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PROCEDURE MODEL FOR THE INDICATION OF CHANGE PROPAGATION

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1. Introduction

Engineering changes (EC) occur within the product development and account for up to 50% of its capacities [Lindemann 1998]. Despite the fact that ECs are necessary to improve a product's quality and that they often are the source for innovation [Fricke 2000], ECs are also costly and bear the risk of propagating further through the product. Propagation occur when a change to one part of the system will trigger subsequent changes in other parts [Yang 2011]. In recent years, many methods on change propagation have been developed which aim at supporting designers assessing alternative change options. These methods, however, often apply to different scopes and intend at answering different questions, which makes it difficult to know which one to choose for one's own specific situation. 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. Thus, 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. Therefore, this work's objective is to develop a procedure model for product developers that can be used as a guide to decide what method for EC propagation fits best to their specific application environment and shall therefore be chosen.

This paper's definition of ECs is based on the definitions from Jarratt et al. [2011] and Conrat [1998]: 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 paper's definition of EC propagation is based on Tang et al.'s [2008] and Koh et al.'s [2012] definition: 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.

2. Research methodology

In order to be able to assess what method suits a product developer's specific environment best, first the various methods on EC propagation needed to be researched and analysed. This was already done in a former study of Helms et al. [2014]. This work first conducted a thorough literature review where in total eleven methods aim for the indication of EC propagation. These methods are shortly introduced in chapter 3. Then, these methods were analysed with regards to their content in order to obtain a classified overview for the purpose of a comparison. This analysis took place by means of Lindemann's [2009] Munich methods modelling (MMM) schemes which enable to extract relevant information from the papers regarding the methods' intended purposes, situations they are applicable to, expected outcomes, their approaches, underlying methods/tools, and a graphic process flowchart. Hence, Helms et al. [2014] prepared eleven such MMM schemes, one for each method. Then, the authors merged the information in the MMM schemes into four tables to compare the methods' purpose, situation, etc. With these tables for comparison a classified overview could be obtained that enables quick assessment what methods, for instance, map component linkages or parameter linkages, which ones are applicable throughout the whole product development process, or which ones are limited to only early stages of the product development process, etc. The authors furthermore prepared a generic process flowchart that visualises the main steps of the methods' approaches so that a product developer can quickly get an idea of what methods have similar steps to one another.

This paper's work uses the outcome from Helms et al.'s [2014] work, i.e. the eleven MMM schemes, the four tables for comparison, and the generic process flowchart, for the procedure model that supports product developers in choosing the most suitable method on EC propagation for their specific application environment (described in chapter 4). After having developed said procedure model, it is evaluated by means of a student project in order to clarify its applicablilty and useablity 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. In chapter 5 the student project is described in more detail as well as the conducted evaluation.

3. State of the art – change propagation methods

As mentioned above, Helms et al. [2014] conducted a literature review in order to find methods that can indicate EC propagation. In total eleven such methods are found which are shortly described in table 1, clustered in methods that are matrix-based, that require a database, or that are based on other underlying concepts.

Table 1. Description of the eleven EC propagation methods

	Method and Author	Description
Matrix-based Methods	**Change Prediction Model (CPM)** Clarkson et al. [2004]	The CPM uses the DSM to map the dependencies between a product's components and then uses risk management techniques to predict the risk of an EC propagating further through the product.
	Change Modelling Method (CMM) Koh et al. [2012]	Based on the CPM and on the House of Quality (HoQ) by Hauser and Clausing [1988], the CMM generates potential change propagation paths that are possibly triggered by different change options and assesses them on their effect on product attributes so that the optimal change option can be chosen by the designer.
	DSM-based EC management system (ECMS) Tang et al. [2008]	The ECMS includes an additional information field next to the DSM where details to the property of dependency can be noted, such as type of dependencies (e.g. material or geometry), and dependency strength. Besides a DSM for the product domain, two additional DSM representations are built, one for the process and one for the organization domain in order to provide a more holistic and comprehensive view on change propagation.
	Functional Analysis of Change	Based on the DSM, the FACP shall help designers in finding

	Propagation (FACP) Flanagan et al. [2003]	possible change propagation paths, evaluating those and then enabling selecting the optimal one, while not only considering dependencies between components, but also functional relations.
	Rapid Redesign Methodology (RRM) Chen et al. [2007]	The RRM is a pattern-based decomposition methodology for rapid redesign that locates only the parts of the design model that have to be recomputed in order to meet the redesign requirements which makes recomputing the whole model redundant.
Methods requiring a Database	**Active Distributed Virtual Change Environment (ADVICE)** Kocar and Akgunduz [2010]	ADVICE shall improve the ECM process by providing textual and graphical information to the designers in a shared, real-time, simulated 3D representation of EC so 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.
	Risk in Early Design Method (REDM) Grantham Lough et al. [2006]	The REDM performs risk assessment before the physical form of a product has been decided, i.e. in the conceptual design phase, and is an extension to the Failure Function Design Method (FFDM) which links product functions to historical failures.
	Unified Feature Modeling Scheme (UFMS) Ma et al. [2008]	The UFMS models associative engineering relations in a unified feature modeling scheme to obtain information consistency control between the different applications of the various product lifecycle stages so that change propagation across the stages can be made more efficient.
Methods Based on Other Underlying Concepts	**Change Favorable Representation (C-FAR)** Cohen et al. [2000]	C-FAR aims at facilitating change representation, propagation as well as qualitative evaluation by extracting information from the Standard for the Exchange of Product (STEP) data model in order to make changes more easily traceable. C-FAR considers a product's dependencies on the attribute level.
	ReDesignIT (RDIT) Ollinger and Stahovich [2001]	RDIT is intended to be used during the first stages of a redesign project and generates and evaluates different proposals of redesign plans. The program ranks the different redesign proposals concerning their effectiveness and indicates how undesired side effects, i.e. change propagation, can be counteracted.
	PLN-based Method (PLN) Yang et al. [2011]	PLN is a method for searching change propagation paths by considering parameter linkages in order to help designers in finding optimal change solutions. By iterating through an algorithm change propagation paths can be searched and evaluated in order to find the optimal path.

4. Procedure model

As mentioned in chapter 2, the methods that were found during the literature review were analysed and classified in the work conducted by Helms et al. [2014]. The outcome of that analysis and classification is necessary for the procedure model developed in this work, called the Application-SIPOC. The Application-SIPOC shall support product developers in choosing the most suitable method for the prediction of EC propagation. The single steps of the Application-SIPOC is designed based on Six Sigma's SIPOC (Supplier, Input, Process, Output, Customer) technique 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]. The SIPOC concept is adapted for this thesis' procedure model 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. The Application-SIPOC, which can be seen in figure 1, explains how product developers can use the results from the analysed and classified methods from Helms et al.'s [2014] work, to adjust their specific application environment to the ones from the various methods in order to select the most suitable one. In the following, the Application-SIPOC's single components will be explained in more detail.

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 1). The eleven methods either require a populated database or experts who can break down the product into its components and who can map its dependencies. Hence, 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, databases or experts are considered as suppliers in this context and the provided data as input. What kind of databases or what kind of expert knowledge is required depends on the method that will be selected.

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 1, the alignment takes place by using the four tables of comparisons and the generic process flowchart. Due to the user's specific application environment not all of the eleven methods are equally suitable. For instance, 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 application environment with the ones from the methods, the four tables for comparison prepared in Helms et al. [2014] are needed. These tables are labelled 'purpose', 'situation', 'effect' and 'tools and methods' and contain criteria which derived by comparing the respective sections in the eleven individual MMM schemes. As mentioned in chapter 2, Helms et al. [2014] used the MMM schemes, developed by Lindemann [2009], to analyse the various methods in a consistent manner so that a structured overview is obtained, allowing a structured comparison. With the MMM schemes the methods are analysed with respect to the purpose which they aim to fulfil, the situation in which they can be applied, their expected effects, the general approach, underlying tools and methods, and a graphic process flowchart that provides a quick and visual overview of the main steps of the method's approach. That is to say, that, for instance, the criteria listed in the 'purpose' table of comparison derive from the content of the purpose section of the MMM schemes, the criteria in the 'situation' table derive from the situation section, etc. Hence, these tables of comparison are now needed for aligning the product developer's specific application environment (see figure 1). With the tables for comparison the product developer can see the feasible methods to their current situation and intention.

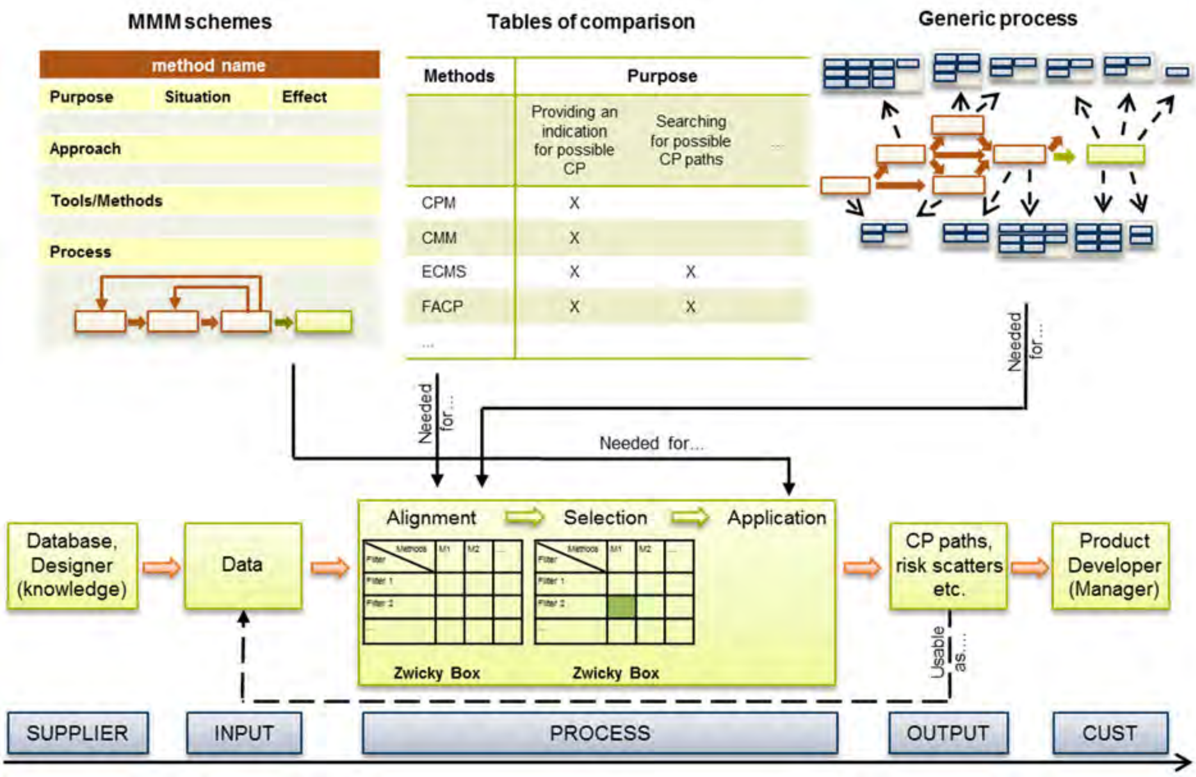

Figure 1. The Application-SIPOC

With these tables of comparison, the product developer can now analyze his own situation by, for instance, answering these following questions (which respond to the criteria in the tables):

- 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?
- 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?

This sample of questions support product developers to identify and specify their own application environment. With the tables for comparison the users see the feasible methods to their current situation and intention. Helms et al. [2014] furthermore prepared a generic process flowchart (see figure 1) that merged the steps of the individual process flowcharts from the eleven MMM schemes into one generic flowchart. For that purpose, overlapping components in the individual process flowcharts were identified, generic wording was generated for the considered similarity among the methods' approaches, and the methods that have the considered component incorporated in their approach were allotted by arrows, assembled in clusters. Hence, by taking this generic process flowchart into consideration, the product developer can identify the main steps of the methods' approaches and thus eliminate the methods whose steps would be out of question.

By means of a Zwicky box the number of possible alternative solutions can be decreased [Zwicky 1966]. 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 top rows of the tables of comparison under the heading, such as 'providing an indication for possible CP' or 'searching for possible CP paths' which indicate two partial problems (see figure 1). 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 1, 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 1 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. 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 1).

5. Evaluation of the procedure model

After having developed the Application-SIPOC, its evaluation took place by means of data from a student project which was carried out within the PSSycle project at the Technische Universität München (TUM) within the Collaborative Research Centre "Sonderforschungsbereich 768 – Managing cycles in innovation processes – Integrated development of product-service-systems based on technical products" (www.sfb768.tum.de). The project as well as the evaluation and the results will be presented in the following.

5.1 Description of PSSycle

Within the PSSycle project at the TUM an e-bike sharing system is to be developed similar to the bike sharing concepts that already exist in multiple large cities. By using an e-bike long distances can be overcome faster than with regular bikes while being more cost-saving than cars. In the PSSycle project, a standard e-bike was bought and was altered so that it is feasible for being shared. This was done by embedding board electronics, a board computer and a locking system into the pedelec (see figure 2). The board computer is a smartphone with software that interacts with the server infrastructure. With the board computer the users register themselves, log in as a member, and, during utilization, 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.

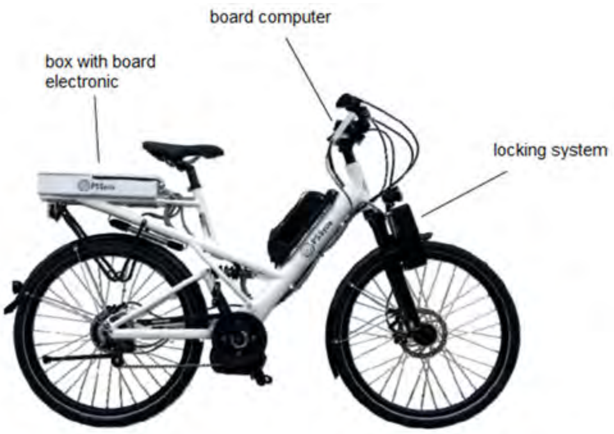

Figure 2. Pedelec with board computer, board electronics and locking system

A student sub-project within PSSycle aimed at developing a feasible locking system prototype for the e-bike that had to fulfill the following requirements:

- 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.

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.

5.2 Conducting the Application of the procedure model

Since it was not possible for the authors 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. 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 analyzed. 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 eleven 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. Analysis of the target deviations showed that all target deviations occurred in the detailed design phase and affected the functional dimension of the locking system. Anaylsis of the ECs showed that 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. After having analyzed the target deviations and ECs, implications concerning the students' application environment can already be drawn and a reduction of the total amount of possible methods can take place (see Zwicky box table 2): 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. 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. This leaves the matrix-based methods (CPM, CMM, ECMS, FACP, and RRM).

Table 2. Zwicky box for the selection of most suitable method

Filter \ Method/Model	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	∑
	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

As the target variations concerned the locking system's functions, only the FACP and the RRM are left for being chosen as these are the only ones that can map functional relations. As the method has to be applicable during the detailed design phase, only methods which are not restricted to the early design stages, e.g. conceptual design phase, can be chosen. Both, the FACP and the RRM, can be applied in the detailed design phase. 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. As the RRM cannot fulfill this purpose, it has to be rejected which leaves the FACP as the most suitable method for the students' application environment. For the students being able to apply the method, they would have to have a look at the corresponding MMM scheme, but also at the specific paper from Flanagan et al. [2003] since this provides all the details about the approach. 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. Discussion and conclusion

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 to a user's specific application environment 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 the comparison this application environment could be aligned with the ones from the methods, hence, filtering could take place. During the filtering process, the total amount of the eleven 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. The Application-SIPOC could furthermore 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.

A limitation of this 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 evaluation in the course of a project could be conducted in future research to further assess the Application-SIPOC's validity. To further strengthen the evaluation, future work could also focus on validating the Application-SIPOC in a real world scenario instead of in an universitary setting. Such a validation could assess whether or not the Application-SIPOC could actually benefit industry. 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 Application-SIPOC is to product developers. In order to be able to assess its benefits in a quantitative way, such a validation could be carried out twofold: one product developer could select a method for his application environment by making use of the Application-SIPOC, and another product developer could select a method without such help, hence by simply reading all the corresponding papers. This approach would allow to evaluate and to compare the time required to make a method decision and can thus indicate how useful the Application-SIPOC is to industry. The results from an industry evaluation could either strengthen the findings from this work's evaluation or could detect flaws that could not be discovered in this work's retrospective evaluation within an universitary setting.

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. 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 eleven 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 eleven methods can be applied and comparable time specifications for the eleven methods can be obtained. These can then be incorporated in the tables for comparison.

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