comprises all the aspects that are relevant for this thesis.

ECM is the process that includes identifying, evaluating, implementing, and auditing ECs.

This thesis ultimately is about the topic on EC propagation. Table 3-2 shows the various definitions that could be found in literature. Both Eckert et al. (2004) and Koh et al. (2012) define EC propagation as a process by which an EC leads to more additional ECs in other parts of the product which wouldn’t have been required if it wasn’t for the initiating change. Tang et al. (2008) rather look at why a change might lead to subsequent ones, i.e. dependencies between items causing changes to propagate.

Table 3-2: Existing definitions on engineering change propagation

Source	Definition
Eckert et al. (2004)	'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'
Tang et al. (2008)	'originates from the relationships or dependencies between items, such as between components, parameters, tasks, and teams'
Koh et al. (2012)	'the process by which an EC to parts of a product results in one or more additional ECs to other parts of the product, when those changes would not otherwise have been required'

As both aspects are relevant throughout this thesis, the definition of EC propagation is as follows:

> EC propagation 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.

Having clarified the definitions that will be valid throughout this work, a deeper insight into the research topic of EC, ECM and EC propagation will be given in the following in order to provide sufficient context for this thesis' subject.

3.2 Overview on EC, ECM and EC Propagation

EC generally can occur throughout the whole product life cycle, as for instance, in the conceptual or the detailed design phase (Jarratt et al., 2011) and are rather the rule than the exception – no matter what country or what company is to be considered (Clark and Fujimoto, 1991). Depending from which perspective it is looked upon, ECs can be perceived as negative or as a chance for improvement. According to Wright (1997), manufacturing and production control, for instance, consider ECs as disruptive concerning production process and balancing manufacturing resources, respectively. Inventory control sees EC as being potentially costly concerning e.g. stocks and resourcing. Fricke et al. (2000) came to similar conclusions by stating that the effects of changes[3] are mainly increased costs and scheduled delays. However, both Fricke et al. (2000) and Wright (1997) point out that changes can also have a positive connotation as they can lead to increased quality of the product and, as marketing often sees

[3] Some of the literature included and quoted in this chapter often uses the more general term 'change'. However, in those papers 'changes' refer to changes in engineering product which is why they are considered to be ECs.

it, changes can be a way of improvement, staying effective and as a chance of innovation.

Eckert et al. (2004) defined two sources of change, namely emergent and initiated changes. Emergent changes, shown in the top half of figure 3-1, are caused by problems in the design of a product during the course of its product development process. Initiated changes, on the contrary, are caused from an outside source such as changing requirements from customers and are represented in the lower half of figure 3-1.

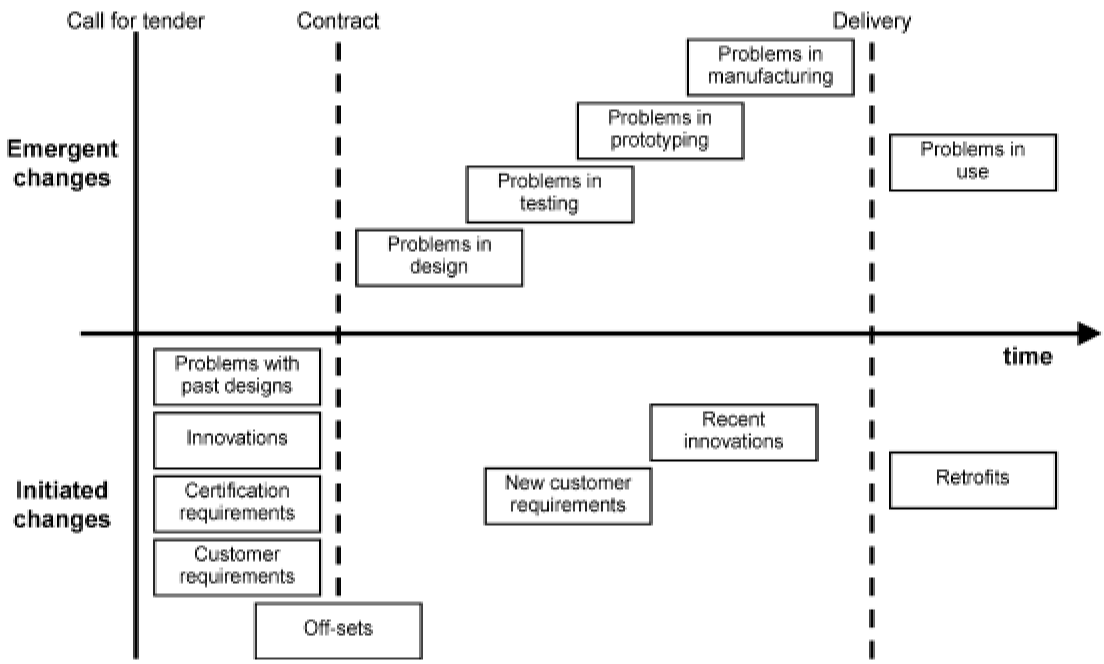


Figure 3-1: Sources of change during the design process, Eckert et al. (2004)

As can be further seen in figure 3-1, ECs can occur from the call for tender to the contract, in the time between contract and delivery, and in the time after delivery, i.e. when the product is in use. The vertical axis 'indicates the impact a change has on the design process, where are greater distance from the time axis (in either direction) represents a greater impact' (Eckert et al., 2004). One can see that between call for tender and contract only initiated changes occur. This is due to the fact that during this time, i.e. before the contract is placed, the conceptual design is determined at a high level. Here, changes are initiated in response to customer requriements, especially when the product is strongly customer driven, in response to innovation, especially when it concerns consumer products, or in response to problems with past designs or certification requirements (Eckert et al., 2004).

Figure 3-1 shows that from the time between the conclusion of a contract and delivery, ECs can be both, initiated and emergent. Emergent changes hereby comprise the problems that can occur throughout the product development process, i.e. from the design to the manufacturing phase. Changed or new requirements from the customer can arise after having signed the contract and therefore cause ECs. Recent innovations can fall into the product development time and can hence call for changes in the design. After delivery, problems can emerge during the use of the product and can require refits. When products have a long life span it is often likely that customers request changes to their purchased products such as upgrades (Eckert et al., 2004).

Langer et al. (2012) recently conducted a study in more than 90 German companies from various sectors of industry and various sizes. The authors found out that the main sources of ECs in the companies are insufficiently defined requirements, human mistakes during process execution, and deficient communication, both external and internal. Huang and Mak (1999) came to similar conclusions concerning the latter when investigating industrial practices in managing ECs within 100 UK manufacturing companies in the late 1990ies: poor communication among the parties involved in the product development process seemed to be one of the major causes for ECs. Hence, companies seem to struggle mostly with emergent changes.

According to Clarkson and Eckert (2005), once the need for an EC has been identified, either initiated or emergent, a six-phase process is triggered which can be seen in figure 3-2. During step one of the process, a request for an EC must be made which is mostly by means of standard forms, either electronically or on paper. The person who raises the EC request (ECR) must indicate reason, priority, type of the EC and what components are likely to be affected.

After that, potential solutions to the ECR have to be identified and assessed regarding their risk and impact of implementation (see step two and three in figure 3-2). During the approval phase, the Engineering Change Board (ECB) will then select and approve a solution which will then be implemented and later reviewed (see steps four to six in figure 3-2). The ECB 'must contain a range of middle to senior ranking staff from all key functions connected to the product' (Clarkson and Eckert, 2005).

During that six-step process iterations are possible, marked by arrows in figure 3-2. For instance, during the risk assessment step, a solution might be too risky which is why the company might want to go back to step two to identify other solutions. Furthermore, there are four break points in figure 3-2, all before an ECR is being approved, which mean that at these points it is possible to bring the process to a halt. Reasons for such a halt can be that the ECR is impractible (halt after step one), that there are no sensible solutions (halt after step two), that the proposed solution is too risky (halt after step three), or that the ECB decides that the proposed solution is not worth proceeding (halt after step four) (Clarkson and Eckert, 2005).

According to Huang and Mak (1999) there are two approaches to manage ECs: either formal or ad hoc. In their study the authors found out that nearly 95% of the investigated companies incorporated a formal approach. Most common activities during an ECM life cycle in the companies were 'proposing ECs', 'approving ECs', 'notifying ECs', and 'recording ECs' which corresponds well to the generic EC process proposed by Clarkson and Eckert (2005). Only few companies adopted an ad hoc approach which means that there are no fixed formats for documents and meetings were held irregularly. These companies, however, state that a more formal approach to ECM would be beneficial (Huang and Mak, 1999).

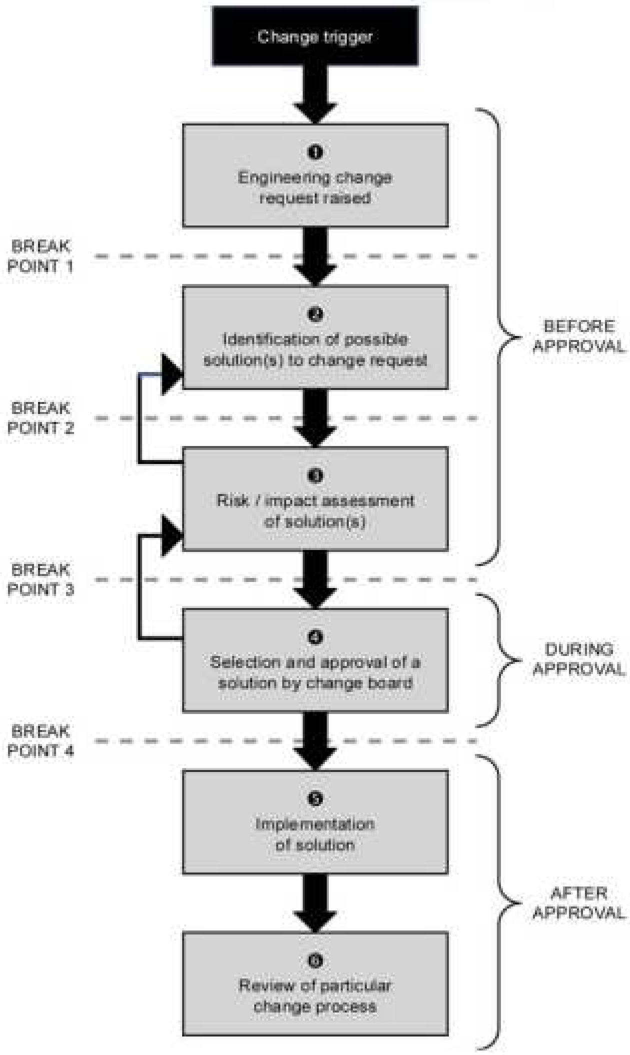


Figure 3-2: A generic EC process, Clarkson and Eckert (2005)

According to Jarratt et al. (2011), ECs affect planning, scheduling, and project costs. It is assumed, that the later in the product life cycle a change takes place the more it will cost. Huang and Mak (1999) found in their study that over 80% of the investigated companies think that 'the later the stage for the problem to be identified, the more expensive and time consuming to solve it'. More specifically, the 'Rule of Ten' says that a change becomes ten times more expensive in a later phase than in a previous phase which means that in a previous phase ten times more changes could be done at the same level of costs (Fricke et al., 2000). Furthermore, the later a change occurs the more people are affected. Jarratt et al. (2011) point out that the people that need to be notified of a change increases dramatically once manufacturing, suppliers, marketing etc. are involved.

In order to find the fine line between having too many ECs that are costly and time-consuming, and having too few that lead to missed quality improvements and innovations, companies need to effectively and efficiently manage ECs. Terwiesch and Loch (1999) found that there are four strategies to reduce the negative effects of ECs. First, it can be tried to avoid unnecessary ECs in the first place by, for instance, spending more time on the first release of a component so that potential rework can be diminished. Second, it can be attempted to detect ECs as early as possible in the product development process since ECs become more costly the later they are detected, as already mentioned above. Terwiesch and Loch (1999) state that rapid prototyping, formal design-for-manufacture methods and computer simulation can help to frontload ECs. Third, the ECM process could be speeded up and thereby process costs can be reduced since long EC lead times can cause late implementations and coordination problems of change efforts among open ECs (Terwiesch and Loch, 1999).

The forth strategy Terwiesch and Loch (1999) suggest, is to reduce the negative impacts of ECs. According to Ulrich (1995), the impact an EC has on a product is fundamentally linked to the product architecture. The product architecture can be described by its arrangement of functional elements, the mapping of those functional elements to physical components, and the specification of the interfaces among interacting physical components (Ulrich, 1995).

Ulrich (1995) states that there are two types of product architecture: the modular and the integral one. In a modular architecture each physical component only carries out one element in the function structure and the interfaces among the components are decoupled. A decoupled interface means that a change to one component won’t cause another component to change (Clarkson and Eckert, 2005). Hence, in fully decoupled modular designs, components can be changed independently by just changing the corresponding part. In an integral product architecture, on the contrary, each physical component carries out more than one functional element (Clarkson and Eckert, 2005). Thus, in fully integral product designs a change to one component requires a change to at least one other component which hence leads to change propagation. Clarkson and Eckert (2005) indicate that most products are somewhere in between fully modular and fully integral product architecture. This means that most products have coupled components to some degree and are therefore subject to potential change propagation.

Jarratt et al. (2011) state that besides a product’s architecture, the complexity of a product as well as the degree of innovation govern an EC’s impact. ECs are more likely to occur and to further propagate when the product is higly innovative since then the degree of knowledge and information is low. Complexity of a product is often measured by the linkages among a product’s elements and their interaction within a product (Jarratt et al., 2011). Lindemann et al. (1998) differ between local changes which only involves one component, and interface-overlapping changes which involve many changes. The latter is common in complex products where connectivity between a product’s elements is high. Hence, ‘the more complex a project, the more difficult it is to control all relevant parameters and their impacts on each other’ (Fricke et al., 2000).

Thus, type of product architecture, a product’s complexity and degree of innovation affect likelihood and impact of an EC propagating further through the product. Eckert et al. (2004) classify change propagation into two types: ending and unending change propagation which can be seen in figure 3-3. Ending change propagation means that the change finishes within the required time. This can either be change ripples which have decreasing change effort as time progresses or change blossoms which first have increasing and then decreasing change

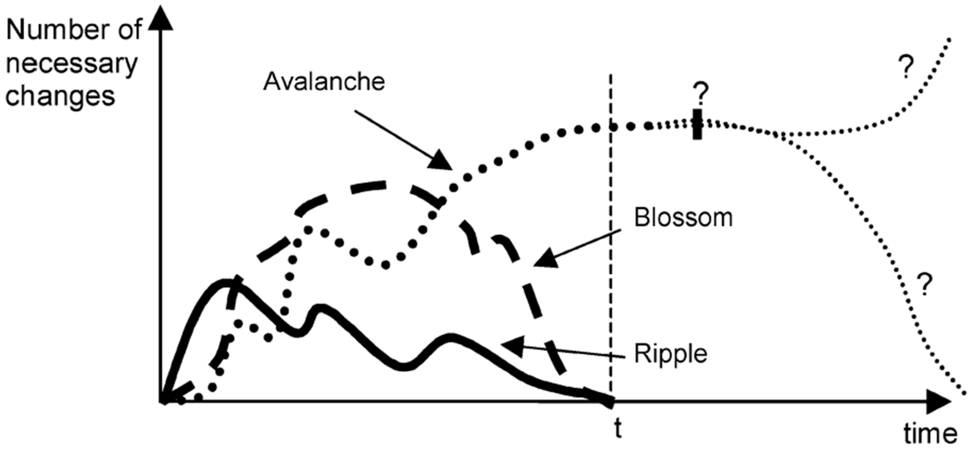


Figure 3-3: Patterns of change propagation, Eckert et al. (2004)

efforts. Change ripples are most likely when only few components are affected and the change propagation effects are manageable. Change blossoms comprise a higher number of necessary changes which are nonetheless still predictable (Eckert et al., 2004).

Unending change propagation, on the other hand, cannot be finished on time and the volume of change efforts increases as time progresses. This kind of change is called change avalanches and is problematic as their effects are unpredictable (Eckert et al., 2004). Change avalanches can occur when unexpected change multipliers come together in the design. A multiplier is one out of four different types of propagation Eckert et al. (2004) defined and which can be seen in figure 3-4: constants, absorbers, carriers and multipliers. Constants are not affected by changes which means that they neither cause changes nor do they absorb other changes.

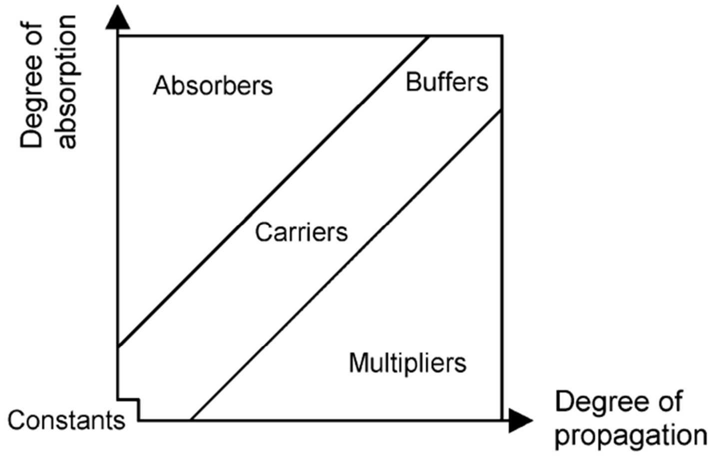


Figure 3-4: Propagation behavior of systems, Eckert et al. (2004)

Absorbers, on the contrary, can absorb more changes than they cause themselves, meaning that they are able to reduce the complexity of the change problem. Carriers cause and absorb a similar amount of changes whereas multipliers cause more changes than they can absorb which means that they add to the complexity of the change problem. Clarkson and Eckert (2005) point out that it 'is critical to appreciate that components can change between the three roles depending upon the size of the change'.

The problematic nature of change propagation requires that product designers assess the potential effects of ECs before implementing them and thereby accidentally causing change avalanches. Especially, when there are more change alternatives for correcting an error or meeting new requirements, product developers 'need to be able to assess the benefits of changes versus the potential costs or drawbacks' (Ariyo et al., 2006).

3.3 Summary

As can be seen from this chapter, ECs are most likely to occur at some point during product development since doing it right the first time and therefore completely avoiding ECs is almost impossible to do. Fricke et al. (2000) point out that completely avoiding ECs is in fact not desired as ECs provide the chance of improving the product's quality and being innovative. However, as they bear the risk of being very costly, strategies to reduce the negative effects of ECs are important for a company to implement. As one particular drawback of EC is its often unforeseen risk for propagating through the product, methods that can tackle this problem have been developed in literature.

Such methods that are able to indicate EC propagation and, hence, aim at supporting designers with the assessment of alternative change options, will be introduced in the following chapter. This shall provide a first overview of the methods' intention and approach before moving on to analyzing them in more detail. As those methods often apply to different scopes and intend at answering different questions, as already mentioned in chapter 1.1, it is difficult for the product developers to know which one to choose. Therefore, in chapter 5, after having introduced the methods in chapter 4, the methods will be analyzed concerning their purpose, situation they can apply to, expected effect, etc. This way a classified overview shall be obtained so that comparison can take place and that the method most suitable to a product developer's specific application environment can be chosen.

4 Change Propagation Methods

During the conducted literature search various methods on EC propagation could be found. In the subsequent chapters it will be first shortly explained what requirements had to be fulfilled by the found papers in order to be taken into consideration for this thesis (4.1). Second, the methods will be introduced divided into the ones which are based on matrices (4.2), require databases (4.3), and are based on other underlying methodologies (4.4). Third, a summary will be given (4.5).

4.1 Requirements for Including Methods

As already mentioned in chapter 2, during the literature search certain requirements had to be fulfilled by the found methods to be further considered in the course of this thesis:

- The methods must be able to predict, track or indicate EC propagation in some way.
- The papers must be written less than 15 years ago in order to provide sufficient pertinence and topicality.

And the requirements implied from the thesis' delimitations mentioned in 1.2:

- The methods must relate to product development of engineering products[4], i.e. methods that deal with e.g. change propagation in the software industry were not included.
- The methods must consider change propagation within a company, i.e. not across companies.

With these requirements at hand, in total 12 different methods could be found that will be explained in the following sections. In the broader field of EC, however, there are more models, methods and tools which aim at, for instance, reducing the need for (unnecessary) EC in the first place. For more insight into this area, Wright (1997) for example offers a structured overview of the EC tools that do already exist in research.

4.2 Matrix-based Methods

Five out of the 12 methods that could be found in literature, are matrix-based. This means that usually the first step of the approach consists of breaking down the product into its sub-systems and mapping their dependencies in a matrix such as the Design Structure Matrix (DSM).

Clarkson et al. (2004) developed a **Change Prediction Model (CPM)** which has been further

[4] Some of the literature included and quoted in this chapter uses the more general term 'change'. However, in those papers 'changes' refer to changes in engineering product which is why they are considered to be ECs.

developed throughout the years. Keller (2005), for instance, introduced several visualization tools for displaying the change propagation data from the CPM. Also, the CPM has been applied various times by means of different systems such as a helicopter, the architecture of a railway valve and a the diesel engine design, and therefore counts among the methods that have been validated in industry most frequently.

The CPM deals with EC that emerge from faults or new requirements in an existing product, and aims at giving an indication for possible EC propagation. By using the DSM which maps the dependencies between a product's components and by using risk management techniques the risk of an EC propagating further through the product shall be predicted (Clarkson et al., 2004). Figure 4-1 shows the full concept of the CPM.

During the first step of the CPM, the initial analysis, preferably a team of experienced designers breaks down the product into its sub-systems to map their dependencies in a component DSM. With the help of risk management techniques, the designers then create the direct likelihood matrix and the impact matrix. Direct likelihood is defined 'as the average probability that a change in the design of one sub-system will lead to a design change in another by propagation across their common interface' (Clarkson et al., 2004). The impact, in turn, is defined 'as the average proportion of the design work that will need to be redone if the change propagates' (Clarkson et al., 2004). The direct risk matrix can be obtained by combining those two matrices. Next, the predictive matrices, which incorporate direct and indirect likelihood, impact and risk, are computed with algorithms that are based on the logic of propagation trees. The resultant risk data, the product risk matrix, shows the combined (=direct and indirect) risk of change propagation where the length indicates likelihood and the width indicates the impact. Thus, the more large rectangles, the more change propagation might take place.

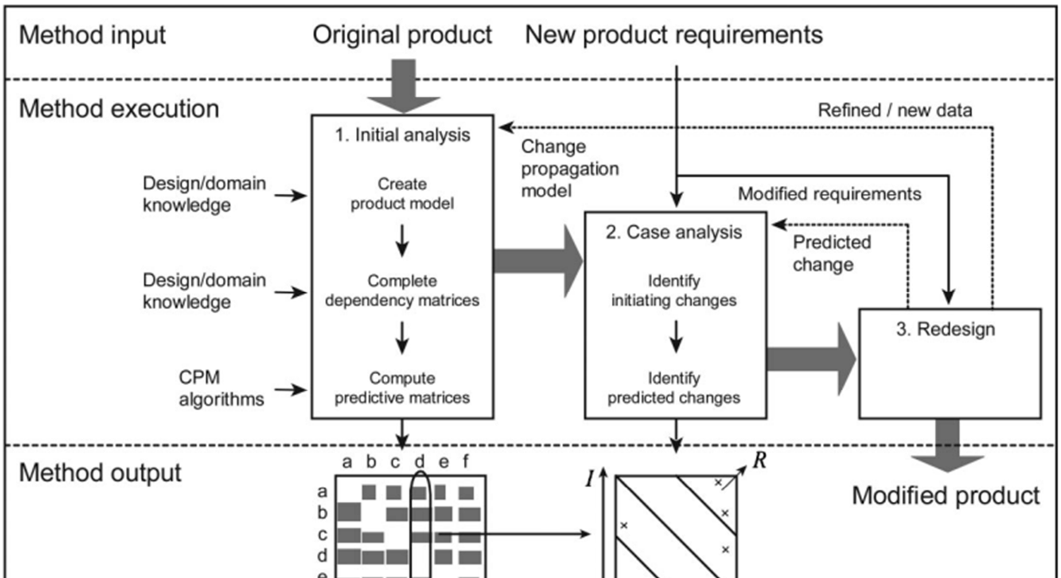


Figure 4-1: The CPM framework, Clarkson et al. (2004)

Once the initial analysis of the product is completed, the second step of the approach can be conducted, the case-by-case analysis. In this stage, the new requirements need to be assigned to one of the sub-systems, and the predicted changes can be then identified by extracting the relevant data from the initial analysis. The likelihood and impact values are plotted on a risk scatter graph for easy comparison. Finally, the redesign can take place where the product model and direct dependency matrices are to be updated for later projects (Clarkson et al., 2004).

The CPM was developed for being suitable for fairly complex products and could be validated in a study at Westland helicopters. However, the product model shouldn't consist of too many components as otherwise the initial analysis becomes cumbersome – a product model with less than 50 components is therefore recommended (Clarkson et al., 2004)..

Koh et al. (2012) recently developed a **change modelling method** which will, for simplification purposes, be called the **CMM** throughout this thesis. This method aims at supporting designers predicting and managing EC propagation during the development of complex products. 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.

Koh et al. (2012) modeled the CMM based on the CPM and on the House of Quality (HoQ). Hauser and Clausing (1988) originally developed the latter as 'a kind of conceptual map that provides the means for interfunctional planning and communications'. Koh et al. (2012) only use the roof of the HoQ, a triangular matrix, for their method. The roof shall indicate the dependencies of different product parameters in order to understand the trade-offs among them. This enables the roof to be used for examination purposes regarding change propagation. However, as the roof only models symmetrical relations and is thus not able to map asymmetrical relations, which are nevertheless common in products, Koh et al. (2012) include the CPM. The Multiple-Domain Matrix (MDM) in figure 4-2 shows how the dependencies between the different domains are modeled.

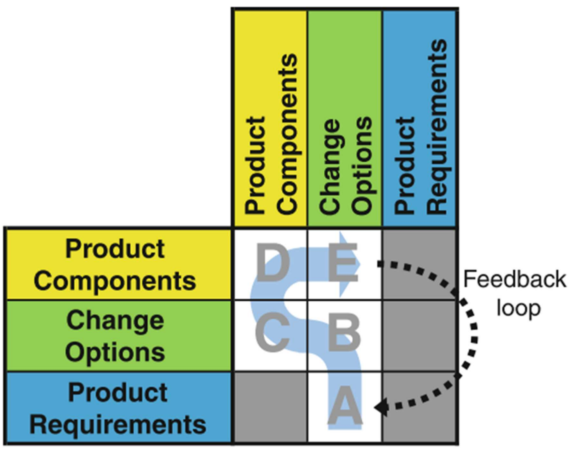


Figure 4-2: The CMM illustrated in a Multi-Domain Matrix, Koh et al. (2012)

In the first step of the method, the user has to assign performance ratings to the change options regarding the product requirements (field A), and to the interactions between the different change options parameters (field B). Next, the change options are linked to the relevant product components (field C) which are required for the change propagation analysis. The change propagation analysis is adopted from the CPM (field D). The resulting outputs are then used to revise the performance ratings for the change options (field E) and are finally used to update field A in a feedback loop. With the quantitative performance ratings at hand, the best change option can be chosen as a solution (Koh et al., 2012).

Tang et al. (2008) developed a **DSM-based EC management system** which will be called the **ECMS** in the following. The ECMS shall support the ECM and change propagation analysis by means of a DSM. The authors claim that just mapping whether or not a relation between two items exists is not enough, instead ‘it is necessary to define the property of dependency, such as types of dependencies (e.g. material or geometry), and dependency strength’ (Tang et al., 2008). To incorporate this idea in their system, the authors added an information field to the DSM where these details can be noted.

Like the other matrix-based methods, the DSM-based EC management system also starts with breaking down the product into its sub-systems and mapping their dependencies. However, here three DSM representations need to be built: one for the product, one for the process and one for the organization domain. Tang et al. (2008) state that the last two have to be included in order to be able to get a more holistic and comprehensive view on change propagation. For traceability purposes those three matrices need to be linked as it can be seen in figure 4-3.

To implement the system, all the dependency relations between the items have to be identified and captured. After having classified the type of dependencies, the user can browse through them, instigate different change options and can see the affected items and detailed information about level and type of change. Also, change propagation paths are shown graphically and by taking into account the concept of the CPM the overall risk caused by the instigating item can be calculated and visually illustrated with risk scatter graphs (Tang et al., 2008).

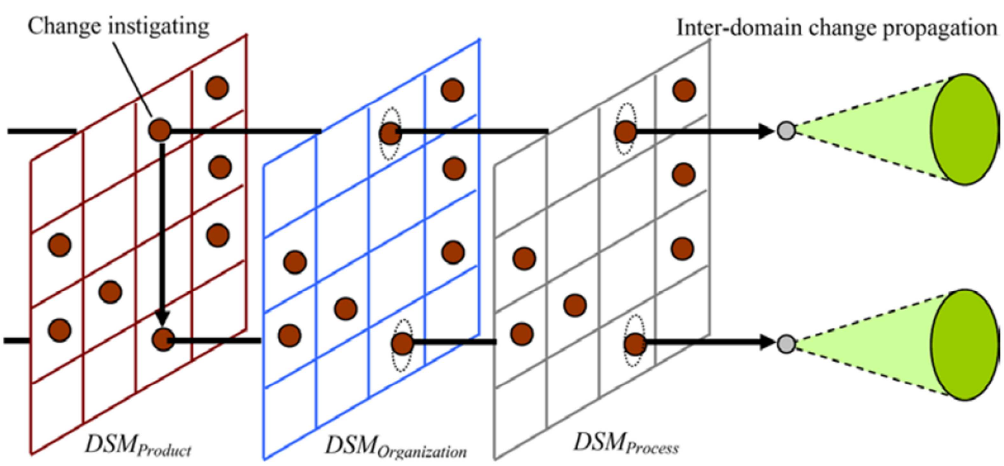


Figure 4-3: Inter-domain change propagation, Tang et al. (2008)

Flanagan et al. (2003) introduced a method for a **functional analysis of change propagation** which is also based on the DSM and which will be called **FACP** throughout this thesis. The authors' aim is to help designers in finding possible change propagation paths, evaluating those and then enabling selecting the optimal one. Whereas some methods only consider dependencies between components, such as the CPM, the method Flanagan et al. (2003) propose also includes functional relations in their analysis. The authors state that change should not only be considered in terms of either function or form but instead shall be considered as both since 'two components (forms) can only affect each other if there is a functional link between them' (Flanagan et al., 2003).

Therefore, the user has to breakdown the product not only with regards to its components but also to its functions as can be seen in figure 4-4. Then, three different matrices need to be created: a component-component matrix, a function-function matrix, and a component-function matrix. With these matrices as input, a computer program will generate the direct connectivity matrix which indicates the dependencies between features. A feature is a component-function pair, i.e. a component that carries out a particular function. The direct connectivity matrix can then be used to identify possible change propagation paths between different features. The user can decrease the number of possible paths by specifying precedence relationships between the different components (Flanagan et al., 2003).

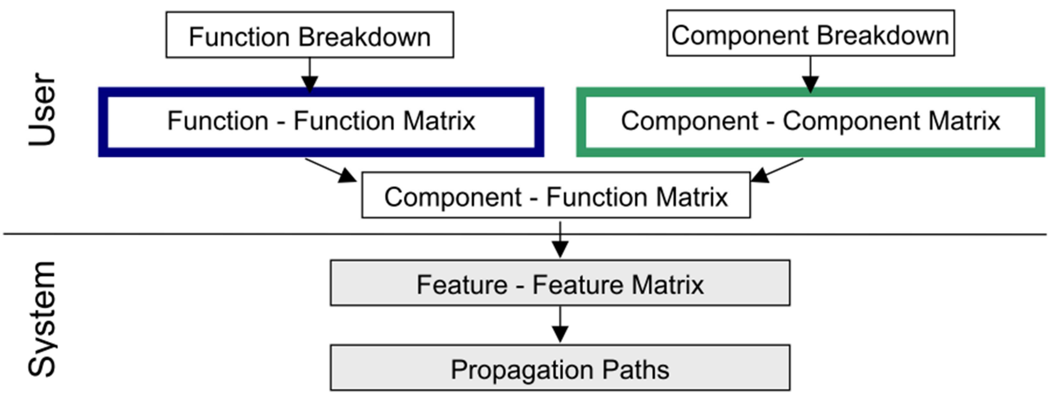


Figure 4-4: Overview of the FACP, Flanagan et al. (2003)

Chen et al. (2007) suggest a pattern-based decomposition methodology for rapid redesign so that design customization in agile manufacturing can be supported. For simplification purposes this method will be called the **Rapid Redesign Methodology (RRM)** during the course of this thesis. 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.

Figure 4-5 shows the overall workflow of this method. With the help of a Design Dependency Matrix (DDM) parameters and constraint functions of the product model are to be mapped. The constraint functions define the design correlations between the parameters. The original DDM then has to be reorganized by cluster formation and alignment so that one of the two types of matrices can be obtained: either an uncoupled matrix where there is no overlapping between the different clusters which means that this is already the resulting matrix, or a banded diagonal matrix where there is overlapping so that this matrix has to be decomposed. This can be done by various matrix partitioning algorithms. The results are different redesign pattern solutions which are then evaluated regarding the scale of necessary redesign and regarding potential propagation. The optimal solution which entails the least redesign effort can then be chosen (Chen et al., 2007).

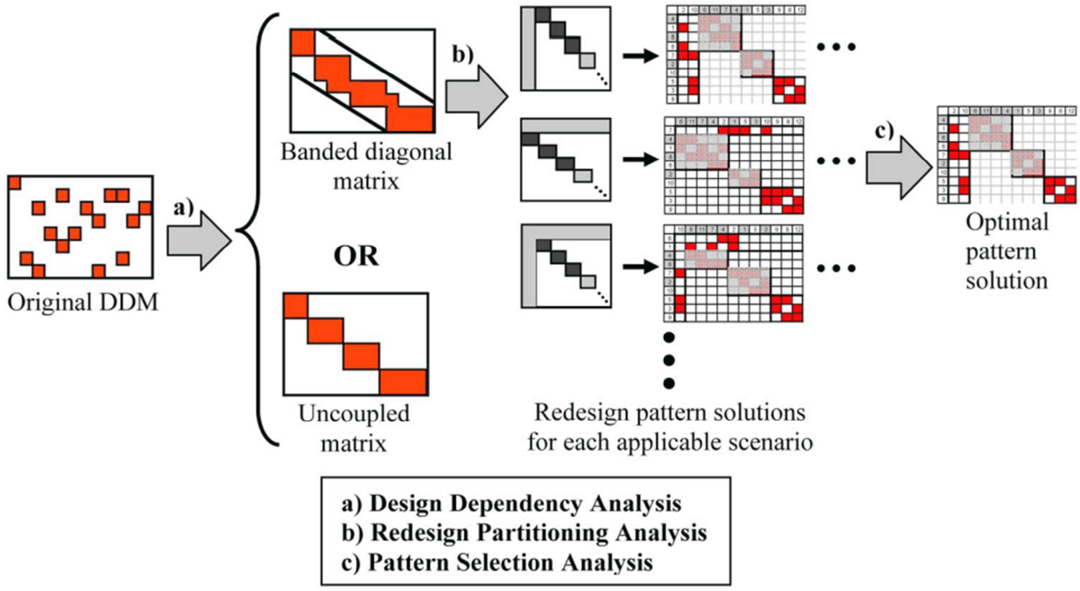


Figure 4-5: Workflow of the RRM, Chen et al. (2007)

4.3 Methods Requiring a Database

Another approach to deal with change propagation is by using a database. Mostly, the authors suggest an approach based on databases in order to reduce the dependence on expert knowledge, to make the method practicable for also novice/non-technical designers, or to involve many people into their usage.

Kocar and Akgunduz (2010) developed the **Active Distributed Virtual Change Environment (ADVICE)** which can be applied during the course of 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 ECB can use it. ADVICE aims at providing support to its users by prioritizing ECRs and by predicting possible propagation.

ADVICE is based on Sequential Pattern Mining techniques which, in general, enable analyzing sequences of data regarding meaningful patterns so that behavior of said datasets can be showed. According to Kocar and Akgunduz (2010) these techniques can also be used to predict change propagation when analyzing datasets of past ECs. By modeling the proposed ECM system in a Virtual Collaborative Design Environments (VCDE) a ‘shared, real-time, simulated 3D representation of EC' can be provided (Kocar and Akgunduz, 2010).

Members of the ECB can initiate ECRs and ADVICE will check the database if there already is a similar change on the same component stored in the database. If the initiated ECR is already in process then it will be rejected automatically. If another change on the same attribute is already recorded in the history then the initiator can decide whether to re-confirm the ECR or to reject it. The approved ECRs will then be ranked by ADVICE's prioritization agent and each ECB member will get a list of ECRs in their area of responsibility. The members can see the component that is to be changed highlighted in 3D models and can analyze the models in more detail by zooming in and out and rotating it. The change propagation agent will give warnings when a change is likely to trigger more changes. Components with probabilities to be changed due to the current ECR will be marked red, yellow or green according to their probabilities (Kocar and Akgunduz, 2010).

Another method which requires a database was developed by Grantham Lough et al. (2006). Their **risk in early design method (REDM)** aims to perform 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.

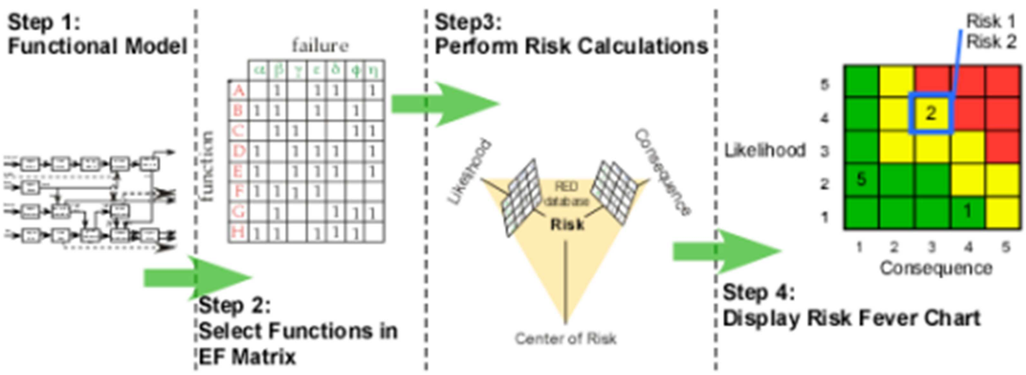


Figure 4-6: Workflow of the REDM, Grantham Lough et al. (2006)

Figure 4-6 illustrates the approach of the REDM: before being able to apply the method, the REDM database has to be populated with failure reports from various products. Then, a functional model of the current product has to be prepared so that the function-failure matrix can be derived by applying the FFDM approach. By the means of the information in that matrix and by applying four different risk formulae the risk likelihood and the risk consequences such as change propagation can be obtained. The results can then be mapped on risk fever charts for quick and easy communication among the designers. According to Grantham Lough et al. (2006) this method is also suitable for inexperienced designers who don't have enough experience on past designs to assess the potential failure risks themselves.

Moktharet al. (1998) created an **information model** intended for the construction industry that shall help coordinating the design process among the different disciplines involved during the detailed design phase. The authors state that changes made by one designer can affect others, i.e. one designer's output is another designer's input, and can therefore propagate across the various disciplines. The developed information model shall therefore facilitate the notification process when designers make changes that will have an impact on other designers' work. This is done by automatically sent messages to the affected designers which contain relevant information about the change (Mokthar et al., 1998).

In order for the information model to be able to work, the data structure of the building components has to be assembled in a database and the links among the building components need to be specified in a configuration model by means of prebuilt and dynamically built rules. Prebuilt rules are the ones that are captured in the beginning of the detailed design phase whereas dynamically built rules are captured during the preparation of detailed drawings, i.e. during the usage of the model, and are therefore added later on. When one of the designers makes a change to a building component attribute, then the affected component itself will check if any of the rules apply, i.e. if the affected attribute is linked to other ones. If one of the rules does apply, then a message to the affected designer is sent automatically to letting them know about the changed attribute (Mokthar et al., 1998).

Besides being able informing designers about current changes, the information model can display possible change paths and their respective effects such as required man-hours or impact on construction costs. Moreover, by means of a tracking module all past changes on a building component as well as all their automatically sent messages in the past can be retrieved.

Ma et al. (2008) developed a method that models associative engineering relations in a unified feature modeling scheme. During the course of this thesis this method will therefore be called the **Unified Feature Modeling Scheme (UFMS)**. The method aims at obtaining information consistency control between the different applications of the various product lifecycle stages by the means of a change propagation algorithm. 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 the inter- and intra-stage relations can be modeled and managed so that change propagation across the stages can be made more efficient and the product information model consistent.

In the UFMS, features which can associate non-geometric information (e.g. attributes) with geometric entities are used in order to obtain 'an intermediate information layer for change propagation and information consistency control in the product development processes' (Ma et al, 2008).

First, the application feature models have to be created. This is done by constructing feature models for the conceptual, the detailed design phase and for the process plan. In a database, the associations between the conceptual and detailed design features and between the detailed design features and the process plan features are stored. With these associations, a dependency network is constructed. When a designer makes a change, then the associations in the dependency network are checked by means of a change propagation algorithm (Ma et al, 2008).

4.4 Methods Based on Other Underlying Concepts

The following methods do not require populated databases and are based on other approaches than using matrices suchas the DSM to break down the product designs in order to map 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 artifacts as objects or entities which, in turn, are described by their attributes (Cohen et al., 2000). Hence, C-FAR considers a product's dependencies on the attribute level.

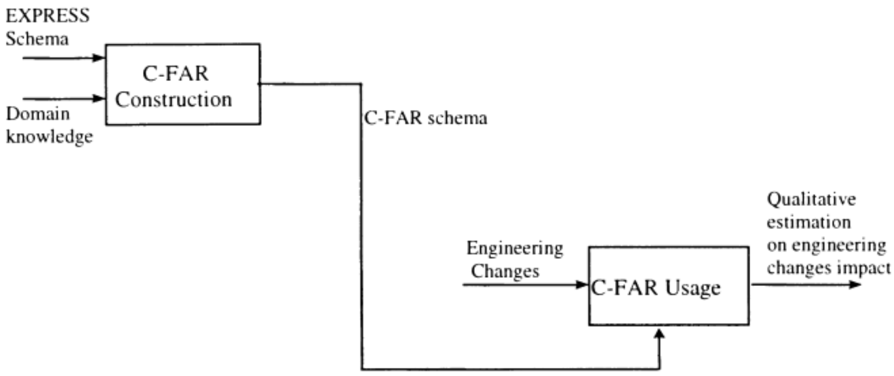


Figure 4-7: C-FAR implementation process, Cohen et al. (2000)

As can be seen in figure 4-7 the implementation process is divided into two main stages: the construction and the usage stage. During the C-FAR construction stage an expert who is knowledgeable in the field of schemas has to prepare the C-FAR matrices by manipulating the EXPRESS data schemas and by mapping and valuing ('low', 'medium' and 'high') the dependencies among the product's attributes. The construction stage only needs to be carried out once for a product which means that the subsequent usage stage is independent from it. That is why also non-experts can carry out the C-FAR methodology once its matrices and schemas are constructed. During the usage stage, the user can identify the attribute to be changed as well as the attributes and entities he wants to see the effect of the initiated change upon. C-FAR then shows the possible change propagation paths and calculates and interprets the linkage values. The higher a linkage value the higher the degree of correlation between the source and the target attribute (Cohen et al., 2000).

C-FAR could be successfully validated in an industrial case setting on a car bumper, an injection molding and a printed wiring board. However, it has to be noted that due to its computational complexity it is rather suitable for small or simple products (Jarratt et al., 2011).

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 indicates 'the degree to which the redesign plan can be expected to achieve the redesign goal, as well as the nature and severity of the side effects' (Ollinger and Stahovich, 2001).

Prior to its usage, a directed dependency graph that maps the causal relationships and their magnitude ('zero', 'low' and 'high') of the product's relevant quantities has to be created. Then, ReDesignIT searches for the parts in the design that will be affected by the change. The program ranks the different redesign proposals concerning their effectiveness and indicates how undesired side effects, i.e. change propagation, can be counteracted. The authors claim that ReDesignIT is especially beneficial for making changes to large scale engineered systems. However, they also 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 (Ollinger and Stahovich, 2001).

Yang et al. (2011) recently developed a method for searching change propagation paths by considering parameter linkages in order to help designers in finding optimal change solutions. In the course of the method a parameter linkage network (PLN) model is constructed which is why this method will be called the **PLN-based Method (PLN)** throughout this thesis.

Figure 4-8 shows the basic procedure of the method. First, the PLN model needs to be created by analyzing the linkages between the product's parameters which shall preferably be carried out by multiple designers. The authors hereby differ between two types of linkages: constraint linkages which can be influenced by the designers, and fundamental linkages which cannot be influenced. Second, the constraint linkages are to be transformed into fundamental ones in order to obtain a hierarchical PLN model structure. In that model the parameters need to classified into three different types: first, direct parameters which can be adjusted by the designers, e.g. geometry aspects, second, target parameters which cannot be adjusted by the designers directly, only by changing direct parameters which will have an impact on the target parameters, e.g. design specifications, third, transition parameters with which can pass changes in direct parameters on to the target parameters, hence, which are subject to change propagation. By iterating through an algorithm change propagation paths can be searched and evaluated in order to find the optimal path (Yang et al., 2011).

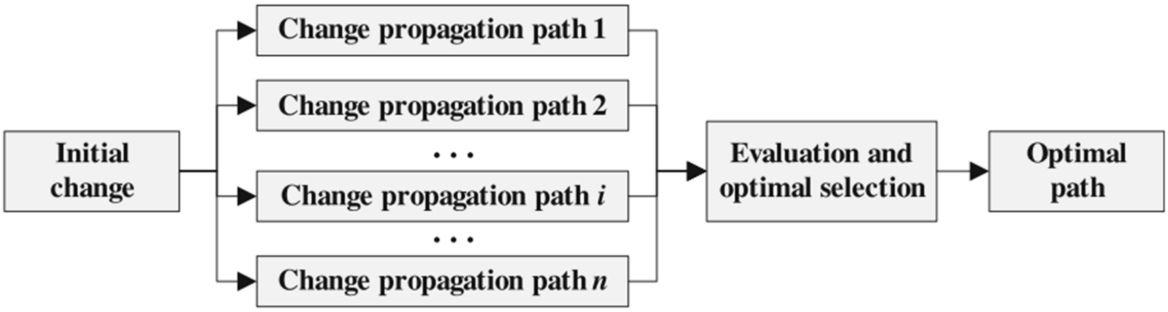


Figure 4-8: Workflow of the PLN, Yang et al. (2011)

4.5 Summary

This chapter aims at answering research question 1, that is to say what approaches, i.e. methods, in literature to EC propagation do already exist. In total, the above described 12 methods on the subject of change propagation that have been developed over the past 15 years could be found in literature. It is already noticeable that some of them have similarities regarding certain aspects such as the product model breakdown and dependency mapping in almost all of the methods, except the ones that use databases. However, it is also striking that the methods do differ to each other regarding other aspects such as what kind of dependencies are mapped, i.e. the ones among components, functions or attributes, or what is aimed at supporting the user with, i.e. providing an indication of the change influence (e.g. change propagation paths) or the risk of a change to propagate.

Therefore, the next step for accomplishing this thesis' purpose is to analyze the above introduced methods further with regards to their intention, proposed approaches, situations they can be applied to etc. This way, first, overlapping and differences shall be identified and hence research question 2 be answered, that is to say how the found methods differ with regards to the requirements of a specific application environment. Second, a procedure model will be developed that shall help product designers in choosing the most suitable method for their specific application environment, which corresponds to research question 3. Both aspects will be further explained in the following chapter.

5 Development of the Preparation-Application-SIPOC² (PA-SIPOC²)

As stated in chapter 1.2, there are currently many different methods in literature which aim at dealing with change propagation one way or the other. 12 such methods could be found during the literature search and are shortly introduced in the previous chapter. When reading through the methods' descriptions it becomes apparent that some of the methods are similar regarding specific aspects, e.g. their expected outcomes, whilst differing in other aspects, such as the situation they can be applied in.

In the following, a procedure model for choosing the most suitable method for the prediction of EC propagation, called the Preparation-Application-SIPOC² (PA-SIPOC²), is developed. First, the motivation for the PA-SIPOC² will be presented in 5.1, second, the requirements that shall be fulfilled will be clarified in 5.2, and, third, the two phases of the procedure model, the preparation and the application phase, will be explained in detail in the chapters 5.3 and 5.4, respectively.

5.1 Motivation for a Procedure Model

As different the above presented methods might be to each other, as different might the application environments be potential users find themselves in. As this procedure model is developed for product developers and/or product development managers, they are meant when using the term 'user' throughout this thesis. Moreover, application environment in this context describes the various aspects that define the situation of the user during product development as well as the kind of support and outcome that the user desires from a method. Users' application environments can differ to each other, for instance, regarding the time an EC becomes necessary (i.e. early vs. late in product development), regarding the complexity of the product (i.e. simple vs. complex products), regarding the desired outcome (e.g. risk assessment that an EC will propagate vs. indication of propagation scale), regarding the data at hand (e.g. populated database with relevant data, expert knowledge), etc.

Thus, it is fair to say that a potential user who finds himself in a situation where an EC to a specific part of a product becomes necessary and where the user would like to seek the support of a EC propagation method, their application environment has to be taken into account when choosing a method. This means that not all of the 12 methods are equally appropriate and suitable for specific application environments. Hence, the procedure model developed in the course of this thesis shall provide support regarding the question of what method is the most suitable in order to fit the user's current application environment.

This procedure model, called the Preparation-Application-SIPOC² (PA-SIPOC²), is developed in analogy to Six Sigma's SIPOC process (**S**upplier, **I**nput, **P**rocess, **O**utput and **C**ustomer) in order to capture the various process steps and the different people involved. The Six Sigma approach which was originally developed at Motorola incorporates various techniques and strategies for continuous improvement concerning an organization's processes. According to Nold (2011), the SIPOC 'provides a process road map focusing on the value stream inherent in any process whether production, decision-making, or innovation related'. By the means of a SIPOC diagram people, sources of material or knowledge, information and resources that are needed to reach a specific object can be mapped in a flow chart (Nold, 2011) which is illustrated in figure 5-1.

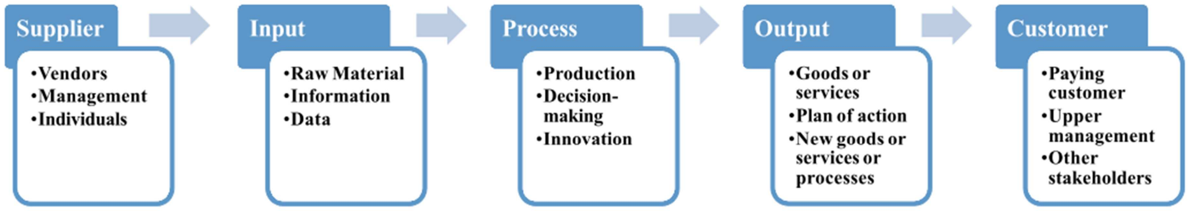


Figure 5-1: Generic SIPOC flowchart, Nold (2011)

The SIPOC concept is adapted for this thesis' procedure model, the PA-SIPOC², for providing a quick overview about the people involved, the individual steps that have to be conducted during the process stage and the needed input as well as resulting output. This shall provide the user with a holistic overview on the value stream inherent in the process.

PA-SIPOC² is created in a twofold manner with regards to the addressed perspectives and therefore contains two phases, the preparation and the application phase. The Preparation-SIPOC explains the necessary steps that have to be conducted in order to find, analyze and classify various methods for their usage in the Application-SIPOC. The Application-SIPOC, on the other hand, explains how product developers or product development managers can use the results from the Preparation-SIPOC, namely the analyzed and classified methods, to adjust their specific application environment to the ones from the various methods in order to select the most suitable one.

Before explaining the two phases in more detail in chapter 5.3 and 5.4, the requirements that have to be fulfilled by the PA-SIPOC² will be discussed in the following chapter.

5.2 Requirements on the PA-SIPOC²

As mentioned above, the PA-SIPOC² is designed in a twofold manner and consists of two phases, the preparation and application phase, which address two different perspectives of usage and which are both designed in dependence on Six Sigma's SIPOC process. The PA-SIPOC² has to fulfill certain requirements which will be discussed below. For structure purposes, the requirements will be presented separately, i.e. first the ones for the preparation and, second, the ones for the application phase, and are clustered according to the SIPOC steps. Table 5-1 shows an overview of all the requirements.

Preparation-SIPOC:

Requirements regarding the **suppliers** and the **input**: The Preparation-SIPOC describes the procedure on how to prepare the methods so that they can be incorporated into the Application-SIPOC later on. As the Application-SIPOC aims at assigning the most suitable method to a certain application environment, the Preparation-SIPOC needs to provide a classified overview of said methods. To do so, first methods that can deal with change propagation in product development of engineering products have to be screened according to their appropriateness in order to be incorporated, i.e. the methods need to fulfill the requirements that were already stated in chapter 4.1.

Requirements regarding the **process** and **output**: In the process part of the Preparation-SIPOC, the found methods must be analyzed in a consistent manner so that they can be compared to each other later on. Furthermore, a classified overview has to be provided.

Table 5-1: Requirements that have to be fulfilled by the PA-SIPOC²

	Area of concern	Requirements
Preparation-SIPOC	**Supplier, Input**	**1. Screening:** Methods from academic papers that address change propagation in product development of engineering products must be included.
	Process, Output	**2. Analysis:** Methods must be analyzed in a consistent manner. **3. Classification:** A classified overview of the methods must be provided.
	Customer	**4. Intended for:** Must be prepared for the Application-SIPOC's.
Application-SIPOC	**Supplier, Input**	**5. Type of data:** Data must be derivable from a database or from an expert.
	Process, Output	**6. Alignment:** Must adjust current situation, purpose and effect desired from the user with situation, purposes and effects of methods. **7. Selection:** Must select most suitable method. **8. Expendability:** The PA-SIPOC² must be expandable by new/other methods.
	Customer	**9. Intended for:** Must be beneficial to product development managers and product developers of technical/engineering products.

Requirements regarding the **customer**: During the Preparation-SIPOC the various methods have to be prepared in a way so that they can be used in the Application-SIPOC. Hence, the output of this phase is intended for utilization during the Application-SIPOC.

Application-SIPOC:

Requirements regarding the current situation, i.e. **supplier** and **input**, at hand: The methods that are incorporated in the procedure model require different product data input. Some methods require a database populated with relevant data, whereas others require at least one expert who has sufficient knowledge of the product's dependencies and who can provide the needed data by breaking down the product into its sub-systems and often by then creating matrices or product models. Hence, data about the product must be either already at hand, in the form of a populated database, or must be derivable by consulting an expert.

Requirements regarding the **process** and **output**: The Application-SIPOC must adjust the current situation, the wished purpose and effect of the user with the different purposes, situations and effects of the methods. After the alignment, the most suitable method has to be selected so that it can be applied by the user. Also, as it is possible that not all methods that consider EC propagation could have been found during the literature search of this thesis, and as also new ones might emerge in the future, it is required that the procedure model is extendable. This way it shall be ensured that the procedure model can grow as new ideas on how to handle EC propagation arise.

Requirements regarding the **customer**: The Application-SIPOC must provide support to product development managers or product developers during the product development of engineering products by the selection of the most suitable EC propagation method.

5.3 The Preparation-SIPOC

The Preparation-SIPOC describes the necessary steps that have to be conducted in order to find, analyze and classify various methods for their use in the Application-SIPOC. This means that the Preparation-SIPOC has to be conducted at least once prior to the Application-SIPOC. However, as other methods might emerge in future and therefore an extension might become necessary or rather desired, the Preparation-SIPOC might not only serve as an initial preparation to the Application-SIPOC, but can also address people who want to extend the PA-SIPOC² in the future. Figure 5-2 shows the Preparation-SIPOC which will be explained in more detail in the following by looking at the entire chain of events, i.e. from supplier to customer[5].

The main purpose of the PA-SIPOC² is to enable adjustment of a user's specific application environment with the available methods for EC propagation. To do so, first those methods need to be found. Therefore, published papers of academics and researchers have to be

[5] The terms 'supplier' and 'customer' are abbreviated as 'suppl' and 'cust' in figure 5-2

screened and analyzed. Consequently, academics and researchers serve as suppliers in this context as they are the ones who develop methods that can deal with EC propagation and hence provide the input for the Preparation-SIPOC.

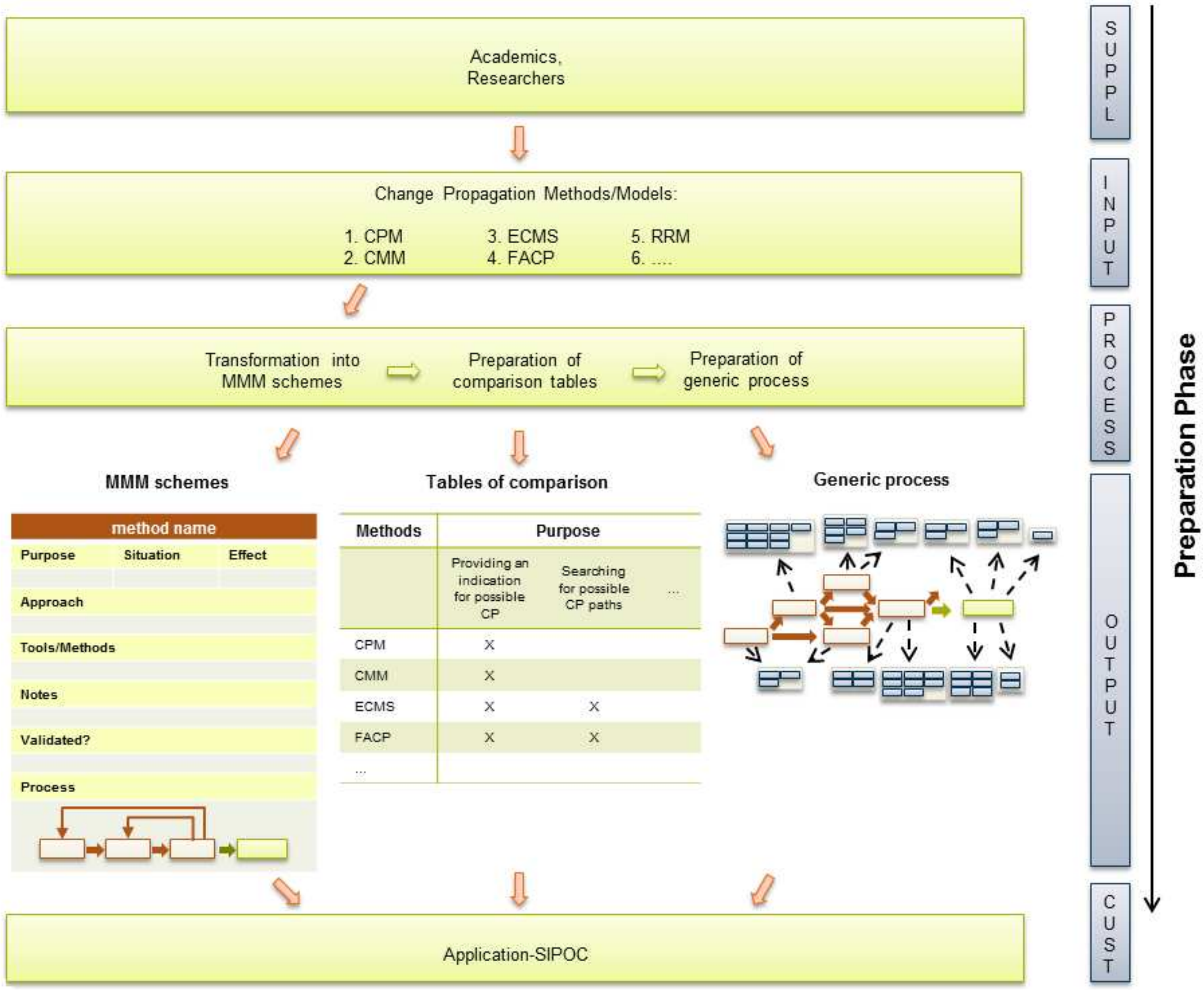


Figure 5-2: The Preparation-SIPOC

Once, papers on the topic of EC propagation could be found, they need to be screened with regards to their content. As stated in chapter 4.1, certain requirements have to be fulfilled for the methods to be further considered. The methods must be able to indicate, predict or track EC propagation in some way and they must have been developed within the past 15 years. Furthermore, methods that consider change propagation in software technology are not included in this thesis, neither are the ones that consider change propagation across companies. When those requirements on the papers could be fulfilled, the proposed methods were considered as input. The methods that could be found during the screening process were already shortly described in chapter 4.

The first step of the process 'transformation into MMM schemes' describes the analysis of the

12 methods concerning their content and explains how they are classified in order to be ready for their utilization during the Application-SIPOC.

In order to provide a systematic way for analyzing methods Lindemann (2009) developed the Munich methods model (MMM) scheme which can be seen in table 5-2 [6]. With the help of the MMM scheme the 12 methods can be analyzed in a consistent manner so that a structured overview can be obtained and a comparison of said methods can take place in the next process step, the 'preparation of comparison tables' (see figure 5-2).

Table 5-2: Munich methods model (MMM) scheme, adapted from Lindemann (2009)

<table>
<tr><td>Purpose
• Tasks in the development process that shall be supported by the used method
• Functioning of the method</td><td>Situation
• 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</td><td>Effect
• Possible effects and side effects of the method
• Product models, artifacts, etc. that result from the application of the method</td></tr>
<tr><td colspan="3">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</td></tr>
<tr><td colspan="3">Tools
• Optional – where reasonable
• Tools or means that can be implemented for supporting the application of the method (software, check lists, etc.)</td></tr>
<tr><td colspan="3">Notes
• Optional – where required
• Additional notes for the application of the method
• Connection of the method with other methods</td></tr>
</table>

The scheme consists of the sections 'purpose', 'situation', 'effect', 'approach', 'tools' and 'notes'. With the help of these sections, the methods can be examined concerning their purpose which they aim to fulfill, 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, tools which can be helpful and supporting, and additional notes.

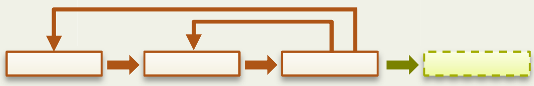
In order to fit the purpose of this thesis, the MMM scheme is modified. Table 5-3 shows the MMM scheme how it is used in this work. First, two additional rows are added, the validation row and the process row. The validation row indicates if a validation of the considered method took place and shows its results (provided that the authors presented and discussed the results). This shall give an idea about the method's maturity and if it was proven to be able to work in an actual industry setting. The process row provides a flowchart of the approach including the expected outcome which shall give a quicker overview of the main steps of the

[6] This MMM scheme is translated into English. The original MMM scheme in German can be seen in Appendix A1.

method's approach.

Table 5-3: Modified MMM scheme

Method Name		
Purpose	**Situation**	**Effect**
• Purpose 1 • Purpose 2 • ...	• Situation aspect 1 • Situation aspect 2 • ... **Marginal Conditions:** •	• Effect 1 • Effect 2 • ... **Output:** • ...
Approach		
Step 1: • ...... **Step 2:** • .... **....**		
Tools and Methods		
Based on: • Tool/Method 1 • ...	**Supporting Tools/Methods:** • Tool/Method 1 •	
Notes		
• ...		
Validation		
Validation in industry: • ...	**Other:** • ...	**Results:** • ...
Process		



Second, the tools row is changed to a tools/methods row and is divided into two sections: the first one now indicates the tools/methods the considered method is based upon in order to quickly obtain an idea of the underlying concept(s). The second section is like the one in the original MMM scheme and is intended for supporting tools supplementary to the method. By means of the modified MMM scheme, each of the 12 methods is analyzed. Hence, in total 12 MMM schemes are produced which can be found in Appendix A2.

It has to be noted that the level of detail has to be similar in order to provide comparability for the next steps. Moreover, since the Information Model by Mokthar et al. (1998) is intended for the construction industry and it hasn't been applied to engineering products yet, it is not clear whether or not it is suitable for this purpose. Hence, this method was analyzed by means of the MMM scheme, however, it is not included in the subsequent analysis process due to its unclear appropriateness for its usage during the development of engineering products. This means that only 11 out of the original 12 methods will be further discussed in the following chapters.

After having finished the first step of the Preparation-SIPOC' process, i.e. 'transformation into MMM schemes', it can be continued with the second process step, the 'preparation of comparison tables' (see figure 5-2). Once all the 12 methods are mapped in the MMM schemes, the content of the remaining 11 methods in the purpose, situation, effect and notes section has to be reviewed in order to find classifying denotations. To do so, the information has to be generalized so that more generic terms can be found that enable clustering the methods with regards to their purposes, situations, etc.

After having modified the MMM schemes regarding their wording, tables for comparison are prepared. In total four tables are made, labeled ‘purpose’, ‘situation’, ‘effect’ and ‘others’ and can be seen below in the tables 5-4 to 5-6. The criteria in the tables derive by comparing the respective sections in the 11 MMM schemes. That is to say, that, for instance, the criteria listed in the purpose table in 5-4 derive from the content of the purpose section of the MMM schemes, the criteria in the situation table in 5-5 derive from the situation section, and the effect criteria in table 5-6 from the respective effect section. Table 5-7 comprises the criteria that can be derived from the method/tools as well as from the validation section of the MMM schemes. Hence, all the information discussed below with regards to the tables’ content is taken from the MMM schemes in Appendix A2.

The ‘X’ in the tables 5-4 to 5-7 indicates that the method fulfills the regarded aspect according to their description in the academic papers. ‘(X)’ indicates that it is not explicitly mentioned in the papers itself; however, it is assumed that the method fulfills the regarded aspect. Footnotes specify the reasoning behind that assumption.

Table 5-4 shows all the criteria regarding the methods’ purposes which can be also found in the purpose section of the MMM schemes in Appendix A2. As can be seen in table 5-4 all methods can indicate EC propagation, be it, for instance, by calculating the risk of EC propagation occurring in the first place, or by searching for possible change propagation paths. However, not all methods explicitly have the purpose to indicate change propagation. RDIT, for example, aims at searching and evaluating redesign plans. The method, however, is able to indicate change propagation, 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 (see chapter 4.1), it is not surprising that all of them fulfill this purpose.

Besides being able to indicate change propagation, table 5-4 furthermore shows that the purposes most often proposed in the papers are to search and evaluate change propagation paths, to support the prediction of change propagation, and to evaluate the influence of an EC.

Change propagation paths in general shall indicate how an initial EC propagates further through the product by analyzing the system’s dependencies and, hence, shall identify the components, functions or parameters that are affected by the change. When looking at the outcomes in table 5-6, it might be striking that even though change propagation paths are certain methods’ output, their purpose (see table 5-4) is not to searching them (i.e. CPM, the UFMS, and C-FAR). This is because these methods generate change propagation paths in the course of their approach, the authors’ emphasis, however, is not explicitly put upon this purpose.

The methods that have the explicit purpose to search for change propagation paths are the ECMS, the FACP, and the PLN method (see table 5-4). As can be seen in table 5-6, these

Table 5-4: Overview of the methods' purposes

METHODS	**PURPOSE**													
	Providing an indication for possible CP	Searching for possible CP paths, evaluation and selection of optimal one	Supporting the prediction (and management) of undesired EC propagation	Providing an evaluation of the change influence	Providing risk assessment (predicting CP/future failures)	Searching for and evaluation of possible redesign plans	Aiming at obtaining a more holistic view on CP	Reducing dependence on expert knowledge	Improving the ECM process by providing textual and graphical information	Prioritization of ECs	Achieving traceability of design change routes in multi-domains (i.e. product, process, and org. domain)	Maintaining the validity and consistency of product models in collaborative and concurrent engineering	Reducing computing effort and expediting redesign solution process	∑
CPM	X		X		X									3
CMM	X		X	X	(X)[7]									3 (4)
ECMS	X	X	(X)[7]	X	(X)[7]		X				X			5 (7)
FACP	X	X		X										3
RRM	(X)[8]					X							X	2 (3)
ADVICE	X		X					X	X	X				5
REDM	(X)[8]				X			X						2 (3)
UFMS	X						X					X		3
C-FAR	X		X	X										3
RDIT	(X)[8]			X		X								2 (3)
PLN	X	X		X										3
∑	8 (11)	3	4 (5)	6	2 (4)	2	2	2	1	1	1	1	1	

[7] The CPM is incorporated in this method which is why it is assumed that this method implicitly can provide the same purposes as the CPM
[8] These methods don't specifically say that their purpose is to indicate CP, however, they are able to do so.

Table 5-5: Overview of the situations the methods can apply to

METHODS	**SITUATION**											
	Marginal Conditions		**Changes to a product resulting from ...**			**explicitly considering EC**	**Suitable**					∑
	Expert knowledge	Database	Faults	New requirements (e.g. improvements, changed customer needs)	Redesign project		...during the course of ECM	...during the first stages of a (re-)design project	...throughout the product development process	...for more complex products /systems	...only for small or simple products	
CPM	X		X	X		X		(X)[9]	X	X		6 (7)
CMM	X			X		X		X		X		5
ECMS	X		X	X		X	X	(X)[9]	X			6 (7)
FACP	X		X	X		(X)[10]						3 (4)
RRM	X				X	(X)[10]				X		3 (4)
ADVICE		X	(X)[11]	(X)[11]		X	X	(X)[9]	X			4 (7)
REDM		X	X			(X)[10]		X				3 (4)
UFMS	X	X	(X)[11]	(X)[11]		(X)[10]		X	X			3 (7)
C-FAR	X			X		X					X	4
RDIT	X				X	(X)[10]		X		X		4 (5)
PLN	X		(X)[11]	(X)[11]		(X)[10]					X	2 (5)
∑	9	3	4 (7)	5 (8)	2	5 (11)	2	3 (4)	4	4	2	

[9] Since this method can be applied throughout the development process it is assumed that it can also be applied during the first stages of design project

[10] The paper deals with changes in engineering design which is why it is assumed that the authors consider EC

[11] It is not explicitly stated in the paper what causes the change, out of its generic context, however, it is assumed that the method can handle changes caused by faults and new requirements

Table 5-6: Overview of the methods' effects

METHODS	**EFFECT**										
	Outcome					**Computerized solution**	**Consideration of**			**Non-experts can use it**	∑
	Change (propagation) paths	Risk scatter graphs / risk fever charts	Redesign plans / patterns	Quantitative ratings (e.g. risk, performance)	Real-time, simulated 3D representation of EC		Component linkages	Functional linkages	Parameter linkages		
CPM	X	X		X		X	X				5
CMM				X		X	X		X		4
ECMS	X	X				X	X		X		5
FACP	X					X	X	X			4
RRM			X			X	X	X			4
ADVICE					X	X		X	X	X	5
REDM		X				X		X		X	4
UFMS	X					X		X	X		4
C-FAR	X			X		X			X	X	5
RDIT			X			X			X		3
PLN	X								X		2
∑	6	3	2	3	1	10	5	5	7	3	

Table 5-7: Overview of the remaining other aspects of the methods

METHODS	**OTHER**					
	Tools and Methods			**Supporting Tools and Methods**	**Validation in industry**	∑
	Matrix-based	Risk techniques	Other			
CPM	DSM	X			X	2
CMM	DSM, DMM	X (CPM)	HoQ	Excel spreadsheets	X	2
ECMS	DSM	X (CPM)				1
FACP	DSM					
RRM	DDM				X	1
ADVICE			VCDE, Sequential Pattern Mining			
REDM	FFDM	X				1
UFMS			JTMS			
C-FAR			EXPRESS, STEP		X	1
RDIT						
PLN				Brainstorming, mind mapping		
∑		4			4	

three methods consider different kinds of linkages inherent in the product: the PLN method searches for change propagation paths from the perspective of parameter linkages whereas the FACP aims at describing and predicting EC propagation through the link between components and functions. The ECMS, on the contrary, considers component and functional linkages. The ECMS furthermore provides an analysis on a multi-domain level: by analzing not only the product domain, but also the process and organizational domain, EC propagation can be captured from a more comprehensive and holistic view and therefore traceability of design changes routes in multi-domains shall be obtained. These two aspects of purpose are indicated in table 5-4 as well.

As can be seen in table 5-4, four out of the 11[12] methods explicitly have the purpose to support the prediction of undesired EC propagation. The CPM, the CMM as well as C-FAR aim to achieve this by generating quantitative ratings (see outcome in table 5-6): the CPM calculates the risk for an EC propagating further through the product and presents the risk assessment in risk scatter graphs. The CMM calculates performance ratings of different change options with regards to their potential change propagation effects. C-FAR calculates

[12] Reminder: the Information Model by Mokthar et al. (1998) has been excluded from the comparison analysis which is why there are now 11 methods discussed instead of originally 12

linkage values which indicate the degree of correlation between two attribtues and therefore shall predict the effect of one attribute to another one. ADVICE, the forth method that aims to support the prediction of undesired EC propagation, analyzes its database regarding patterns of past ECs and provides a 3-D simulation (see outcome table 5-6) where users are informed which components are highly likely to be changed due to an initiated EC.

Furthermore, table 5-4 shows the methods that have the purpose to provide an evaluation of the change influence. By means of the resultant change propagation paths, the ECMS, FACP and the PLN method aim at indicating and evaluating the impact an initiated EC has on other components, functions or parameters. As already mentioned above, during the course of the CMM and C-FAR ratings are calculated which are used to assess the change influence. RDIT aims at providing an evaluation of a change influence by searching for undesired side effects (such as propagation) and suggesting ways of counteracting those.

As mentioned above, the CPM has the purpose to assess the risk of an EC to propagate. As the CMM and the ECMS incorporate the CPM, these two methods implicitly also aim at providing risk assessment to the user (see table 5-4). The REDM analyzes archived knowledge of past failures in designs in order to assess the risk of future failures in the current design. Table 5-6 shows that besides the CPM, the ECMS as well as the REDM have the outcome of risk scatter graphs or risk fever charts.

The remaining columns of table 5-4 show the less prominent purposes which only one or two of the methods have incorporated: the RRM and RDIT aim to search and to evaluate possible redesign plans during a redesign project. As already mentioned above, the ECMS aims at obtaining a more holistic view on change propagation by incorporating the process and organizational domain. The UFMS wants to provide a more holistic view by considering the propagation of information across the product life cycle stages as a coherent whole. This way validity and consistency of product models in collaborative and concurrent engineering shall be managed in a more efficient way. As also can be seen in table 5-4, ADVICE as well as REDM aim at reducing the dependence on expert knowledge by analyzing past data stored in databases instead of relying on experienced designers' know-how. As can be seen in table 5-5 these two methods are the only ones which therefore don't require an expert for conducting the method as opposed to all the other methods. ADVICE moreover aims at improving the ECM process by providing graphical and textual information by means of their 3D-simulation to its users (see table 5-4). Furthermore, ADVICE can not only indicate which component is likely to be subject to EC propagation, but can also prioritize raised and approved ECs. Finally, table 5-4 shows that the RRM has the purpose to reduce the computing effort and therefore to expedite the redesign solution process.

Table 5-5 shows the criteria from the situation section of the methods' MMM schemes in Appendix A2. 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 ADVICE and the REDM, requires experts or experienced designers who are able to do the initial product model breakdown and dependency mapping. ADVICE and the REDM, on the contrary, require a populated database. ADVICE needs a database where past ECRs are stored whereas the REDM needs past failure reports recorded in a database. The UFMS also requires a database. However, this one doesn't have to be populated prior to the methods usage as it serves as a storing place for the associations of the product's features after it has been broken down.

Furthermore, it can be seen in table 5-5 what kind of change the methods can deal with: with the changes that result from new requirements, such as changed customer needs, or the ones that become necessesary because faults have been made during the design. Six out of the 11 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.

All methods can be applied to engineering products as can be seen in table 5-5. This shouldn't be surprising since a requirement on the methods was to be applicable to the product development of engineering products (see chapter 4.1) and the one method that could not fulfill that requirement certainly enough, the Information Model of Mokthar et al. (1998), was already excluded from the analysis.

At what point during the product development process the various methods are suitable is varying, as can be seen in table 5-5. Some methods are only intended for the first stages during the product development life-cycle (i.e. CMM, REDM, UFMS, and RDIT) whereas others can be applied throughout the whole development process (i.e. CPM, ECMS, ADV, and UFMS). ECMS as well as ADVICE 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 change propagation in more complex products (i.e. CPM, CMM, RRM, and RDIT) whereas other methods' effort would be too large for complex products, which is why they are only suitable for simple products (i.e. C-FAR and PLN). 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. For future research, however, there could be more work done in testing what the methods are able to do and thus to figure out the blank cells.

Table 5-6 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 change propagation paths, followed by risk scatter graphs and quantitative ratings. The outcomes were already discussed in more detail above when the different purposes of the methods were examined.

Table 5-6 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 5-6 shows whether or not non-experts can use the respective methods. Only ADVICE, REDM and C-FAR are explicitly suitable for non-experts to use.

Table 5-7 shows the criteria that are derived from the 'tools/methods' and the 'validation' dection of the MMM schemes. It can be seen that six out of the 11 methods are matrix-based

(CPM, CMM, ECMS, FACP, RRM and REDM). Mostly they are based on DSMs. The CPM as well as the RED incorporate 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 tools/methods the methods are based upon are the HoQ (CMM), VCDE and Sequential Pattern Mining (ADVICE), JTMS (UFMS), and EXPRESS and STEP (C-FAR). Only the CMM and the PLN indicated supporting tools/methods, namely Excel spreadsheets and brainstorming and mind mapping, respectively.

Table 5-7 also shows that only four out of the 11 methods have been validated in industry up until now. Other methods may have been validated as well, however, not in real-life case study settings. This means that it is still questionable if they are actually feasible for industrial purposes.

With these four tables for comparison at hand, potential users can now quickly get an overview of the various methods, without first having to read through all the different papers for grasping their intention and situational constraints. This saves time and resources, as prior screening of the literature for EC propagation methods, reading through all of them, as well as identifying similarities and differences among them became redundant. Now, potential users can simply look at these tables which will give them first cues on the content of the methods, and, when the most interesting method(s) for their specific situation are identified, they could still look at the according MMM schemes or at the complete corresponding papers for more information.

Having prepared the four tables for comparison means that the second step of the Preparation-SIPOC's process, 'preparation of comparison tables', is completed (see figure 5-2). This step led to an overview on the methods' purpose, situations they can apply to, expected outcome, etc. However, the tables for comparison do not include a quick overview of how the individual approaches look like and if there too are similarities between the different methods. This will therefore be done in the next step, the 'preparation of a generic flowchart' (see table 5-3).

In order to not only obtain an overview of the methods' purposes, situations and effect, 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 5-3 shows the general layout of a process flowchart in the MMM schemes, including a legend for clarifying the process flowcharts' components.

As mentioned above, the original MMM scheme by Lindemann (2009) is extended, amongst others, 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.

Figure 5-4 shows all the process pictures of the matrix-based methods, figure 5-5 the ones from the methods that require a database, and figure 5-6 the ones using other underlying concepts.

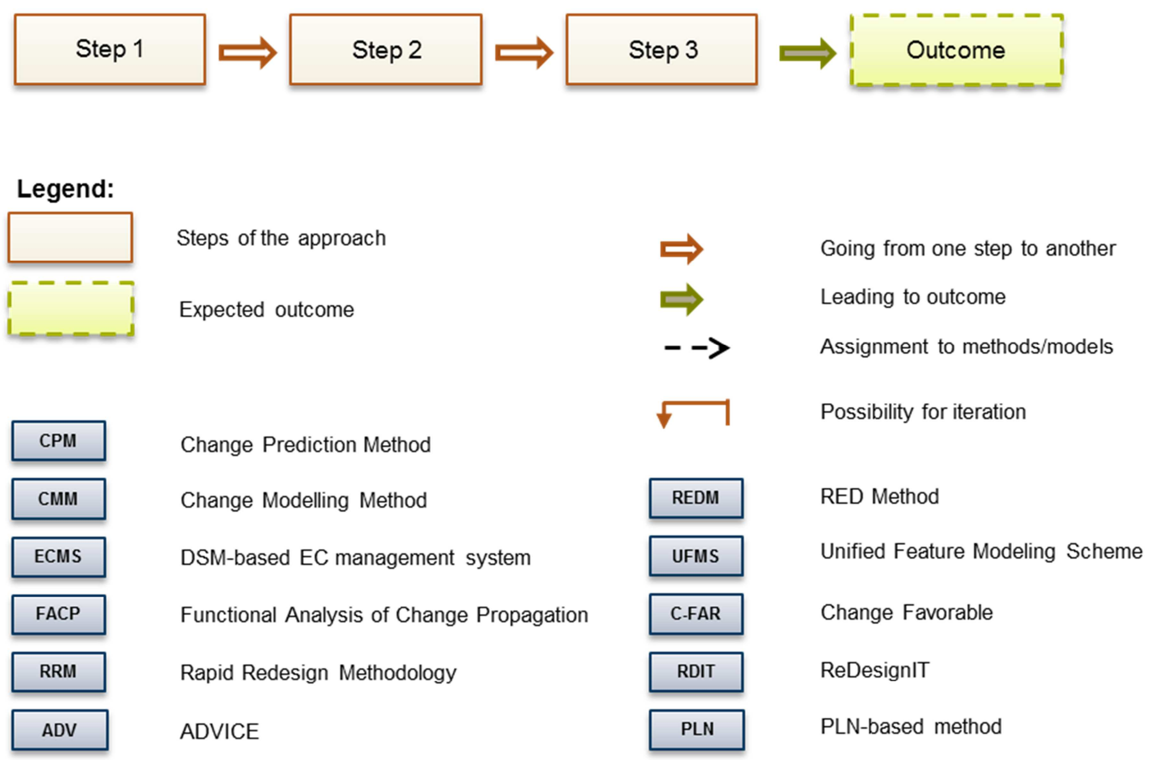


Figure 5-3: General layout of process flowcharts, including an explaining legend

For being able to prepare a generic process flowchart for all the 11[13] methods, the methods' individual process flowcharts have to be analyzed 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. The so obtained generic process flowchart can be seen in figure 5-7. Following, it will be further explained how its individual steps are generated.

When comparing the first component in the tables 5-4 to 5-6, it becomes evident that all methods, except the ones that require a database, initially have to breakdown the product into its sub-systems so that the inherent dependencies can be mapped. This overlapping is incorporated into the generic process flowchart in figure 5-7 by marking the procedure step 'Mapping of dependencies' and allotting all the methods that initially construct product models, matrices, dependency graphs, etc. to it.

Eight of the 11 methods then continue to further analyze these dependencies. Some assign ratings to the available change options, like the CMM, or classify the mapped parameters, like

[13] Reminder: the Information Model by Mokthar et al. (1998) has been excluded from the comparison analysis which is why there are now 11 methods discussed instead of originally 12

the PLN. Others, on the contrary, generate matrices or networks from their initial dependencies mappings, as for instance the FACP or the UFMS. In the generic process flowchart this is summarized in the component 'Analysis of dependencies'.

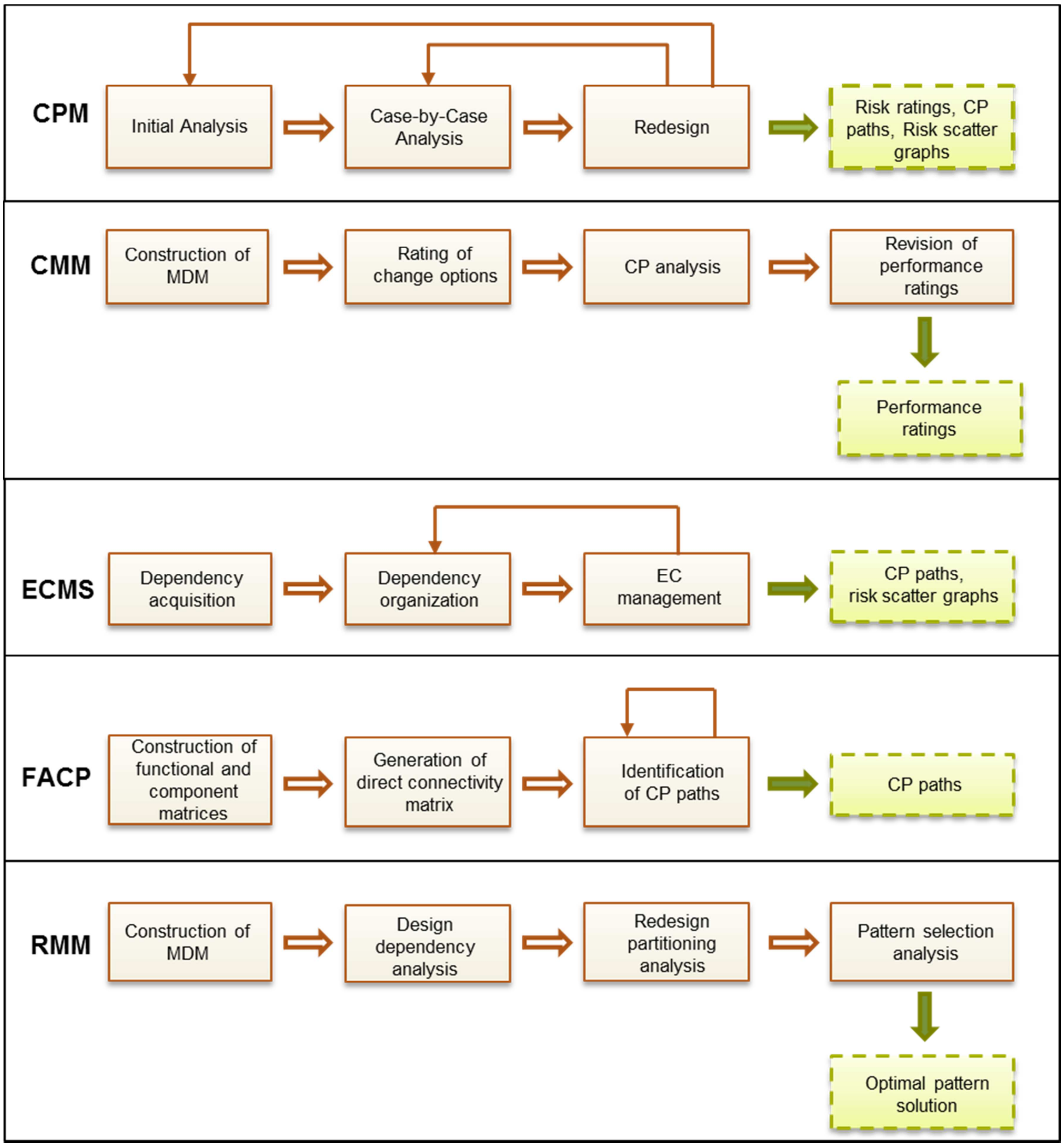


Figure 5-4: Process pictures of matrix-based methods

For the methods that require a database (see table 5-5), the first step is to populate the database prior to its usage. Figure 5-7 indicates this step by having a component marked 'Populating database'. During the course of the approach, the methods extract the data that is needed fo the analysis from the populated databases, hence the step 'Checking/retrieving data from database' in the generic process flowchart.

After having completed the initial dependency mappings and analysis, or the database population and the checking of the relevant data, the change propagation analysis takes place.

This step is common in all 11 methods. However, this analysis differs in their execution: some methods, such as the PLN method or the FACP method, hereby browse the dependencies for searching change propagation paths, whereas others, like the CPM or the REDM, apply risk calculations. In the generic process flowchart the step is therefore labeled

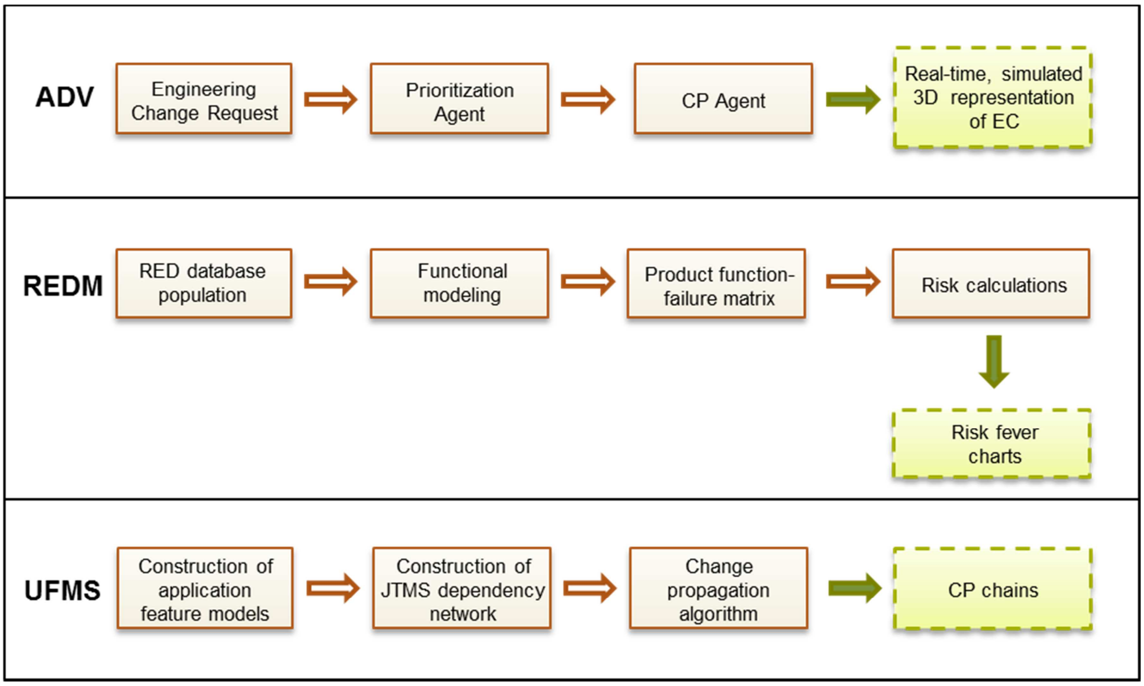


Figure 5-5: Process flowcharts of methods that require a database

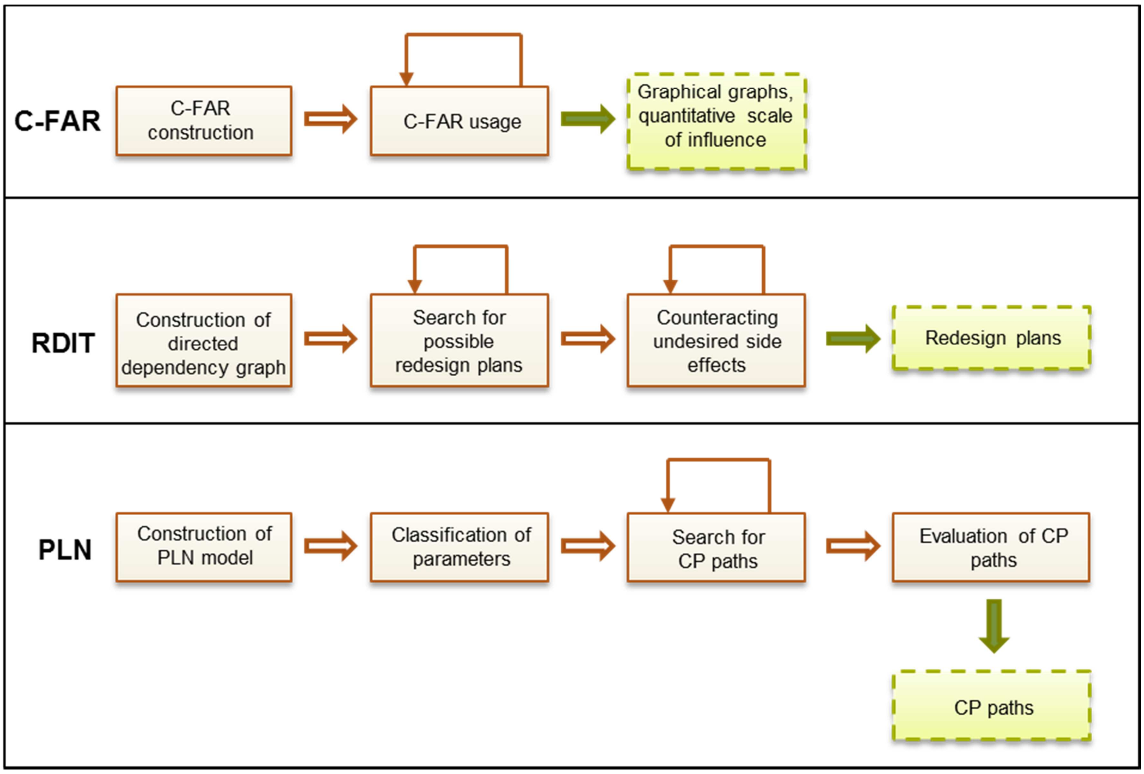


Figure 5-6: Process flowcharts of methods with other underlying concepts

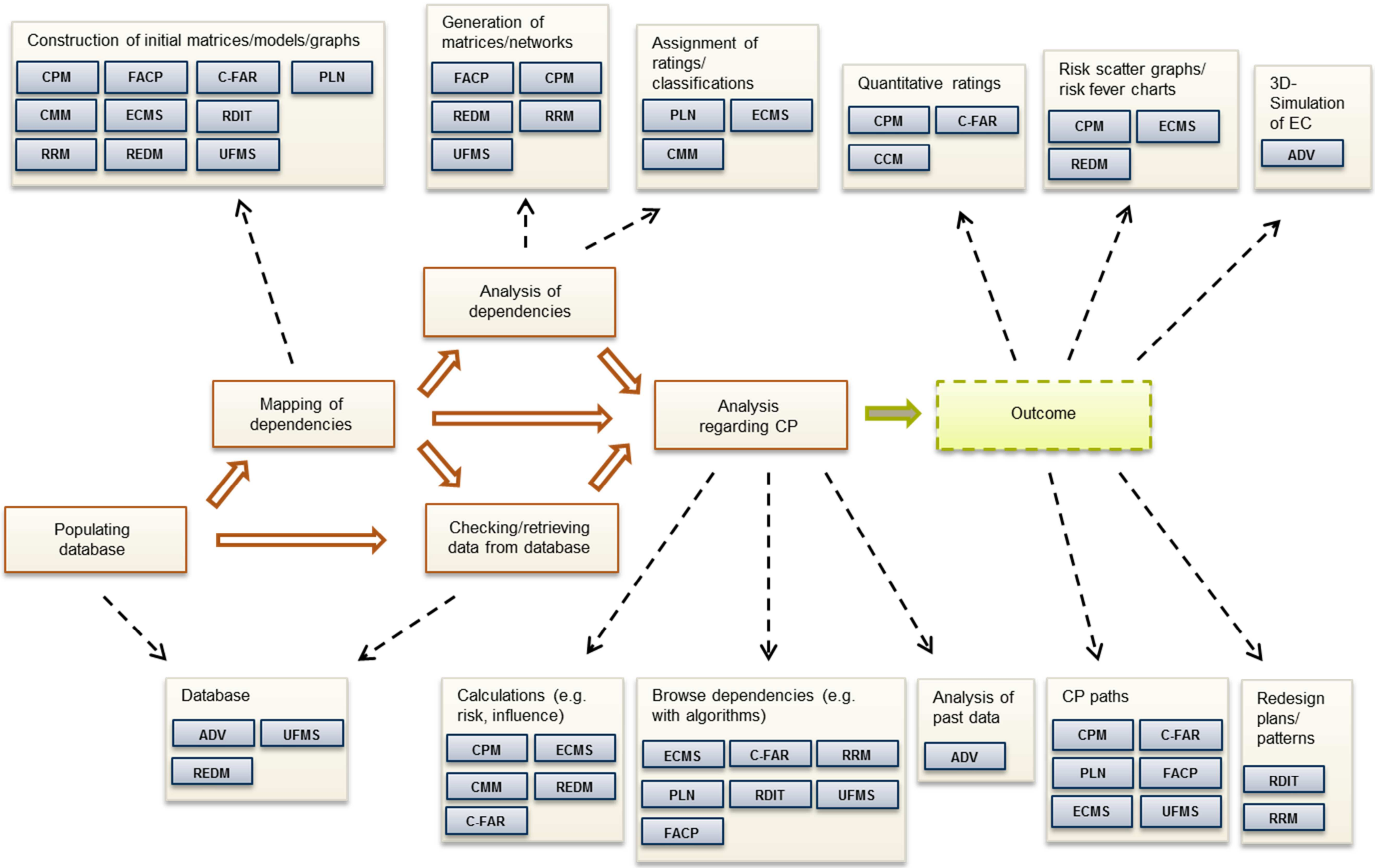


Figure 5-7: Generic process flowchart of all the 11 methods

‘Change Propagation Analysis’ and the allotted clusters are divided into the ones that browse the dependencies to identify possible change propagation paths, the ones that apply calculations, and the one that analyzes past data from the database.

Having completed the change propagation analysis, various outputs are obtained. When comparing the 11 process flowcharts in the figures 5-4 to 5-6, five different clusters can be identified: methods that identify potential change propagation paths, that provide quantitative ratings, that generate risk scatter graphs or risk fever charts, that suggest redesign plans or patterns, and the one that provides a 3D-simulation. These outputs can also be seen in the effect table from the previous chapter (table 5-7).

The completed generic process flowchart in figure 5-7 is the output of the third and the last step of the Preparation-SIPOC’s process (see figure 5-2), ‘Preparation of generic process’. 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.

Summing up, in total three outputs result from the steps in the process described above: first the MMM schemes of the methods, second, the four tables for comparison and, third, the generic process flowchart. Those will be required during the process step of the Application-SIPOC which will be further explained in 5.4. Hence, the Application-SIPOC is regarded as the customer of this Preparation-SIPOC.

5.4 The Application-SIPOC

After having conducted the initial Preparation-SIPOC and having hence in total 11[14] methods prepared and classified at hand, the Application-SIPOC can be applied. The Application-SIPOC now uses the resulting outputs from the Preparation-SIPOC to align the specific application environments of potential users with the purposes, situations, effects, etc. from the 11 methods. With the initial Preparation-SIPOC having already been conducted in this thesis, users, e.g. product developers, can only focus on the Application-SIPOC and don’t have to concern themselves with the foregoing procedure. However, if they do wish to extend the Application-SIPOC by other or new methods, then the Preparation-SIPOC will be of interest for them as well as it explains the process of incorporating methods.

In figure 5-8[15] the Application-SIPOC is added to the Preparation-SIPOC and thus shows the complete PA-SIPOC². In the following, the five SIPOC steps of the application phase as well as the link to the preparation phase will be explained.

All the methods which are able to be chosen in the process step of the Application-SIPOC need input data in order to work (see figure 5-8). The input data must either be already at hand in form of data in a populated database or must be derivable by having experienced designers available who can contribute with their knowledge concerning the product. Thus,

[14] Reminder: the Information Model by Mokthar et al. (1998) has been excluded from the comparison analysis which is why 11 out of the 12 methods are fully prepared for their utilization during the Application-SIPOC.

[15] The terms ‘supplier’ and ‘process’ in the Preparation-SIPOC are abbreviated as ‘sup’ and ‘proc’. The term ‘customer’ in the Application-SIPOC is abbreviated as ‘cust’

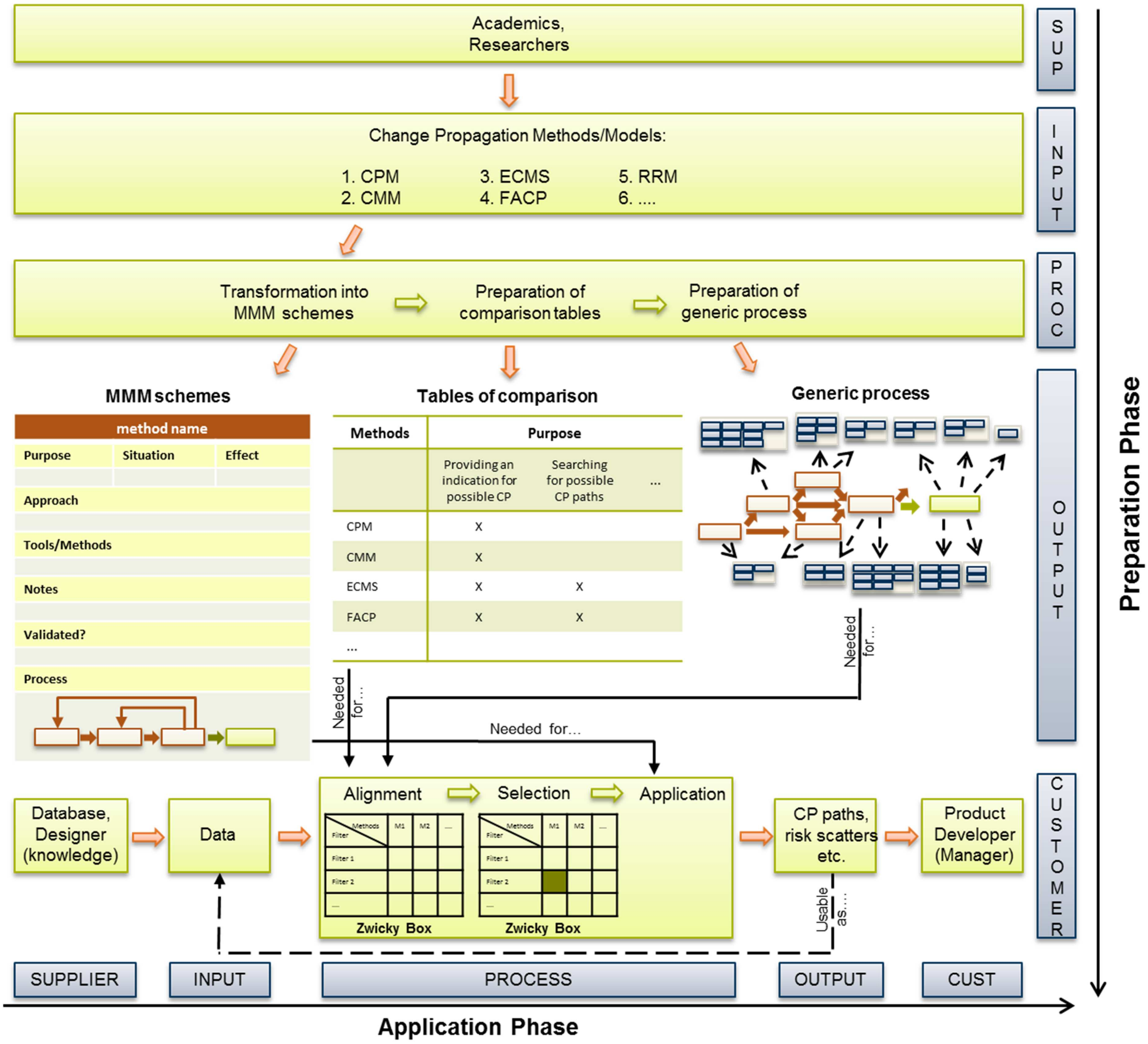


Figure 5-8: The complete Preparation-Application-SIPOC² (PA-SIPOC²)

databases or experts are considered as suppliers in this context. What kind of databases or what kind of expert knowledge is required depends on the method that will be selected.

As mentioned above, depending on what is required from the chosen method, either data from a database or data delivered by experienced designer will serve as input.

During the process step of the Application-SIPOC, the purpose, situation etc. from the user, i.e. their application environment, is aligned to the purpose, situation, etc. of the methods so that the most suitable one can be selected and applied. As can be seen in figure 5-8, the alignment takes place by using the four tables of comparisons and the generic process flowchart from the Preparation-SIPOC introduced in chapter 5.3. In the following, the individual steps of the Application-SIPOC's process will be explained.

With the initial Preparation-SIPOC having prepared 11 different methods, those are theoretically all available for the user to apply. However, due to the user's specific application environment not all of them are equally suitable. For instance, if a user does not have a populated database at hand but wants to apply a method for EC propagation instantly those methods which require one won't be suitable. Nevertheless, if the user plans on using a method for EC propagation in the future, then he could, prior to the application, implement the required database and populate it with the needed data. Or if the development of the product already is in a later stage of the product lifecycle when a method shall provide support with regards to EC propagation, then all those methods which are only suitable to early design stages won't fit.

Therefore, during the alignment phase the user's application environment has to be adjusted with the ones from the various methods. For aligning the user's current situation with the ones from the methods, the tables regarding the 'situation' as well as the 'other' aspects, i.e. table 5-6 and 5-8, are needed. The user can now analyze his own situation by, for instance, answering these following questions:

- Do I have a populated database with the relevant data or experienced designers at hand?
- Do I need a method for an instantaneously occurred EC or am I planning ahead for future ECs?
- What underlying concept, method or tool, do I want to use, or rather which one of these am I or the experienced designer most knowledgeable in?
- Is the EC resulting from faults or from new requirements?
- Do I need a method early in the development process or throughout it?
- Do I only want to take methods that were already successfully validated in industry into account?

For aligning a user's intention and desired outcome, the tables regarding the methods' purpose and effect have to be taken into account (i.e. tables 5-5 and 5-7). The user has to clarify his specifications on the method by answering e.g. these questions:

- What do I want the method being able to do, or rather to support me with?
- What kind of dependencies do I want to have mapped?
- What output would be the most beneficial for my situation?

With this sample of questions the users can identify and specify their own application environment. With the tables for comparison the users can see the feasible methods to their current situation and intention. Moreover, by taking the generic process flowchart into consideration, the user can identify the main steps of the methods' approaches and hence eliminate the methods whose steps would be out of question.

Next, by means of a Zwicky box[16] the number of possible alternative solutions can be

[16] A Zwicky box (named after its inventor, Fritz Zwicky), also referred to as morphological box, is an n-dimensional matrix where the total set of possible relations or configurations of a problem can be investigated. Thereby, first, the parameters of the problem have to be identified and defined. Then, each parameter is assigned a calue or condition. By means of the Zwicky box these parameters can be investigated by setting them against each other. Each cell of the Zwicky box hereby contains a particular 'value' or condition from each of the parameters. This way a particular state of a problem can be marked (Ritchey, T., 1998).

decreased. Lindemann (2009) suggests applying a staged approach where first the most important partial problems are considered. A partial problem in this context comprises the filter possibilities indicated in the two top rows of the tables under the heading, such as ‘marginal conditions - database’ or ‘marginal conditions – expert knowledge’ in table 5-6 which indicate two partial problems. By adding up all the partial problems that are listed in the four tables for comparison, a total of 39 can be obtained.

Hence, by first clarifying the user’s application environment, the partial problems that need to be solved by the method can be chosen, preferably first the ones that are the most critical to the user. By filtering the partial solutions, i.e. the methods, according to the selected partial problems, the total amount of feasible methods can be reduced as only the ones that are able to meet the partial problem remain in the Zwicky box.

After having chosen several partial problems and hence reduced the amount of feasible methods by means of a Zwicky box, the most suitable method can be selected. Preferably, this would be the method that remains last after the filtering.

However, it could happen that more than one method remain after the filtering. One solution could be to add more partial problems so that further reduction can be obtained. Another solution would be for the user to decide to short list the methods that remained after the reduction and to have a look at the generic process flowchart, delete the rejected methods of the filtering so that only the remaining methods are left, and then to have a closer look at their approaches. Taking into account the steps of the methods’ approaches, the user could further filter the methods. Last, the user could consult the MMM schemes for more details of the remaining methods and can then select the one that seems the most suitable for him.

After having chosen the most suitable method the user can apply it. As can be seen in figure 5-8, the according MMM scheme is needed for the application of the selected method as it gives an explanation of the approach that provides a first and rough overview of the individual steps. Furthermore, the MMM scheme also provides the reference to the paper where the method was found and where a more detailed description of the approach can be found.

In figure 5-8 one can see that there are different possible outcomes such as change propagation paths or risk scatter graphs. This is due to the fact that the outcome of the Application-SIPOC depends on what method has been chosen. Thus, depending on the selected method the outcome is one of the five output options that can be found in table 5-7.

The customers of the Application-SIPOC are the people who find themselves dealing with EC during product development and who wish to apply a suitable method for support, i.e. product development managers or product designers (see figure 5-8).

5.5 Fulfillment of Requirements

Both parts of the PA-SIPOC², the Preparation-SIPOC as well as the Application-SIPOC, have to fulfill certain requirements that are discussed in chapter 4.1. At this point, it will only be discussed whether or not the Preparation-SIPOC can fulfill its requirements since the Application-SIPOC is evaluated by means of a student project and therefore the assessment whether or not it can fulfill its requirements will be discussed at the end of chapter 6.

Table 5-8 once again shows the requirements on the Preparation-SIPOC and indicates whether or not the respective requirement could be fulfilled. As can be seen in table 5-5, all the 11 methods that are included in the analysis deal with EC, be it explicitly or implicitly, and as can be seen in table 5-4, all methods can give an indication to EC propagation, either explicitly or implicitly, which means that requirement 1 is fulfilled.

Table 5-8: Fulfillment of requirements of the Preparation-SIPOC

	Area of concern	Requirements		Fulfillment
Preparation-SIPOC	**Supplier, Input**	**1. Screening:** Methods from academic papers that address change propagation in product development of engineering products must be included.	→	The 11 methods included in the analysis can all give indication to EC propagation.
	Process, Output	**2. Analysis:** Methods in a consistent manner must be analyzed.	→	By means of the MMM scheme the methods could be analyzed in a consistent manner.
		3. Classification: A classified overview of the methods must be provided.	→	The resultant tables for comparison provide a classified overview of the methods.
	Customer	**4. Intended for:** Must be prepared for the Application-SIPOC's	→	Application-SIPOC needs the output of the Preparation-SIPOC during its process

By having examined all the methods with the help of Lindemann's (2009) MMM schemes, the different methods are analyzed in a consistent manner. The tables for comparison discussed in chapter 5.3 do provide a classified overview of the methods which allows comparison. Hence, both requirements regarding the process and the output of the Preparation-SIPOC can be fulfilled. As the Application-SIPOC makes use of the Preparation-SIPOC's outputs, it is evident that requirement 4 is fulfilled as well. All in all it can be concluded that the Preparation-SIPOC developed in this thesis can fulfill all its requirements.

5.6 Summary

This chapter introduced the procedure model that is developed in the course of this thesis, the Preparation-Application-SIPOC², short PA-SIPOC². After having answered RQ 1 in chapter 4, i.e. what methods in literature to EC propagation do already exist, by shortly introducing the found methods, this chapter aimed at giving answers to the remaining two research questions.

The Preparation-SIPOC of the PA-SIPOC² can give an answer to RQ 2, i.e. how the found methods differ to each other with regards to the requirements of a specific application environment. The analysis takes place by means of the Munich methods model (MMM) scheme developed by Lindemann (2009). Hereby, the methods are analyzed concerning their content, i.e. their intended purposes, situations they can be applied to, expected outcomes, etc. Then, four tables are prepared in order to enable drawing comparison of the methods' purpose, situation, effect, etc. Hence, with these tables for comparison a classified overview can be obtained. Furthermore, by having prepared a generic process flowchart an overview of the methods' approaches can also be provided which gives further insights into how the methods differ to one another.

The Application-SIPOC intends to answer RQ 3, i.e. how a procedure model could look like so that product developers can use it as a guide to decide what method for EC propagation fits best to their specific application environment and shall therefore be chosen. By identifying one's own application environment and by taking the tables for comparison and the generic process flowchart into account, the user can reduce the amount of available methods by means of a Zwicky box. The most suitable method can then easily be selected and with the help of the according MMM scheme and the corresponding paper, the user can apply the chosen method.

In the following chapter, the Application-.SIPOC is evaluated with the help of a student project conducted at the Technische Universität München (TUM) which shall demonstrate whether or not it is applicable and usable in a practical setting.

6 Evaluation of Procedure Model

After having developed the PA-SIPOC², an evaluation of the Application-SIPOC takes place by means of data from a student project which was carried out within the PSSycle project at the Technische Universität München (TUM). The project as well as the evaluation and the results will be presented in the following. In chapter 6.1, the type of evaluation will be clarified, chapter 6.2 will give a description of the PSSycle project, and chapter 6.3 will describe the conducted evaluation.

6.1 Type of Evaluation

As already stated in chapter 2, Blessing and Chakrabarti (2002) suggest to conduct a **Descriptive Study II** after the Prescriptive Study where an evaluation of the developed support, i.e. of the procedure model, takes place. The authors differ between two types of evaluation: the application evaluation which aims at identifying whether or not the developed support can be used for the intended task, i.e. the focus is on its applicability and usability. The success evaluation, on the other hand, aims at identifying whether or not the developed support has the expected impact and thus can contribute to success, i.e. the focus is on its usefulness.

As there is not enough time to conduct both types of evaluation, an application evaluation is carried out since it first has to be tested if the procedure model developed in the previous chapter is at all applicable and usable in a practical setting before it can be tested *how* useful it really is. For assessing the evaluation, the following three questions need to be answered:

1. Is the method applicable?
2. Does the method address the central aspects?
3. Are those central aspects influenced as intended?

Since the Preparation-SIPOC serves the purpose of analyzing the methods and preparing classified overviews for their usage during the process step of the Application-SIPOC, and since it has to be conducted once prior to the Application-SIPOC and therefore does not necessarily have to be conducted more often (unless someone wishes to extend it), it will not be evaluated in the following. Hence, only the Application-SIPOC, the part of the PA-SIPOC² that is intended for utilization by e.g. product developers, is evaluated.

Thus, first it has to be tested if the Application-SIPOC can be at all applied in the PSSycle project. Second, it has to be evaluated if the Application-SIPOC can address its central aspects, that is to say if it can adjust the PSSycle project students' application environment with the ones from the various methods. And third, it has to be assessed if the central aspects are influenced as intended, hence, if the methods get filtered by means of the Application-SIPOC so that a reduction of choices takes place and the most suitable method can be selected.

6.2 Description of the PSSycle Project

Within the PSSycle project at the TUM an e-bike sharing system is to be developed. The motivation behind that project is a scenario that sees large cities' population further increasing and more companies settling in the city centers to satisfy their need for personnel. This will lead to more traffic which will overload the intra-urban infrastructure and thus cause more traffic jams and delays. Simultaneously, the desire for possessing an own car in large cities decreases while flexibility and purposeful mobility increase. Therefore, sharing concepts, such as car or bike sharing already became more and more popular over the past years and this trend is likely to sustain in the future (März, 2013).

The PSSycle project's idea is to develop an e-bike sharing system similar to the bike sharing concepts that already exist in multiple large cities. By using an e-bike, also called pedelec, long distances can be overcome faster than with regular bikes while being more cost-saving than cars. In the PSSycle project, a standard pedelec was bought and was altered so that it is feasible for being shared (März, 2013). This was done by embedding board electronics, a board computer and a locking system into the pedelec which can be seen in Figure 6-1.

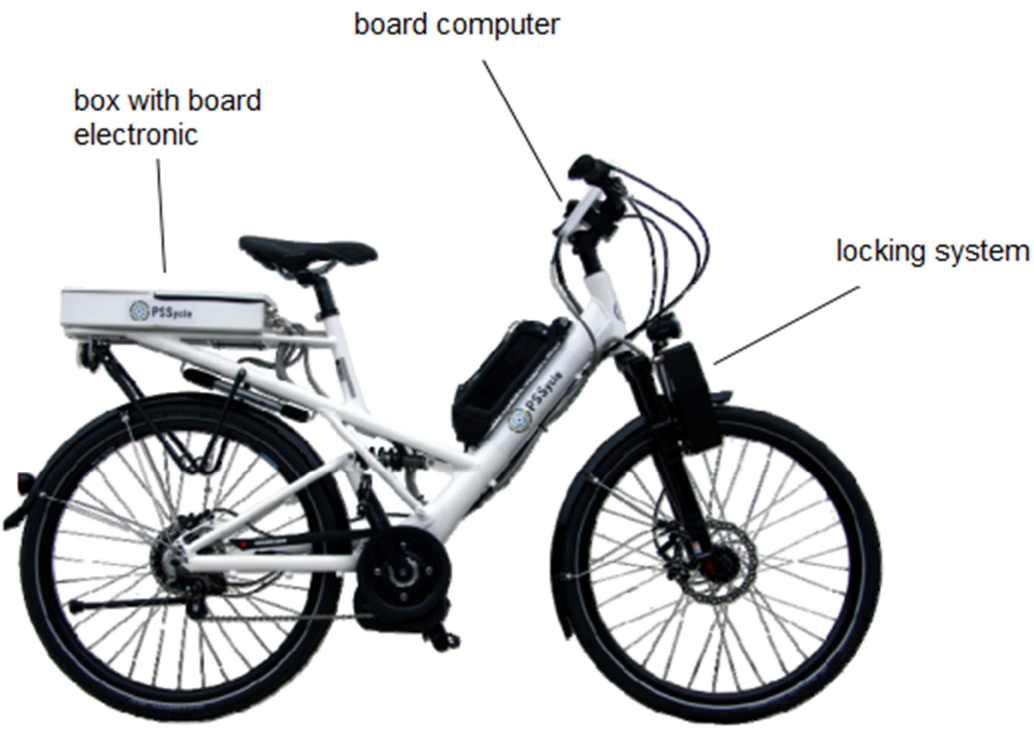


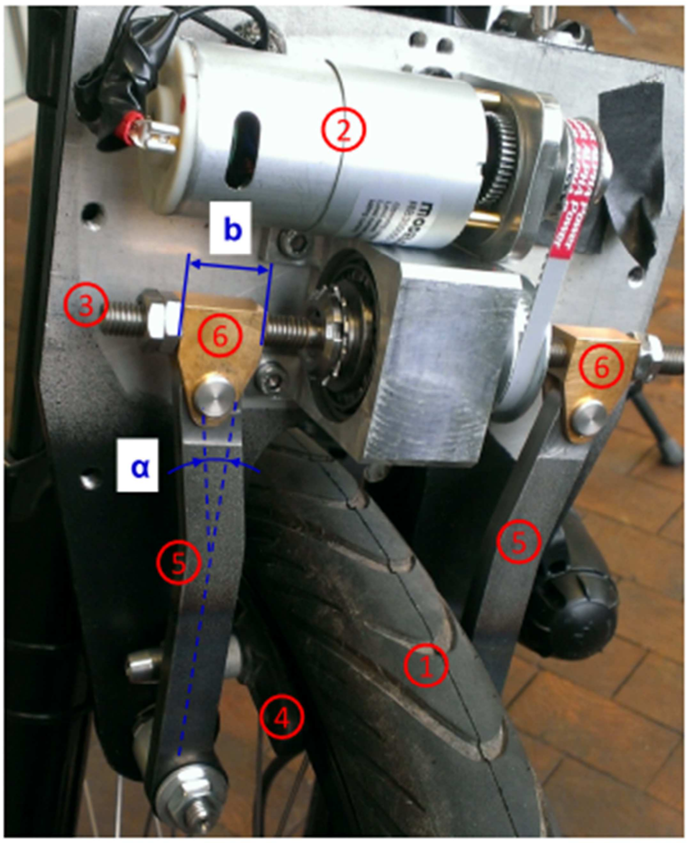
Figure 6-1: Pedelec with board computer, board electronics and locking system, Schreiber (2013)

The board computer is a smartphone with software that can interact with the server infrastructure. With the board computer the user can register themselves, can log in as a member, and, during utilization, can use functions such as navigation and motor support settings. A mount at the handlebar shall prevent the smartphone from being stolen. The board electronics which are located in a box in the back are the interface between the board computer, the locking system and the internal communication system. The locking system is located at the front, at the suspension fork, and shall block the front wheel when not in use. Once a user has authenticated himself, the board computer orders the board electronics to unlock the locking system. After utilization the locking system reblocks the pedelec again (Schreiber, 2013).

A student sub-project within PSSycle aimed at developing a feasible locking system prototype for the pedelec that had to fulfill the following requirements (März, 2013):

- The locking system shall be operable in a fully automated manner for the user's convenience.
- The locking system shall be opened/closed at the push of a button.
- Lending and return of the pedelec shall take place within few seconds.

That locking system prototype which is located at the front wheel can be seen in figure 6-2. (opened). Its key parts function together as follows: The electric motor (2) drives the spindle (3). Two armatures (6) are shifted translationally in the spindle axis by rotating the spindle (3). The armatures (6) transmit their motion to two rotationally mounted lifting arms (5) which, in turn, press two brake shoes (4) against the felloe of the front wheel (1). This way the rotation of the front wheel can be blocked (Schreiber, 2013).



(1): front wheel
(2): electric motor
(3): spindle
(4): brake shoes
(5): lifting arms
(6): armature

b: width of armature
α: dihedral angle of lifting arms

Figure 6-2: Prototype of locking system, located at the front wheel of the pedelec, Schreiber (2013)

During the development of such a locking system, target deviations occurred which forced the student team to make modifications to their design. These target deviations and ECs are used for evaluating the Application-SIPOC and will be further explained in the following chapter.

6.3 Conducting the Application-SIPOC

Figure 6-3 once again shows the Application-SIPOC that is described in detail in chapter 5.4, and also shows the output from the Preparation-SIPOC, i.e. the MMM schemes, tables for comparison and the generic process, which are needed for conducting the Application-SIPOC.

Since it was not possible for the author of this thesis to participate in the student project due to time constraints, the Application-SIPOC could not be evaluated during the course of the student project but after it has been finished. The students documented all their ECs and target variations as they occurred during their project so that this data can be used in retrospective in this evaluation.

In the following sub-chapters the five steps of the Application-SIPOC, supplier, input, process, output and customer, will be discussed in more detail.

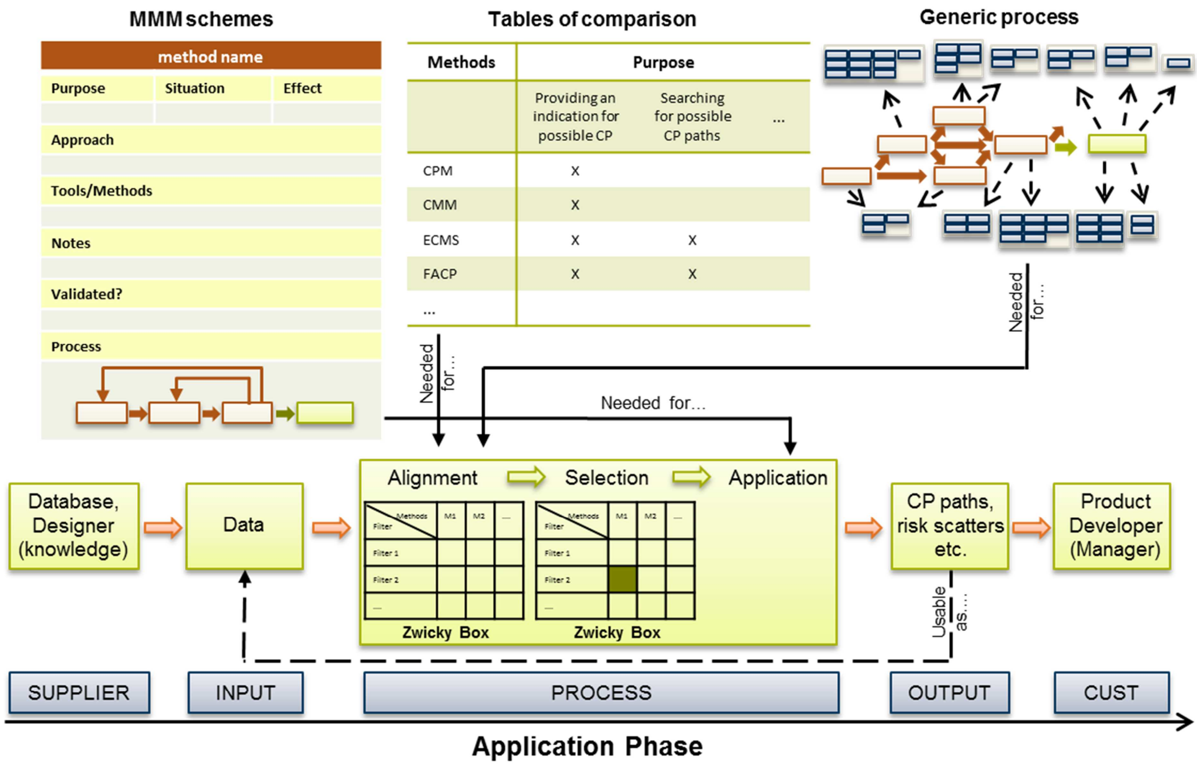


Figure 6-3: The Application-SIPOC

Potential suppliers of the necessary data could be either the students themselves or a populated database. Since the students don't have a database at hand for their project and will therefore have to deliver the input data by breaking down the product into its sub-systems they are considered as suppliers. How exactly this will be done and what kind of dependency analysis will have to take place depends on the method that will be selected during the process step.

For finding the most suitable method, the application environment of the students has to be identified. To do so, the target deviations as well as the ECs that occurred during the project have to be listed and described. Then, with the help of the tables for comparison the situation aspects that are inevitable to consider and the desired support of the method, i.e. the desired purpose, have to be indicated. Afterwards, the choices are used to filter the 11 methods by means of a Zwicky box so that, preferably, one method is left which will be the one that is to be selected. Finally, only the approach of the selected method will remain in the generic process flowchart after having eliminating the rejected methods, and will hence already provide the students a rough overview of the steps that have to be conducted in the course of the chosen method.

In total four target deviations occurred and seven ECs took place during the development of the locking system. Table 6-1 shows the target deviations:

Table 6-1: Target deviation that occurred during the development of the locking system

Target deviation	**Description**	**Phase in product development**	**Dimension**
Toothed belt	Rotation direction of drive shaft can further a loosening of the suspensed screw connection of the power train.	Detailed design phase	Functions
Toothed belt	Toothed belt couldn’t be assembled. Belt was too short.	Detailed design phase	Functions
Armature	At first, steel was intended for the armature and the spindle. Scarce greasing of the screw thread involves the risk of seizing which would cause the locking mechanism to fail.	Detailed design phase	Functions
Attachment screw	No tightening torque could be assembled to the attachment screw at the front fork as access with tools was not possible.	Detailed design phase	Functions

As can be seen in table 6-1 all target deviations occurred in the detailed design phase and affected the functional dimension of the locking system. Those four target deviations led to a need for change and therefore caused four of the seven ECs which are shown in table 6-2.

Table 6-2: EC that occurred during the development of the locking system

EC	Description	Number of change alternatives	Duration of decision making process [h]
Toothed belt	Rotation direction of drive shaft can further a loosening of the suspensed screw connection of the power train.	3	1
Toothed belt	Toothed belt couldn't be assembled. Belt was too short.	5	1
Armature	At first, steel was intended for the armature and the spindle. Scarce greasing of the screw thread involves the risk of seizing which would cause the locking mechanism to fail.	4	1
Armature	At first, non corrosion-resistant steel was intended for the armature. Humidity causes rust which increasingly blocks the screw thread.	2	0,5
Armature	Increased friction in the screw thread caused by a tilted armature.	3	0,5
Attachment screw	No tightening torque could be assembled to the attachment screw at the front fork as access with tools was not possible.	3	0,5
Top casing	By means of the 3D-CAD model it became apparent that the clamping jaw collides with the top casing.	4	0,5

As can be seen in table 6-2, there were always more than two change alternatives for the students to choose. This means that, indeed, a method which could have assessed the different change options' effects regarding EC propagation would have been beneficial for the students before having to choose an option. For the decision making process, i.e. which of the alternatives was about to be chosen, the students gave themselves between half an hour and one hour time. This implies that the method to be selected shouldn't be too complex and time consuming.

With these two tables at hand, implications concerning the students' application environment can already be drawn: the method has to be applicable during the detailed design phase. Hence, methods which are only suitable for the early design stages, e.g. conceptual design phase, are not appropriate for the students' application environment. Neither are the methods that cannot map a product's functional relations as the target variations concerned the locking systems functions (see table 6-1).

Moreover, since the students didn't have a database at hand, the methods that require one cannot be chosen and are therefore rejected. Also, as already mentioned above, the students only gave themselves a limited amount of time for the changes to be implemented, which is why the method needs to be fairly easy to apply, i.e. there is no time for the students to gain extra knowledge prior to the application. Therefore, methods which are matrix-based seem reasonable as the students have enough knowledge in building up matrices.

As the students had more change alternatives at hand, they were interested in if and how a change option might trigger more changes to other parts. Hence, the method to be chosen should be able to indicate potential change propagation paths.

After having clarified the students' application environment, a reduction of the total amount of possible methods can take place with the help of the four tables for comparison in chapter 5.3. The resulting Zwicky box can be seen in table 6-3.

As the students don't have a database at hand, those methods that require one, are eliminated which rejects ADVICE, the REDM and the UFMS. As mentioned above, the students don't have enough time to acquire enough knowledge in the concepts other than matrix-building. Thus, the five matrix-based methods are left (CPM, CMM, ECMS, FACP, and RRM). Only two of them can map functional relations, namely the FACP and the RRM. Both these methods can be applied in the detailed design phase. However, only the FACP can search for change propagation paths, which was the desired purpose of the students.

As can be seen in table 6-3, the reduction of the potential methods can successfully be done since only one method, the FACP, is left. This means that the FACP by Flanagan et al. (2003) is selected to be the most suitable to the students' specific application environment and would could have supported the students during their project when the target deviations occurred and EC had to be implemented.

Table 6-3: Zwicky box for the selection of most suitable method

Method/ Model / **Filter**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	Σ
	CPM	CMM	ECMS	FACP	RRM	ADV	REDM	C-FAR	RDIT	PLN	UFMS	11
Marginal Condition: No database	CPM	CMM	ECMS	FACP	RRM	C-FAR	RDIT	PLN				8
Tools/Methods: Matrix-based	CPM	CMM	ECMS	FACP	RRM							5
Situation: Functional relations	FACP	RRM										2
Situation: Not limited to early design stage	FACP	RRM										2
Purpose: CP paths	FACP											1

By screening out the eliminated methods from the generic process flowchart, a rough overview of the steps that need to be conducted can be seen in figure 6-4. There it can be seen, that the students will first have to map and analyze the locking system's dependencies before carrying out the actual EC propagation analysis. The analysis takes place by browsing the locking system's dependencies in order to find possible change propagation paths.

For the students being able to apply the method, they would have had to have a look at the corresponding MMM scheme in Appendix A2.4, but also at the specific paper from Flanagan et al. (2003) since only there all the details about the approach can be found.

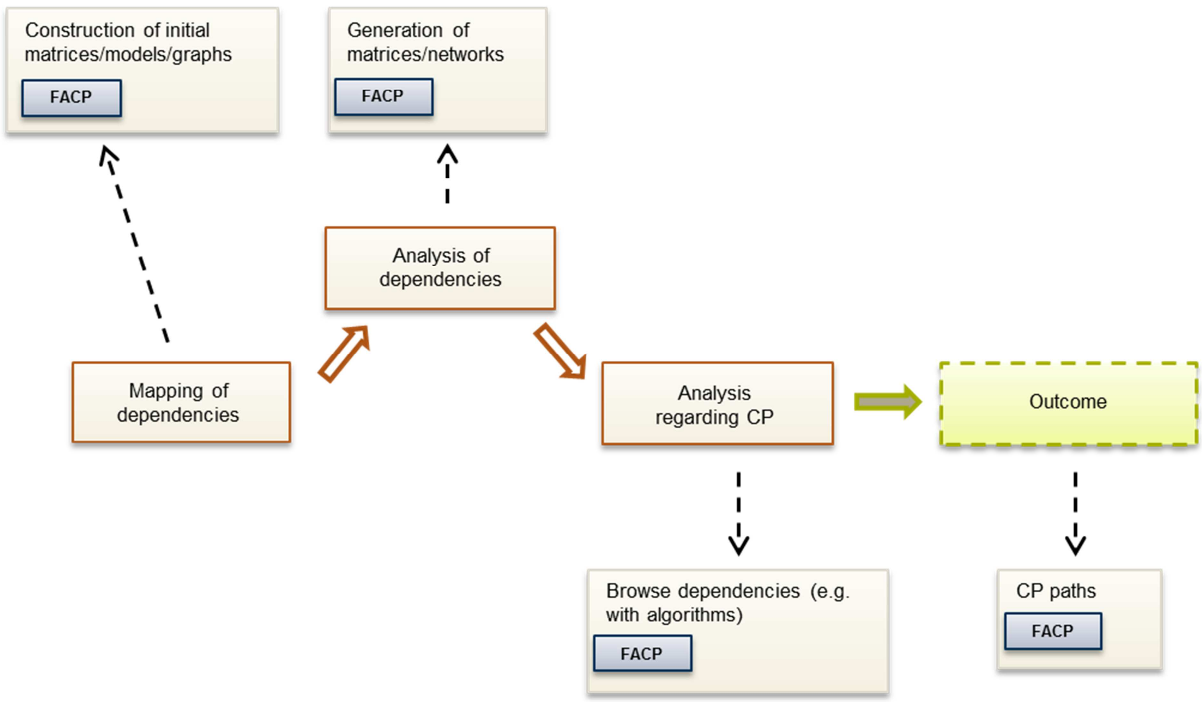


Figure 6-4: Generic process after screening of rejected methods

When looking at figure 6-3, then the output and the customers are left to be identified. Obviously, the customers of the Application-SIPOC in this evaluation study are the students from the PSSycle project which are designing the locking system for the pedelec. The output the students will expect is the output from the selected method, i.e. the Functional Analysis for Change Propagation, hence in this case various possible change propagation paths.

6.4 Summary

The evaluation which is carried out by means of the student project that developed a locking system for the pedelec is an application evaluation according to Blessing and Chakrabarti (2002) and intends to answer the following questions:

1. Is the method applicable?

2. Does the method address the central aspects?
3. Are those central aspects influenced as intended?

The Application-SIPOC only could be applied in retrospective which is why the first question cannot be answered with certainty. It is still unclear whether or not the Application-SIPOC can be used *during* the course of product development when EC become necessary and various change options are available. However, since the students documented all the occurring target deviations and EC, the Application-SIPOC could be applied and used in retrospective and therefore suggests to being able to fulfill question 1.

The central aspect of the Application-SIPOC is the alignment of a user's specific application environment to the ones from the various change propagation methods so that the most suitable method can be chosen. By analyzing the circumstances when and where the target deviations and EC occurred, the students' application environment could be quickly clarified. With the tables for comparison this application environment could be aligned with the ones from the methods, hence, filtering could take place. This means that the Application-SIPOC does address the central aspect it was intended for, i.e. question 2.

During the filtering process, the total amount of 11 methods could be quickly reduced by the chosen filtering options. As a result, only one method was left which means that this one is the most suitable method for the students' purpose and situation. Hence, the application evaluation could prove that the Application-SIPOC is indeed applicable and useable, albeit only in retrospective, and could show that the central aspects can be addressed and influenced as intended.

Having evaluated the Application-SIPOC by means of a practical setting, it can now be assessed whether or not it fulfills its requirements which are discussed in chapter 5.2. Table 6-4 once again shows said requirements and whether or not they could be fulfilled. For the procedure model to work in the first place, data must be derivable either from a populated database or from product developers that have experienced knowledge for applying the corresponding method. Since the students have sufficient knowledge in the field of matrix-building, the requirement for applying the Application-SIPOC can be fulfilled.

As already stated above, the Application-SIPOC can align the students' application environment with the ones from the various methods and the most suitable method can be chosen. Thus, requirement 2 and 3 can be fulfilled. With the thorough description of how the various methods are prepared, analyzed and classified in the Preparation-SIPOC in chapter 5.3, the PA-SIPOC² theoretically can be extended by new/other method in the field of EC propagation that might emerge in the future. However, since an application evaluation has not been carried out for the Preparation-SIPOC, a certain answer whether or not the PA-SIPOC² is extendable is still pending.

The Application-SIPOC can be carried out in a quick and easy manner and made screening through literature for change propagation methods, reading through all of them, analyzing and comparing them to each other redundant for the students to do. Hence, the Application-SIPOC is indeed beneficial for product developers of engineering products as it saves time by already providing a classified overview of the various methods on EC propagation and by providing a hand-on guide to selecting the most suitable one. Hence, requirement 5 can be fulfilled as well.

Table 6-4: Fulfillment of requirements on the Application-SIPOC

	Area of concern	Requirements		Fulfillment
Application-SIPOC	**Supplier, Input**	**1. Type of data:** Data must be derivable from a database or from an expert	→	Students can provide necessary data input for methods based on matrices
	Process, Output	**2. Alignment:** Must adjust current situation, purpose and effect desired from the user with situation, purposes and effects of methods	→	By means of the tables for comparison the situation, purpose and effect desired by the students could be aligned with the ones from the methods
		3. Selection: Must select most suitable method	→	FACP was selected to be the most suitable method
		4. Expendability: The PA-SIPOC² must be expandable by new/other methods	→	Theoretical possibility of extension by using the Preparation-SIPOC
	Customer	**5. Intended for:** Must be beneficial to product development managers and product developers of technical/engineering products	→	Redundance of screening, analyzing and comparing methods showed benefit for students

7 Discussion

After having developed a procedure model, the PA-SIPOC², and after having evaluated the Application-SIPOC, the thesis' approach and results as well as potential future work will be discussed in the following.

7.1 Discussion Regarding the Thesis' Approach

The purpose of this thesis is first to obtain an overview of the existing change propagation methods and then to develop a procedure model as a hands-on guide when ECs occur that supports product developers in choosing the most suitable method for their specific application. In order to obtain this purpose, three research questions (RQ) are formulated. The procedure of this work which was introduced in chapter 2 corresponds to these RQs that were formulated in a staged manner: RQ 1 could be answered after having conducted the first step of the thesis' procedure, the literature review. RQ 2, which builds up on RQ 1, guided the development of the first phase of the PA-SIPOC², the Preparation-SIPOC. Together with the second phase, the Application-SIPOC, RQ 3 could be answered. Hence, the procedure of this thesis suggests being suitable for answering the three research questions and to achieving the defined purpose.

However, during the evaluation of the Application-SIPOC it was discovered that the time aspect was critical to the students. That is to say that it would have been beneficial for the students to have the time it takes to conduct the individual methods included in the tables for comparison as a criterion. Hence, by incorporating a feedback loop from the evaluation to the development of the PA-SIPOC² this aspect could have been considered. For taking into account the evaluation's results and for improving the PA-SIPOC² accordingly, the evaluation would have had to be conducted earlier in the course of the thesis. However, due to timing issues among this thesis and the students project this could not be done since the results of the student project were not ready at an earlier point in time.

During the literature review key words such as '(engineering) change propagation method' were used in order to find methods that can deal with change propagation. Also, references of found papers served as a guide for the subsequent literature review. With these, methods that can indicate change propagation but that do not have it as a primary purpose could be found. The REDM, for instance, is such a method. As the authors of these methods neither use 'change propagation' in the title nor use the term in their papers those methods would not have been found with just the defined key-words. They were only found by taking into account references of already found papers. While this procedure of literature review was proven to be beneficial in the course of this thesis for finding more methods, it also suggests that it is likely that there are more methods that are able to indicate change propagation but that do not mention the term explicitly. Hence, it cannot be claimed that the found sample of methods in this work is exhaustive. In future work it could be tried to find more of these methods by further broadening the scope of the literature review.

7.2 Discussion Regarding the Thesis' Results and Future Work

The results of the evaluation discussed in the previous chapter show that the Application-SIPOC is applicable und useable in a practical setting: the tables for comparison resulting from the Preparation-SIPOC support the definition of the students' application environment by indicating the aspects they have to decide upon whether or not they are critical for their specific purpose and situation. For instance, the students had to determine that the type of underlying concept is matrix-based since that one is the one they felt competent to apply later on. Hence, by means of the tables the students can see the various choice options and can determine the ones that are important to consider.

After having clarified the application environment and what partial problems shall be solved, a quick reduction of the available methods can be achieved by using once again the tables for comparison. Only few steps are necessary to reduce the amount of methods so that only one method is left which is considered to be the most suitable method for the students' application environment. Hence, the Application-SIPOC is quickly applicable and therefore helps to save time in choosing a suitable method.

Being able to successfully apply the Application-SIPOC also implies that the results of the Preparation-SIPOC, namely the MMM schemes, tables for comparison and the generic process flowchart, are appropriate for their utilization during the Application-SIPOC. This is due to the fact that the Application-SIPOC requires the outputs from the Preparation-SIPOC; hence, the success of the former is dependent on the output from the latter. Therefore, a successful evaluation of the Application-SIPOC allows the implication that the Preparation-SIPOC's analyzes, prepares and classifies the methods in an appropriate manner for their utilization during the Application-SIPOC.

Furthermore, it could be shown that the requirements that were put on the Preparation-SIPOC and the Application-SIPOC could be mostly fulfilled. Only one requirement could not be answered with certainty: since the Preparation-SIPOC has not been evaluated separately it is unclear whether or not it is possible to extend the PA-SIPOC² by new/other methods. Thus, in future work, when new or other methods have been found, the Preparation-SIPOC could be applied and this way it can be assessed whether or not the PA-SIPOC² is extendable.

One weekness of the work is that the Application-SIPOC could only be evaluated in retrospective, i.e. not during the student project's execution. This is why assured evidence of its applicability and usability is still pending. An application evaluation in the course of a project as well as a success evaluation could be conducted in future research to further assess the PA-SIPOC²'s validity. The results from an application evaluation during a project could either strengthen the findings from this thesis' evaluation or could detect flaws that could not be discovered in this retrospective evaluation. Furthermore, additional to another application evaluation a success evaluation could be carried out in future. This could give answers to the question *how* useful the PA-SIPOC² is to product developers.

During the evaluation, the students' time was a scarce resource which is why it was important for the students to have a method at hand that won't take too much time. As already mentioned above in chapter 7.1, an indication of how much time it takes to conduct the various methods would be a beneficial choice option to be included in the tables for comparison. For this purpose, it would be required to apply all the 11 methods on the same case study in order to gain comparable results on how long it takes for them to be conducted. In future work it therefore can be attempted to find an appropriate case study so that all 11 methods can be applied and comparable time specifications for the 11 methods can be obtained. These can then be incorporated in the tables for comparison.

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. 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 correspondant 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 fulfill other criteria which were not explicitly stated in the respective papers.

Lastly, future research could test if the PA-SIPOC² can be extended by methods that were not included in the scope of this thesis. For instance, the scope was delimited to methods that deal with change propagation within companies, and not across companies. Hwang et al. (2009) for instance developed a method which deals with the representation and propagation of EC information in collaborative product development, i.e. when multiple companies are involved. Another delimitation was that change propagation methods for the software industry were not included. Future research could also include this field of application and therefore possibly broaden the applicability of the PA-SIPOC².

8 Summary and Conclusion

This thesis' purpose is to support product developers with choosing the most suitable method that can indicate change propagation with regards to the product developer's specific application environment. Hence, a procedure model, the Preparation-Application-SIPOC² (PA-SIPOC²), is developed. The PA-SIPOC² is based on Six Sigma's SIPOC (**S**upplier, **I**nput, **P**rocess, **O**utput, **C**ustomer) technique in order to provide a quick overview of a process' core elements, i.e. the people involved as suppliers and customers, required input and resulting output, and the process itself. The PA-SIPOC² provides a hands-on guide to product developers when ECs occur on what method to choose that fits the product developer's specific application environment best.

In literature there are many different methods that can deal with the subject of change propagation. Therefore, a literature search within this thesis takes place where in total 12 methods can be found. At the moment, there is no classified overview of the methods in literature that can provide deeper insights into what aspects of the various methods differ or are similar to one another. However, this is particularly important for product developers to know in order to assess the methods' appropriateness to their specific application environment and to being able to choose the one that fits best.

For that reason the PA-SIPOC² contains two phases, the Preparation-SIPOC and the Application-SIPOC. The Preparation-SIPOC provides a guide for preparing, analyzing and classifying the methods so that a structured overview can be obtained which is required for the Application-SIPOC. The Application-SIPOC, on the contrary, provides a guide to align a product developer's application environment to the ones of the methods so that the most suitable one can be selected.

The methods that were found during the 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 change propagation). For obtaining a classified overview so that comparison can take place, the first step of the Preparation-SIPOC's process suggests to analyze the methods by means of Lindemann's (2009) Munich methods modeling (MMM) schemes. This way in total 12 MMM schemes could be obtained which provide information about the methods' intended purposes, situations they are applicable to, expected outcomes, their approaches, underlying and/or supplementary methods and tools, and an indication if the method has been validated, and a graphic process flowchart.

During the second process step of the Preparation-SIPOC a classified overview can be provided so that an assessment of the methods' appropriateness to certain application environments can be enabled. Four tables for comparison, one for the methods' purpose, one for the situational aspects, one for the effects, and one for other aspects such as validation, were obtained. With these at hand, it can quickly be assessed 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.

The third step of the Preparation-SIPOC illustrates how an overview of the methods' approaches can be gained. The resultant generic process flowchart contains generic process steps with allotted clusters indicating which method utilizes the corresponding step.

The outputs of the Preparation-SIPOC, i.e. the MMM schemes, the tables for comparison and the generic process flowchart, are required for the Application-SIPOC to work. Having initially conducted the Preparation-SIPOC during this thesis, i.e. having already obtained the necessary outputs, product developers can now just apply the Application-SIPOC for identifying the most suitable method to their specific situation. However, since it is most likely that more methods on change propagation emerge in future, these can be incorporated into the PA-SIPOC² by conducting the Preparation-SIPOC.

With the results from the Preparation-SIPOC at hand, the Application-SIPOC can be applied. The first step that needs to be conducted by the product developer in order to find the most suitable method is to identify their application environment. This can be done by looking at the tables for comparison which help to indicate what kind of aspects needs to be clarified. So for instance, the product developer has to decide what purpose is desired from the method to fulfill, has to indicate in what phase of the product development life-cycle the EC occurred, etc.

Having settled the application environment, i.e. what partial problems have to be solved, a reduction of the available methods is performed. This is done by means of a Zwicky box. When one method is left after the filtering process then this one is the most suitable one and hence ready for selection and application. When more methods happen to be left after the filtering process, then there are three options for action: first, more filtering options from the tables for comparison can be chosen so that further reduction can be obtained. Second, the methods that remained after the reduction can be short listed and a look at the generic process flowchart can help to choose the method based on the preferred approach. Third, the MMM schemes of the short listed methods can be consulted for more details and the one that seems to be the most suitable can be selected, based on the product developer's own assessment.

After having developed the PA-SIPOC², an evaluation of the Application-SIPOC took place by means of a student project in order to clarify if it is applicable and useable in practical settings. The student project is part of the PSSycle project at the Technische Universität München (TUM) which develops an E-bike sharing concept similar to bike and car sharing concepts. For that purpose a standard pedelec is altered so that it is feasible for being shared. The student project's goal is to develop a locking system for the pedelec. During the development, target deviations occurred which led to seven ECs which were documented by the students. This documentation serves as a basis for the evaluation conducted in this thesis. The Application-SIPOC could successfully be applied since with only few steps the application environment of the students could be clarified, an alignment with the available methods could be done, and, as a result, one method was left which indicates that this one is the most suitable method for the students' specific application environment.

The discussion and reflection of this thesis' results shows that the PA-SIPOC² can fulfill this thesis' purpose and requirements. By means of the PA-SIPOC², screening literature for change propagation methods, reading through all of them, analyzing their content, and comparing them to each other, became redundant. This saves time and resources since now product developers can take the PA-SIPOC² and align their application environment to the ones of the methods within few steps.

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10 Abbreviations

ADVICE	Active Distributed Virtual Change Environment
C-FAR	Change Favorable Representation
CMM	Change Modelling Method
CPM	Change Prediction Method
DDM	Design Dependency Matrix
DMM	Domain Mapping Matrix
DRM	Design Research Methodology
DSM	Design Structure Matrix
EC	Engineering Change
ECB	Engineering Change Board
ECM	Engineering Change Management
ECMS	DSM-based ECM system
ECR	Engineering Change Request
FACP	Functional Analysis of Change Propagation
FFDM	Function Failure Design Method
HoQ	House of Quality
MDM	Multiple-Domain Matrix
MMM	Munich methods model (Münchener Methodenmodell)
RDIT	ReDesignIT
REDM	Risk in Early Design Method
RRM	Rapid Redesign Methodology
PA-SIPOC²	Preparation-Application-SIPOC²
PLN	PLN-based method
SIPOC	Supplier, Input, Process, Output, Customer
UFMS	Unified Feature Modeling Scheme
VCDE	Virtual Collaborative Design Environment

Appendix

A1 Original MMM

The original Münchener Methodenmodell in German, by Lindemann (2009)

Bezeichnung der Methode

Zweck	*Situation*	*Wirkung*
• Tätigkeiten im Entwicklungsprozess, die durch den Einsatz der Methode unterstützt werden • Funktion der Methode	• Anwendungsbereiche und Problemstellungen, für die der Einsatz der Methode sinnvoll ist • Rahmenbedingungen, die erfüllt sein müssen, damit die Methode die erwünschte Wirkung bringt	• Mögliche Wirkungen und Nebenwirkungen des Einsatzes der Methode • Ereignisse, Produktmodelle, Artefakte, die bei der Methodenanwendung als Ergebnisse entstehen

Vorgehen

- Schritte, die bei der Anwendung der Methode zu durchlaufen sind
- Anwendungshinweise für die Durchführung einzelner Schritte
- Regeln, die bei der Methodenanwendung zu beachten sind

Werkzeuge

- Optional – soweit sinnvoll
- Werkzeuge oder Hilfsmittel, die bei der Anwendung der Methode unterstützend eingesetzt werden können (Formblätter, Checklisten, Software etc.)

Hinweise

- Optional – soweit erforderlich
- Ergänzende Hinweise zur Methodenanwendung
- Verknüpfung der Methode mit anderen Methoden

Weiterführende Literatur | Verweis auf Abbildungen

A2 MMM Schemes of the 12 Methods

A2.1 Change Prediction Method (CPM) (Clarkson et al., 2004)

CPM
(Change Prediction Method)

Purpose	Situation	Effect
• Providing an indication for possible change propagation • Supporting the prediction and management of undesired EC propagation • Providing risk assessment: o Predicting the risk of change propagation	• Changes to an existing product resulting from: o Faults, or o New requirements • Throughout the product development process (yet: recommended as early as possible) **Marginal Conditions:** • A team of experienced product designers is required (initial matrices need to be created based on their knowledge and based on data from past design changes)	• Computerized solution • Component linkages are considered **Output**: • Quantitative risk ratings • Change propagation paths • Graphical risk scatter graphs (case risk plot)

Approach

Initial Analysis:

- Create the product model (break down the product into its sub-systems and create a component Design Structure Matrix (DSM))
- Complete the dependency matrices:
  - o Direct likelihood and direct impact matrices can be created by experienced product designers
  - o Direct risk matrix can then be obtained by combining the direct likelihood and direct impact matrices
- Compute the predictive matrices:
  - o Combined likelihood, combined impact and combined risk (combined = direct and indirect) are computed with the help of algorithms which are based on the logic of propagation trees (hereby change propagation paths become apparent)
- Product risk matrix:
  - o Resultant risk data will be presented in one single matrix where rectangles show the combined risk of change propagation (length indicates likelihood, width indicates the impact)

Case-by-Case Analysis:

- Identify initiating changes (associate new requirement with one of the product sub-systems in the product model)
- Identify predicted changes:
  - o Extract relevant data for the specific case from the complete change propagation data (s. initial analysis)
  - o Rank predicted changes in order of descending risk
  - o It is recommended that the resulting list of predicted changes is discussed within the team rather than acting as an absolute indication of changes that will take place
- Case risk plot:
  - o The likelihood and impact values (0→1) are plotted on a risk scatter graph for the sake of immediate comparison of data

Redesign based on analysis can take place (product model and direct dependency matrices shall be updated for later projects)

Tools and Methods

Based on:	Supporting Tools/Methods:
• Design Structure Matrix (DSM) • Risk management techniques	------

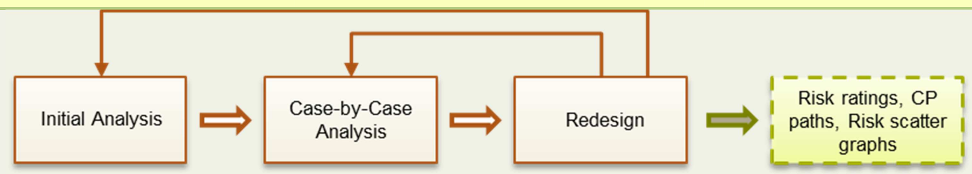
Notes

- Based on subjective assessment of designers (initial analysis)
- Recommended to have less than 50 components for the model

Validation

Validation in industry:	Other:	Results:
• Initial validation took place at Westland Helicopters: • Initial analysis: model consisted of 19 sub-systems (total time to build model: 20 hours) • Case-by-case analysis: three different cases were examined	• Furthermore: other fields of application, as for instance for the architecture of a railway valve and for the diesel engine design	• High level of agreement between predicted and observed results • However, three change scenarios cannot provide statistical validity

Process



A2.2 **Change Modelling Method (CMM) (Koh et al., 2012)**

CMM
(Change Modelling Method)

Purpose	Situation	Effect
• Providing an indication for possible change propagation • Supporting the prediction and management of undesired EC propagation • Providing an evaluation of the change influence	• Changes to an existing product resulting from: o New requirements • Focus on the change propagation effects on product attributes during the design of complex products • Shall be carried out as early in the design process as possible **Marginal Conditions:** • Expert knowledge is required (for ratings)	• Computerized solution • Component and parameter linkages are considered **Output**: • Quantitative performance ratings

Approach

Construction of MDM:
- Generate a MDM (Multiple-Domain Matrix) which is an amalgamation of DSMs and DMMs (Domain Mapping Matrices)

Rating of change options and interactions (based on HoQ):
- Assign performance ratings to the change options with respect to the product requirements (Matrix A)
  - '-5' to '5' bipolar rating scale is used
  - Direct risk matrix can then be obtained by combining the direct likelihood and direct impact matrices
- Assign ratings to the interactions between the different change option parameters (Matrix B)
  - '-1' to '1' rating scale is used ('-1' for conflicting (i.e. negative interaction) and '1' for complementing (i.e. positive interaction))
- Gather required information from design databases or through discussions

Change propagation analysis (based on CPM):
- Link the change options to relevant product components (Matrix C)
  - '1' and '0' binary scale is used ('1' if a change option is related to a given product component, '0' if not)
- Use CPM method to predict the combined likelihood of change propagation between product components by modeling the direct and indirect dependencies (Matrix D)

Revision of performance ratings with the results from the analysis:
- Link the combined change propagation likelihood of affected product components back to the relevant change options (Matrix E)
  - '1' and '0' binary scale is used ('1' if a change option is related to a given product component, '0' if not)
- Revise the performance ratings for the change options by using an equation which considers their initial performance ratings, potential interactions between relevant parameters and the combined likelihood of component change propagation
- Use the revised performance ratings to update Matrix A (feedback loop)

Selection of best change option:
- Select the best change option based on the revised performance ratings (quantitative) with:
  - the best (i.e. highest) performance rating against a given product requirement, or
  - the best overall product attributes (sum of performance ratings against all product requirements)

Tools and Methods

Based on:	Supporting Tools/Methods:
• Design Structure Matrix (DSM), Domain Mapping Matrix (DMM) • House of Quality (HoQ) • Change Prediction Method (CPM)	• Microsoft Excel spreadsheets

Notes

- Based on subjective assessment of designers
- Difference between DSM, DMM and MDM:
  - DSM: square matrices that model asymmetrical dependencies between entities of a given domain
  - DMM: non-square matrices that link related information across different domains
  - MDM: square matrix that models the dependencies within and between different domains

Validation

Validation in industry:	Other:	Results:
• Case study carried out at an aerospace company (design of a jet engine fan)	------	• Method is suitable for assessing change options during ECs

Process

Construction of MDM ⇒ Rating of change options ⇒ CP analysis ⇒ Revision of performance ratings ⇒ Performance ratings

A2.3 **DSM-based EC management system (ECMS) (Tang et al., 2008)**

ECMS
(DSM-based EC management system)

Purpose	Situation	Effect
• Providing an indication for possible change propagation • Helping designers to search for possible change propagation paths, to evaluate them and to select the optimal one • Providing an evaluation of the change influence • Aiming at obtaining a more holistic view on change propagation by: o Considering product, process and organization domain of ECs • Aiming at achieving traceability of design change routes in multi-domains	• Changes to an existing product resulting from: o Faults, or o New requirements • Throughout the product development process **Marginal Conditions:** • Experienced designers are required (knowledge needed to map item interactions in DSM)	• Computerized solution • Component and parameter linkages are considered • User can simulate and predict situation of the change result **Output**: • Graphical visualization of change propagation paths and change risk (risk scatter graphs)

Approach

Dependency acquisition:
- Study item interactions (design documents and experienced designers can help to map information flow between items)
- Build DSM representation (3 DSMs for product, process and organization domains)
- Capture direct dependencies
- Capture indirect dependencies

Dependency organization:
- Filter valuable dependency relations and classify type of dependency (e.g. level of interaction (low, medium, high), context of interaction (e.g. physical connectivity) and milestone of interaction (e.g. conceptual design, embodiment design, etc.))

EC management:
- Browse dependencies (by going through the direct dependencies in the DSM a designer can choose an instigating change)
- View change results (affected items can be identified with associated properties like type and level of change)
- Visualize change propagation (graphically display change propagation paths; risk concept of CPM can be taken into account, hence risk can be calculated and visualized)
- EC post-analysis (record frequency of typical EC for future design reuse)

Tools and Methods

Based on:	Supporting Tools/Methods:
• Design Structure Matrix (DSM) • Change Prediction Method (CPM) for risk calculation and visualization	------

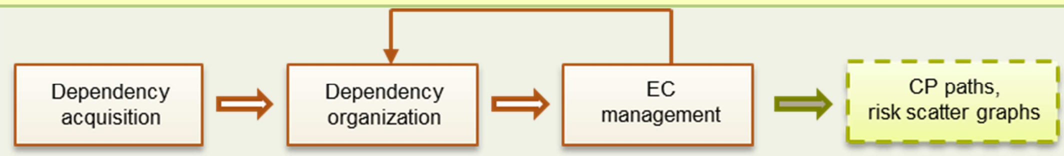
Notes

- Dependent on subjective assessment of designers

Validation

Validation in industry:	Other:	Results:
• Not yet validated in industry	------	------

Process



A2.4 **Functional Analysis of Change Propagation (FACP) (Flanagan et al., 2003)**

FACP
(Functional Analysis of Change Propagation)

Purpose	**Situation**	**Effect**

• Providing an indication for possible change propagation
• Helping designers to search for possible change propagation paths, to evaluate them and to select the optimal one
• Providing an evaluation of the change influence
	• Changes to an existing product resulting from:
	  o Faults, or
	  o New requirements
	
	Marginal Conditions:
	• Experienced designers are needed (breakdown of product)
		• Computerized solution
		• Linkages between components and functions are considered
		
		Output:
		• Change propagations paths

Approach

Construction of functional and component matrices:

- Generate a functional and component breakdown of the system and display the relations in a
  - function-function matrix (not necessarily symmetric)
  - component-component matrix (symmetric)
- Build component-function matrix
  - This matrix can be derived from the former two matrices (features are to be considered)
- These 3 matrices serve as input for the computer program which generates a connectivity matrix

Generation of direct connectivity matrix:

- Connectivity between multiple features within one component
  - The system generates a matrix indicating which component -function pairs (features) are connected (by masking the component-function matrix over the function-function matrix)
- Connectivity between components
  - By masking the component-component matrix over the component-function matrix, the direct connectivity of different components that perform a common function can be found
- Direct connectivity matrix can be generated

Identification of change propagation paths:

- Direct connectivity matrix is used to identify change propagation paths between the different features
- Numbers of possible paths can be reduced by the user (can specify precedence relationships between components)
- Routes can be queried by the user
- User can evaluate the validity of certain links in the context of the proposed modification

Tools and Methods

Based on:	**Supporting Tools/Methods:**
• Design Structure Matrix (DSM)	------

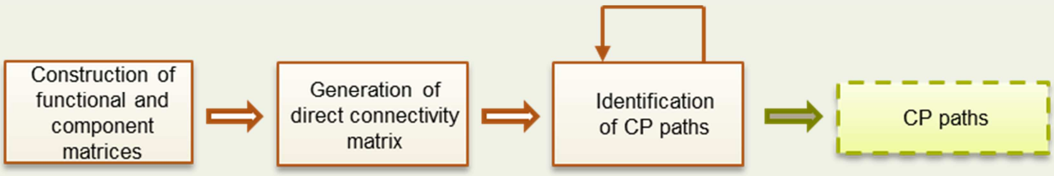
Notes

- Dependent on subjective assessment of designers
- Generating all possible paths can be overwhelming and should therefore be limited by specifying precedence relationships between components

Validation

Validation in industry:	**Other:**	**Results:**
• Not yet validated	------	------

Process



A2.5 **Rapid Redesign Methodology (RRM) (Chen et al., 2007)**

RRM
(Rapid Redesign Methodology)

Purpose	Situation	Effect
• Searching for and evaluation of possible redesign plans • Reducing computing effort in redesign practice when dealing with complex redesign problems: o Advocating re-computing over only those portions of the design model that require it instead of whole entire design model o Expediting the redesign solution process	• Changes to product in the course of a redesign project • Suitable for complex products **Marginal Conditions:** • Experienced designers are needed (breakdown of product)	• Computerized solution • Functions and components are considered **Output**: • Redesign pattern solutions (redesign roadmap)

Approach

Construction of DDM:
- Map the dependencies of elements in a first DDM (Design Dependency Matrix)

Design dependency analysis:
- Reorganize the input DDM by analyzing the functional dependencies and couplings inherent in the design model with the help of:
  - cluster formation: arrange rows and columns of input DDM so that the 1 elements are brought close to another to form clusters
  - cluster alignment: arrange formed clusters along the main diagonal so that possible overlapping between clusters can be checked (i.e. couplings or interactions)
- This way either an uncoupled matrix can be obtained (no overlapping), or a banded diagonal matrix (overlapping) which will require further partitioning to reveal exact patterns that are possible

Redesign partitioning analysis:
- Transform banded diagonal matrix into multiple (unique) redesign pattern solutions by using certain matrix partitioning algorithms

Pattern selection analysis:
- Evaluate and quantify the different pattern solutions by deriving two matrix pattern metrics:
  - Intensity metric: estimates the scale of redesign potentially involved in improving the deficient performance levels (i.e. considers location and distribution of target entities in a redesign pattern solution)
  - Interdependency metric: estimates the redesign propagation potentially induced due to coupling (i.e. considers overall interaction between the blocks in a redesign pattern solution)
- Select optimal pattern solution (i.e. the one which entails the least potential redesign effort)

Tools and Methods

Based on:	Supporting Tools/Methods:
• Design Dependency Matrix (DDM)	------

Notes

- Dependent on subjective assessment of designers
- DDM: rectangular matrix that represents the dependency relationships between two sets of elements

Validation

Validation in industry:	Other:	Result:
• Validation on a vehicle powertrain, mechatronic motor systems	------	• The RRM methodology is applicable and suitable and can significantly and consistently reduce the computing effort in redesign practice

Process

A2.6 **ADVICE (Kocar and Akgunduz, 2010)**

ADVICE
(Active Distributed Virtual Change Environment)

Purpose	Situation	Effect
• Providing an indication for possible change propagation • Supporting the prediction of undesired EC propagation • Reducing dependence on expert knowledge: o Instead: using information from the database to check if there has been a similar change in the past to facilitate current ECR handling • Improving the ECM process by providing both textual and graphical information • Prioritization of ECs and storing details of ECRs for the future (so that past experience won't be forgotten)	• Changes to an existing product resulting from: o Faults, or o New requirements • During the course of ECM • Throughout the product development process **Marginal Conditions:** • Database with previous ECR data is required (the more history the better) • 3 sources of information required: BOM tables (in MRP/ERP database), Product Structure (PS) database (CAD systems), ECR database	• Fully computerized solution • Functional and parameter linkages are considered • Non-technical members of the Engineering Change Board can use the method • Reduces redundant activities **Output**: • A shared, real-time, simulated 3D representation of EC

Approach

Initiated Engineering Change Request:
- ECR is issued through 3D graphical representation and the initiator has to state a reason for the request (reason codes)
- Systems checks if there is a similar change in history and stores ECR in database (if change is already in process then ECR gets rejected)

Prioritization Agent:
- After the ECR got confirmed, the Prioritization Agent prioritizes the ECs according to their impact on the product structure (PS) in a company's product range
- AprioriAll algorithm is used in order to identify sequential change patterns (that are frequent among the PSs in the data history) which are then used to calculate Priority Indices which in turn are then transformed into Priority Codes
- Every ECR gets a Priority Code ranging from 'A', 'B' and 'C'
- When the ECR go approved, every member of the Engineering Change Board gets access to the ECRs in their responsibility in ascending order of priority and time

Change Propagation Agent:
- Before an ECR notification is released, the Change Propagation Agent gives warnings for possible change propagation
- MINEPI algorithm is used to first search for transactional change sequences and then to come up with potential patterns and frequency of occurrences (probabilities) following an EC
- Those probabilities of possible patterns are then transformed into one of the color codes 'RED', 'YELLOW' and 'GREEN'
- Components that are highly likely to be changed due to an ECR are marked 'RED' (can be graphically seen in the 3D models)

Tools and Methods

Based on:	Supporting Tools/Methods:
• Virtual Collaborative Design Environments (VCDE) • Sequential Pattern Mining	------

Notes

- Populating the ADVICE database is vital for effectively using the proposed ECM system
- Based on three approaches: ECM, VCDE and Sequential Pattern Mining (using AprioriAll and MINEPI algorithms)

Validation

Validation in industry:	Other:	Results:
• Not yet validated in industry	• Validation of Prioritization Agent and Change Propagation Agent in an experiment where 4 PS of office tables were generated (number of components <30)	• Results considered as satisfactory for validating the agents

Process

A2.7 The Risk in Early Design Method (REDM) (Grantham Lough et al., 2006)

REDM (Risk in Early Design Method)

Purpose	Situation	Effect
• Reducing dependence on expert knowledge (by using a more automated risk generation) • Providing risk assessment: o Based on archived knowledge of past failures o Identifying and then communicating risks of future failures o Predicting the risk of change propagation	• Changes to an existing product resulting from: o Faults • Conceptual design phase (before the physical form of the product has been decided) **Marginal Conditions:** • Database populated with past failure reports is required	• Computerized solution • Functional linkages are considered • Aid for novice designers who are lacking experience with past failures **Output**: • Graphic 'risk grid' or 'risk fever chart' for the sake of communication among the designers

Approach

RED database population:
- Gather failure reports from various products and record them in a database

Functional modeling:
- Generate a functional model of the product

Product function-failure matrix (FFDM):
- Compile a list of the product functions from the functional model
- Create a function-component (EC) matrix and a component-failure (CF) matrix
- Derive the function-failure (EF) matrix: EF = EC x CF

Risk calculations:
- Translate the information obtained with the FFDM with the four different formulae of the RED method into categorized risk likelihood
  - o The likelihood mappings ('low'-'high')
    - identify the specific function-failure combinations
    - rank the frequency of historical failure mode occurrence by function
- Use the catalogued failure severity information to calculate the risk consequences ('1'-'5')

Risk result communication:
- With the risk calculations four pieces of information of product risk can be derived (i.e. function, failure mode, consequence, likelihood)
- Plot these four items on risk fever charts for easy communication ('green', 'yellow' and 'red')
- Experts shall apply their knowledge to tailor the results to make them more accurate as the RED serves more as a preliminary risk assessment

Tools and Methods

Based on:	Supporting Tools/Methods:
• Function Failure Design Method (FFDM) approach • Risk assessment	------

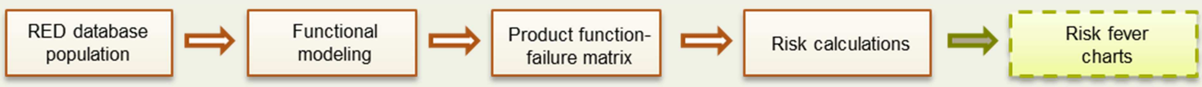
Notes

- RED is an extension to the FFDM approach which links product function to historical failures

Validation

Validation in industry:	Other:	Results:
• Not yet validated in industry	------	------

Process



A2.8 **Information Model (Mohktar et al.,1998)**

Information Model

Purpose

- Providing an indication for possible change propagation
- Providing an evaluation of the change influence
- Providing support to improve the design coordination process through better management of design changes
- Informing affected designers by a change made by other designers by assigning the propagation of design changes task to the building components themselves
- Tracking past design changes and planning/scheduling future ones

Situation

- Intended for the construction industry
- During the detailed design phase
- When information needs to be transferred across disciplines (i.e. when output serves as input for others)

Marginal Conditions:

- Project database is required (consisting of a building components database and a management database)

Effect

- Computerized solution
- Component is responsible for forwarding design change propagation instead of designers

Output:

- Automatically sent messages (to designers) which contain relevant information about the change
- Change paths

Approach

Configuration of model:

- Assemble the data structure of the building components using the configuration module
- Specify links between the building components with the help of prebuilt and dynamically built rules
    - Prebuilt: captured at the beginning of the detailed design phase (i.e. during the configuration of the model)
    - Dynamically built: captured 'on the fly' during the preparation of detailed drawings and the use of the model

Propagation of design changes:

- Perform a change to a building component attribute:
    - The component checks prebuilt and dynamically built rules if any of these apply to the change
    - If it does, then a message is automatically sent to the affected designers (message contains information about changed attributes and building components and provides guidelines on how to react to the design change)

Tracking Module:

- Retrieve design changes that are made by a discipline to a building component
- See all the automatically messages that have been sent by a specific building component

Planning and scheduling design changes:

- Let display possible change paths for future changes so that alternative change solutions can be assessed concerning interrelated design changes, required man-hours, impact on construction costs, etc.

Tools and Methods

Based on:

- Model modules are implemented in the software environment LEVELS Object
- Database is structured in MS ACESS

Supporting Tools/Methods:

Notes

- The success of the model largely depends on the linkage knowledge that is captured from the designers
- Questionable if model is also applicable to product development of technical/mechanical products

Validation

Validation in industry:

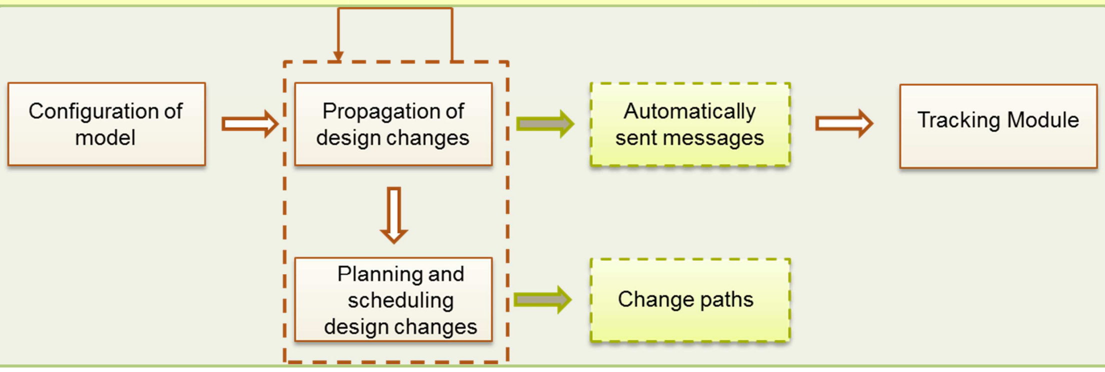
- Not yet validated in industry

Other:

- Validated with a case study from literature (design changes that occurred in the case study were performed in the model)

Results:

Process



A2.9 **Unified Feature Modeling Scheme (UFMS) (Ma et al., 2007)**

UFMS
(Unified Feature Modeling Scheme)

Purpose	Situation	Effect

• Providing an indication for possible change propagation
• Aiming at obtaining a more holistic view on change propagation by:
  o Managing product lifecycle stages as a coherent whole as they are inter-related and mutually constraining
  o Representing the whole product information model as a dependency network
• Aiming at maintaining the validity and consistency of the product models in collaborative and concurrent engineering more efficiently
	• Across product lifecycle stages (especially across conceptual design and detail design)
	• Concurrent engineering
	
	Marginal Conditions:
	• Central database is required for storing the associations
	• Experienced designers are needed (construction application feature models)
		• Computerized solution
		• Functional and parameter linkages are considered
		
		Output:
		• Change propagation chains
		• Permission or rejection of change

Approach

Construction of application feature models:

- Generate a conceptual design feature model:
  - o Consists of abstracted critical faces, constraints, and other specifications (functions and behaviors)
- Generate a detail design feature model:
  - o Specified conceptual design features are associated with the corresponding detail design features (relative position, orientation, motion, connection and fit relations)
  - o These corresponding reference or refinement associations are registered in the *UnifiedFeatureModel* object
- Generate a process planning feature model:
  - o Derives from the detail design feature model according to design specifications, available manufacturing resources and user-specified objectives (e.g. cost or time)
  - o These corresponding reference or refinement associations are registered in the *UnifiedFeatureModel* object

Construction of JTMS dependency network:

- Two types of associations:
  - o Constraint-based associations (describe geometric and non-geometric dependency relations between entities)
  - o Sharing associations (represent that two features refer to the same geometric or topological entities)
- Record the constraint-based associations in a JTMS dependency network (one each for the conceptual design and detail design phase)

Change Propagation Algorithm:

- When a designer makes a change the algorithm for change propagation uses the dependency network to find out the affected features

Tools and Methods

Based on:	Supporting Tools/Methods:
• Justification based Truth Maintenance System (JTMS)	------

Notes

- JTMS dependency network:
  - o Plain squares to represent entities (e.g. functions, features, feature properties)
  - o Squares with round corners represent constraints or rules
  - o Circles represent justifications
  - o Arrows are directed from antecedents to justifications, and further to consequents

Validation

Validation in industry:	Other:	Results:
• Not yet validated in industry	------	------

Process

A2.10 **Change Favorable Representation (C-FAR) (Cohen et al., 1999)**

C-FAR
(Change Favorable Representation)

Purpose	**Situation**	**Effect**
• Providing an indication for possible change propagation • Supporting the prediction of undesired EC propagation • Providing an evaluation of the change influence	• Changes to an existing product resulting from: o New requirements **Marginal Conditions:** • An expert for the C-FAR construction is required (knowledgeable in the field of schemas)	• Computerized solution • Parameter linkages are considered • User does not have to have knowledge in EXPRESS or data modeling **Output**: • Graphical paths • Quantitative scale of influence

Approach

C-FAR construction:

- Prepare the EXPRESS data schema so that the incorporation of C-FAR matrices can be facilitated
- Break down products into their entities and build up the C-FAR matrix by mapping the relations among their attributes
    - o Number of rows and number of columns represent the number of attributes of the entities
    - o Intersection shows the linkage value (‘high’, ‘medium’ or ‘low’)
    - o Domain experts are responsible for building the matrices

C-FAR usage:

- Present changeable elements and choose change source and change target
- Check if source entity and target entity are connected and, if they are, then show C-FAR paths (i.e. which entities the paths go through)
- Utilize linkage values from C-FAR matrices to calculate the linkage value interval
- Result interpretation
    - o C-FAR results range from 0 to 0.9 (with 0 meaning no influence and 0.9 strong influence)
    - o C-FAR selects a simple path set which will give the user more insights into possible change propagation and what elements are involved in the change

Tools and Methods

Based on:	**Supporting Tools/Methods:**
• EXPRESS information model (which defines its artifacts as objects/entities, which in turn are described by their attributes) • Standard for the Exchange of Product (STEP) data model	------

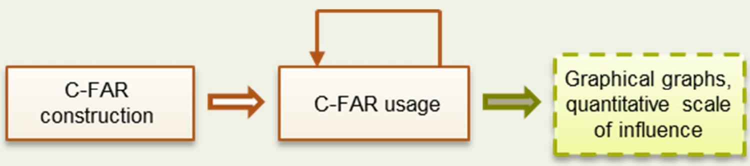
Notes

- Based on subjective assessment of designers (C-FAR matrix)
- Construction only needs to be carried out once and later usage is independent from it
- Appropriate for rather small or simple products (due to its computational complexity)
- An inaccurate EXPRESS model will influence the C-FAR results

Validation

Validation in industry:	**Other:**	**Results:**
• Validation in industrial case studies with a car bumper, an injection molding and a printed wiring board • In total more than 10 scenarios and more than 100 change consequences were tested	------	• C-FAR estimation of impact of change matched the consulted expert in more than 80% of the cases

Process



A2.11 **ReDesignIT (RDIT) (Ollinger and Stahovich, 2001)**

RDIT
(ReDesignIT)

Purpose	**Situation**	**Effect**
• Providing an evaluation of the change influence • Helping designers in finding a set of possible redesign plans to achieve the design goal o Generating and evaluating proposals of redesign plans for engineered devices by using a computer program which uses model-based reasoning o Listing certain and probable side effects of change possibilities and identifying ways to remedy these side effects	• During the first stages of a redesign project • Particularly useful for modifications to large scale engineered systems **Marginal Conditions:** • Experienced designers are required (construction of directed dependency graph)	• Computerized solution • Parameter linkages are considered • Redesign plans can indicate how undesired side-effects can be counteracted • Redesign plans are ranked according to their effectiveness **Output**: • Several possible redesign plans (by which the target change can be achieved)

Approach

Construction of directed dependency graph:
- Identify relevant physical quantities, list causal relationships between those quantities and construct a directed dependency graph (magnitude of the causal relationships is described in qualitative measures ‘low’, ‘zero’ and ‘high’)

Search for possible redesign plans:
- When a redesign task becomes necessary, then the program will search for ways to achieve it by identifying quantities in the graph
  - that have a causal influence on the specified performance goal and
  - whose values can be directly set by the designers (= exogenous quantities)
- The program will suggest changes that have a positive causal influence on the performance goal

Counteracting undesired side effects:
- As undesired side effects may arise (e.g. further changes to other quantities) the program will search for additional exogenous quantities that can counteract the undesired side effects caused by the initial change
- Ideally, this search for additional quantities stops when there is a redesign plan in which all side effects are counteracted

Tools and Methods

Based on:	**Supporting Tools/Methods:**
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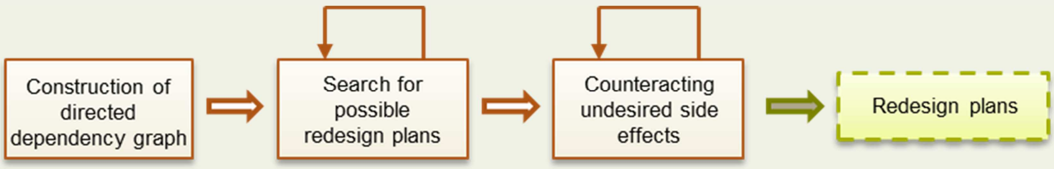
Notes

- The obtained redesign plans are rather abstract (they specify which quantity should be changed and in which direction it should be changed)

Validation

Validation in industry:	**Other:**	**Results:**
• Not yet validated in industry	------	------

Process



A2.12 **PLN-based method (PLN) (Yang and Duan, 2011)**

PLN
(PLN-based method)

Purpose	Situation	Effect
• Providing an indication for possible change propagation • Helping designers to search for possible change propagation paths, to evaluate them and to select the optimal one • Providing an evaluation of the change influence	• Changes to an existing product resulting from **Marginal Conditions:** • A team of designers is required to obtain an optimized PLN model	• Parameter linkages are considered • When PLN is flawed then false change propagation paths might emerge or critical ones might not get detected **Output**: • Change propagation paths

Approach

Construction of the PLN model:

- Analyze the linkages between the parameters and develop a PLN model (differ between constraint linkages (can be influenced by designers) and fundamental linkages (cannot be changes by designers))
- Done by a team of designers, preferably from different disciplines
- Transform constraint linkages into fundamental ones in order to obtain a simple PLN model with a clear hierarchical structure

Classification of parameters in PLN:

- Classify parameters into:
  - o direct parameters which can be adjusted by designers (e.g. can be the geometry of a product)
  - o target parameters which cannot be adjusted directly, only indirectly by changing direct parameters (represent design specifications)
  - o transition parameters which are subject of change propagation and describe how direct parameters can determine target parameters

Search for change propagation paths:

- Iterate through the algorithm for searching as many possible change propagation paths as possible

Evaluation of change propagation paths:

- Evaluate the paths and select optimal one and take it as a final change solution

Tools and Methods

Based on:	Supporting Tools/Methods:
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Notes

- Based on subjective assessment of designers
- Not yet ‘ready’ for complex designs
- A computer support tool for this method is under development

Validation

Validation in industry:	Other:	Results:
• Not yet validated in industry	• Validated in a simple case study (only a few coupled parameters) with data collected from related literature	------

Process