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SPECIFICATION RISK ANALYSIS: INTRODUCING A RISK MANAGEMENT METHOD FOR PRODUCT ARCHITECTURES

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1. Introduction

This paper introduces a method to identify and mitigate potential deficiencies of a product architecture. The risk management method was developed on the basis of the Failure Mode and Effect Analysis (FMEA) and is suitable for the phase of embodiment design.
Successful product development is determined by the fulfillment of customer needs through a product under constraints of time, cost, and quality [Lindemann 2006, Ulrich & Eppinger 2003]. Risk or uncertainty adds a forth dimension that is difficult to address [Crawley et al. 2004]. According to Browning et al. [2002], risk is a qualifier on schedule (time), cost, and performance (quality). Effectively managing risks in new product development can reduce the likelihood of cost, schedule, and performance deviations during execution. Risk management therefore is tightly connected to the success of a product development process. Managing product development processes thus requires a reliable method for assessing the risks and challenges of the product to develop. Unfortunately, only a very limited number of work methods exist which facilitate this.

2. State of the Art

As product development is a combined task to create information and as it is influenced by numerous factors [Lindemann 2006], various uncertainties exists. Many risks inherent in a product and/or the development process are defined with the product architecture. The architecture of a product is elaborated in the phase of embodiment design, a term coined by Pahl & Beitz [2006]. In this phase, requirements are incorporated into the design and the physical layout of the product is elaborated. Numerous aspects are not defined until then and the phase is crucial for the later success of the product.
Ulrich [1995] defines architecture as the arrangement of functional elements, the mapping from functional elements to physical components, and the specification of the interfaces among interacting physical components. During embodiment design, the overall risk of potential product deficiencies is high (see Figure 1). As design work proceeds, certainty increases that the evolving product design will achieve the objectives [Browning et al. 2002]. With increasing availability of information, the overall risk in product development decreases. Arguing that the ability to influence costs decreases as the product development process proceeds, it is important to identify and mitigate potential deficiencies as early as possible.
In embodiment design, various decisions affect costs, schedule, and performance of the later product. A survey conducted in the automotive industry pointed out that the final state of a product is determined by how successfully the requirements have been incorporated into a design solution. But the survey also showed that requirements are often not fulfilled throughout a solution [Almefelt et al.

2006]. Thus, the application of a method preventing deviations from target specifications may achieve significant benefits.

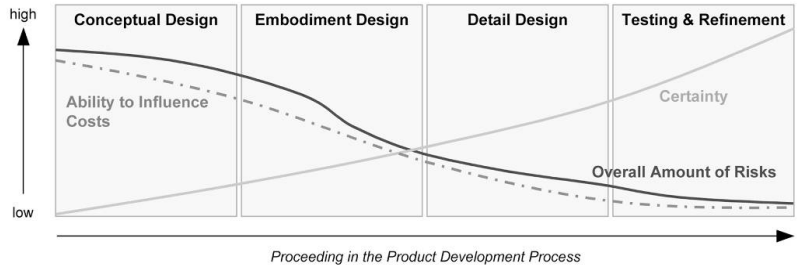

Figure 1. Decrease of Risk as Product Development Proceeds [adapted from BROWNING ET AL. 2002]

Risk Management (RM) offers promising approaches to deal with uncertainties in early product development phases. Although various frameworks in product development, project management, or Supply Chain Management are described (e.g. Githens 2002), easily applicable and step-by-step methods suited for product development are missing. The existing frameworks divide the Risk Management process roughly into five phases: 1) Initialization, 2) Identification, 3) Assessment and Priorization, 4) Mitigation, 5) New Situation and Monitoring. In the first phase, the RM process starts. In the phase of Identification risks are identified and described in more detail. Afterwards, the risks are assessed - mostly regarding the likelihood of occurrence and the impact of a risk. Usually, numerical values are assigned and the risks can then be prioritized by means of them. In the Mitigation phase, strategies and measures are developed to cope with the risks. After the implementation of the mitigation measures, a new situation is achieved. The effectiveness of the measures is controlled and the risks are monitored.

For instance, the Failure Mode and Effect Analysis (FMEA) is an "analytical technique used by a product design team as a means to identify, define, and eliminate, to the extent possible, known or potential failures of a (…) system" [Otto & Wood 2001, p. 565]. It is a well-understood method in engineering and its procedure follows the same scheme the generic risk management frameworks are based on. The method is a systematic approach to analyze designs, processes, systems, or services, and implement corrective actions and controls. It helps to focus on core challenges while still including a wide range of risks. Since the nature of risks and quality issues is very similar, the general idea and framework of an FMEA may possibly be adapted successfully for risk management.

Adapting the FMEA to earlier phases of the product development process seems highly reasonable. Thus, the procedure of the method could be used to anticipate deficiencies in product development and prevent them effectively.

3. Development of the Approach

In order to create a risk management method for product development, a traditional FMEA was gradually adapted to meet the specific needs of a design course at MIT, and later on evaluated and generalized. This paragraph describes the adaptation in detail.

A first draft for a risk management concept was formulated based on the FMEA. This approach was tested with data derived from an undergraduate course at MIT. In this course, student teams developed small products together. They defined requirements, elaborated several concepts and a product architecture. Their product architectures were analyzed regarding potential risks. Two profound insights could be gained: The method could either concentrate on risks related to the process of product development or on risks related to the product itself. Carbone & Tippett [2004] present a methodology to manage project risks, which they call "Project Risk FMEA". This approach shows some potential for a successful adaptation as a risk management tool in product development processes, although modifications might be necessary. For risks regarding the product performance, no

such tool was found in literature. Thus, the decision was made to concentrate on risks regarding the product. Product performance is indicated by its requirements defined at the beginning of the development process. Or to be more specific, to what intent these requirements are met. This leads to the conclusion, that the method to develop will concentrate on product performance and risks of not meeting requirements. Risk is interpreted as an occurrence with an unknown probability and consequences adversely affecting the intended performance of the product to develop. Thus, the consequences can also be expressed as an undesired derivation from the planned objectives. Hence, the term "failure" of the original FMEA was replaced by "risk" (see Figure 2).

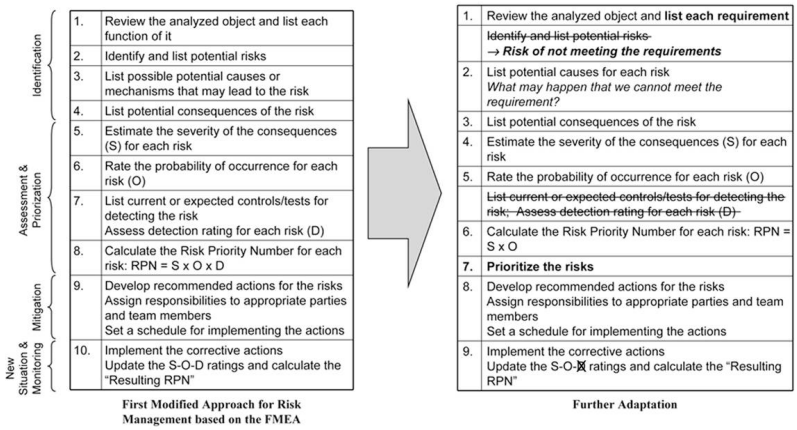

Figure 2. First Draft for the Risk Management Method

The method was then customized to analyze product requirements (see Figure 2). The second step in the procedure of traditional FMEAs has become redundant since the method will concentrate on risks regarding requirements; thus identifying risks was adapted to negating requirements. The steps regarding the assessment of the probability and severity were retained. Adapted for requirements, it needs to be understood what may happen that the requirement cannot be met, and how severe the consequences are. The step of detection was omitted since the new method focuses on detecting and identifying risks; it would be redundant. Instead, prioritizing risks was introduced since this is not explicitly addressed in the FMEA. The steps for mitigation as well as monitoring remained. They form a very thoughtful approach and seemed to be highly elaborated.

The described procedure formed the basis for the development of a method to manage product performance risks. It was continuously refined based on interviews with colleagues at MIT's Lean Product Development Group, taking several examples gathered from the undergraduate course into account.

A major change was made in adapting the assessment phase: New assessment scales were introduced to estimate the likelihood and severity of requirement risks. How likely the analyzed product architecture will meet the requirement can be assessed by means of two dimensions. First, it has to be estimated whether enough information was collected to answer this question (accessibility of information). Second, an estimation of the candidate architecture's technical feasibility indicates whether the analyzed object will meet the requirement or not (feasibility). The severity of a risk and its consequences is indicated by the presence of alternatives in case the requirement cannot be met (contingency). In a last step, the term "requirement" was narrowed down to "specification". Specifications were chosen because they are more explicit and provide less room for interpretation.

4. Specification Risk Analysis

In this section, the Specification Risk Analysis method is presented as it emerged from the adaptation described in the previous paragraph.

4.1 Situation and Objectives

The method is designed for an application during embodiment design, when one or sometimes several product architectures are elaborated. The method represents a means for critical reviews and seeks to identify potential risks inherited in a product architecture. Within the Specification Risk Analysis, risk is exclusively treated in the context of not achieving product specifications. Thus, the objectives can be summarized as three statements:

- The method identifies, assesses, and ranks product specifications that are most challenging to achieve.
- The method avoids product deficiencies and provides a systematic approach to develop appropriate mitigation measures.
- The method prevents time and cost-consuming changes at a later point.

4.2 Procedure

First, an experienced moderator needs to be chosen and relevant team members who are particularly familiar with the product architecture should be invited. The moderator guides through the meeting, helps with upcoming questions regarding the procedure, and reconciles in case of disagreements. A spreadsheet for the analysis, which contains all current specifications, may be prepared in advance.

1. Review the Candidate Product Architecture

The analysis is started by reviewing the candidate product architecture. Any form of visualization for the candidate architecture is useful, from simple drawings up to a computer-aided model mock-up. If changes have been made recently, it is reasonable that a team member briefly explains the current architecture to the others. The team members should familiarize themselves with the architecture. Different views should be discussed and open questions should be answered at this point.

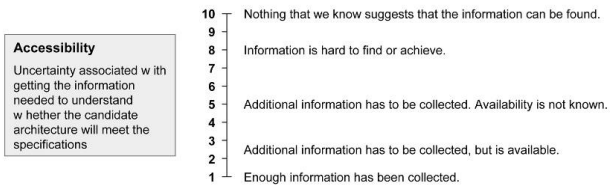

Figure 3. Assessment Scale for the Accessibility Rating

2. List the Specifications and Decide Which Ones Will Be Analyzed

Afterwards the product specifications are listed and reviewed. Specifications are derived from customer needs and usually consist of a verbal description, a value assigned, and a unit. The objective is to check if there are any deficiencies and if all specifications are up to date. If there is not enough time in the meeting to address all specifications, the team may choose the most important ones or may schedule a follow-up meeting.

The product specifications are analyzed according to three key figures. Therefore, steps 3-5 are repeated for each specification.

3. Rate the Accessibility of Information

The first assessment estimates whether the current state of knowledge is sufficient to achieve the product specification or if additional information has to be collected. This dimension is named Accessibility (A). It is defined as *the uncertainty associated with getting the information needed to understand whether the candidate architecture will meet the product specification.* Limiting conditions like the time frame or an existing budget have to be taken into account.

If the team is certain that they have already collected enough information, the assessment would correspond to the lowest Accessibility rating (1) (see Figure 3). On the opposite site, the highest Accessibility rating indicates that nothing suggests that the information needed can be found. The range in between gives the team the possibility to assess the difficulty to get the information. Verbal

descriptions on the right side of the scale offers suggestions for the rationale. Descriptions are not provided for every rating. Thus, nuances can be expressed in the assessment.
Similar to the FMEA, the rating represents more a means of comparison rather than an absolute value. Nevertheless, the team should agree on one number after a discussion and provide a brief description of the rationale in the spreadsheet. This provides not only documentation but also emphasizes their traceability for later reviews.

4. Rate the Feasibility

By means of this rating, it is estimated if the product specification can be achieved. The Feasibility (F) is defined as *the likelihood that the candidate architecture will meet this product specification.* A low rating (1) indicates that the team feels certain about the achievement of the product specification (see Figure 4). For example, this may be based on the fact that all similar products on the market are known to meet it. The higher the rating, the more challenging it will be to achieve the product specification. The highest rating (10) indicates that nothing suggests a potential achievement of the specification at the moment. Again, the rationale for the assessment is described in the corresponding scale on the spreadsheet.

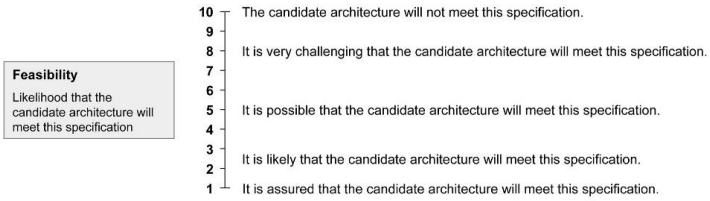

Figure 4. Assessment Scale for the Feasibility Rating

5. Rate the Contingency

At last, the severity of consequences is estimated. This is achieved by means of the key figure Contingency (C). It expresses the opportunity for recovery in case the architecture does not meet the specification. The Contingency is defined as *the expression for the robustness of the candidate architecture, indicated by the existence of alternative solutions.* An alternative is defined as any other variant that probably fulfills the regarded specification. It could be a simple change in material, dimensions, or even a completely different subsystem. For the assessment, the other specifications must not be neglected. It is important that alternative solutions seem to be feasible regarding performance, development efforts, and cost. At this point, however, a detailed assessment of all aspects is not possible. The fulfillment of all specifications can only be roughly taken into account. Therefore, the scale for the Contingency rating offers a broad spectrum for the assessment (see Figure 5). Additionally, it would be useful if existing alternatives were briefly described in the spreadsheet for a potential follow-up.

6. Calculate the Risk Priority Number

After having assessed the Accessibility (A), the Feasibility (F) and the Contingency (C) during the previous steps, the Risk Priority Number (RPN) can be calculated. This is simply achieved by multiplying the individual ratings: RPN = A x F x C. A team should not be afraid of high Risk Priority Numbers. The RPN ranges from 1 to 1000, and other teams would probably come to different results for the same candidate architecture. The RPN is a means to compare the single product specifications to each other rather than an “absolute“ value. Note that it doesn’t scale linearly.

7. Prioritize the Specifications

By means of the RPN, the product specifications can then be prioritized according to their exposure to risk. This helps the team to identify potential deficiencies of the product architecture. The ranking of the specifications gives the team a good idea which ones might be challenging to achieve. Then, the team has to decide which specifications they would like to address first. There is no critical RPN recommended, as this has to be determined individually for each analysis. Nevertheless, it may help to set a threshold or visualize the results, e.g. by means of a Pareto diagram. A high RPN does not

indicate that the team is not able to achieve those specifications but that it might be harder - compared to others. The highest ranked specifications can be interpreted as exclusion criteria for the final product. The sooner it is known if the product will meet those specifications the lower the overall risk is. Additionally, specifications with high individual ratings (A, F, or C) may be considered.

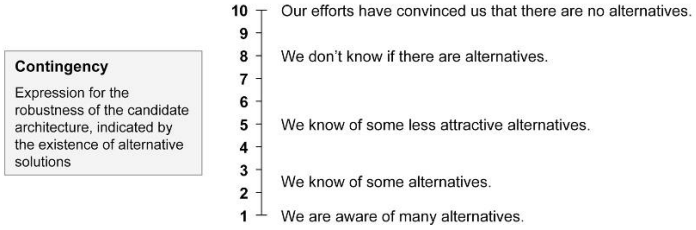

Figure 5. Assessment Scale for the Contingency Rating

8. Develop Corrective Actions, Assign Responsibilities, and Set a Schedule for the Implementation

After the team has decided which specifications they plan to address, corrective actions need to be developed. They have to be described in the spreadsheet and a responsible person as well as a completion date should be assigned. The recommended activities may address one or more of the following aspects:

- Procurement of additional information (e.g. literature reviews, tests, surveys, ...)
- A reviewed estimation of the feasibility (e.g. due to calculations, simulations, …)
- Development or improvement of alternative solutions

Actions may not only be recommended for the highest ranked specifications but also for those where risks can be minimized with little effort, even if they have a lower RPN rating.

9. Implement the Corrective Actions, Update the Ratings, and Recalculate the RPN

The developed corrective actions have to be implemented and the specification risks should be monitored. The monitoring of the risks is achieved by re-estimating the individual assessments. After the recommended actions have been implemented, the RPNs are updated. The difference between the "Resulting RPNs" and original ones is a measurement of the effectiveness of the actions taken.

10. Reflect and Decide about Future Proceeding

It is advisable to review the procedure and results of the Specification Risk Analysis. Potential improvements for further applications may be gained. At this point, there are two options: First, if the team is content with the effects of the mitigation measures and the achieved results, it can finalize the procedure and archive its results for reasons of documentation and for future projects.

Second, if the team is not content with the results yet, they may carry on with step 6. Since there is no target RPN that has to be achieved, there may be several iterations. It is the decision of the team or the management how much risk they are willing to accept, depending on the product's influence and scope. It is not deemed necessary that the analysis is conducted in a team. For a follow-up, one team member may update and review the ratings individually and present the results to the group. Thus, controversial decisions can still be discussed without taking too much time.

4.3 Effects

By means of the Specification Risk Analysis several effects can be achieved. First of all, the method represents a structured approach to review a product architecture. It ensures that no specification falls behind. The structured, objective procedure emphasizes the expression of concerns that might have been concealed otherwise. Furthermore, product specifications are documented that might become difficult to achieve. Corrective actions, responsibilities, and implementation dates are written down as well. This helps to follow up the critical specifications identified. Additionally, the documentation of challenging specifications and developed actions may give teams with similar projects a good idea what challenges they might face and how to address them.

4.4 Field Study

A field study was conducted with four graduate student teams of a product development course. The study sought to achieve two objectives: Testing and refining the method as well as assisting the development teams regarding their key challenges. After the teams had started to define their product architectures, a meeting with each group was held and the risk analysis was conducted. Two potential applications of the method in the product development process were identified in the meetings. For a single architecture, the method helps to identify and manage challenging specifications and seeks to assign corrective actions and responsibilities. For two architectures or more, it was found to be too time-consuming and inefficient to assign corrective actions for each candidate. Nevertheless, the Specification Risk Analysis identified challenges the individual candidates might face. It seemed much more efficient to analyze several architectures in parallel because the variants could then be compared regarding a certain specification. It has to be noted that the results did not replace the decision making process for a single solution, but instead gave hints which information was still missing.
Furthermore the field study showed that the more accurate specifications were defined, the more efficient the analysis could be conducted. Requirements can be interpreted too broadly and it was found to be useful if target values (or at least an interval) for the specifications were defined. The field study identified the method as a good means to review current architecture(s) and discuss different opinions and open issues. Aspects that had fallen behind could be identified. During the team meetings, specifications were eliminated, modified, or described more precisely because they had not been up to date. In a feedback questionnaire, the 17 participants were asked to evaluate the method and its results. 88 % agreed that the results would help them with the project's progress. Half of the participants believed that the method imposed new actions they hadn't previously considered. And 78 % agreed that the method would have helped them in previous and similar projects they had done. In the final evaluation at the end of the course, the teams who conducted the Specification Risk Analysis performed on average more than a grade better than the other six teams of the course.

5. Reflection & Outlook

5.1 Reflection Regarding the Specification Risk Analysis

The Specification Risk Analysis represents a tool that offers a structured approach to analyze one or several product architectures regarding their key challenges. It helps designers to identify potential deficiencies of the later product regarding its specifications. Specifications that might become exclusion criteria for the current design are identified in an early phase. Furthermore, the method emphasizes the development of corrective actions and fallback solutions, as well as the assignment of responsibilities and completion dates. Thus, time and cost-consuming late term changes can be avoided. Findings from the field study confirmed these benefits. It is highly beneficial in product development, if a team anticipates risks and masters the challenges of product development at low costs within little time. Little development time, low cost, and high quality can be seen as the key drivers to the success of a product development system. The method presented aims to address all of these dimensions.

5.2 Potential Improvement and Future Research

The method presented in this paper inherits some room for improvement. Specifications' varying importance is not taken into account at the moment. This is only incorporated indirectly, and there might be better ways - e.g. by introducing a fourth assessment scale considering the importance of a specification. For complex products it might not be possible to analyze every specification. A procedure to select the specifications to be analyzed is needed. To what extent a specification cannot be met and how this influences the consequences, is not taken explicitly into account. The Contingency scale measures the consequences in case a specification cannot be met; it estimates the performance of an alternative (or more), its cost-effort-ratio, and its easiness of replacement. However, this might not be the best approach to measure the severity of consequences.
In future, it would be beneficial to apply the method to an industrial project. It could be analyzed whether the complexity of requirements might form a problem or if a potential cooperation with

existing requirements management tools might be possible.
To the authors' knowledge, no generic model to access the value of risk management is described in literature. A detailed study of its effects might achieve new insights. By means of the Specification Risk Analysis, this could be empirically proven, e.g. by the percentage of performance deviations from the originally defined product specifications. The fundamental procedure of the FMEA is similar to the generic problem solving approach engineers love to follow. It inherits far more potential than for the analysis of quality issues or specification risks. It might be possibly adapted for other fields as well, e.g. for manufacturing risks, technology risks, etc. Especially by tailoring assessment categories to specific situational needs, significant benefits may be achieved.

6. Summary

In this paper, an adaptation of the FMEA as a risk management tool for embodiment design was presented. The development of the approach and important decisions were described. By means of three dimensions, risks of not meeting specifications can be assessed and prioritized. Furthermore the method enhances the development and follow-up of mitigation measures. So far, the method has been tested by product development teams of a university course. The field study identified the Specification Risk Analysis as a useful tool to mitigate potential deficiencies of a product architecture. Additionally, it was shown that the highly matured procedure of the FMEA can be adopted for various purposes and is not limited to quality issues.

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