HANDLING OF EXPLICIT UNCERTAINTY IN REQUIREMENTS CHANGE MANAGEMENT

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ABSTRACT

Innovation projects are characterized by numerous uncertainties. Typical concepts in development management like the application of safety coefficients imply limitations of the solution space. In contrast, explicit handling of uncertainties can support engineers in understanding the problem space and in utilising the full potential of the design space along iterative product development steps. As a result from literature analysis, there is a lack of a support for product development that addresses the specific problem of uncertainty and risk in the context of requirement changes. The aim of the contribution at hand is to enhance the efficient development of complex interdisciplinary systems by enabling uncertainty handling in requirements change management. Based on a classification of uncertainty types resulting in a descriptive model, risk management measures are identified to support requirements engineers. The proposed method includes identification & modelling, analysis, treatment and monitoring of risks and counter-measures. By applying this method, engineers are supported in adopting agile approaches and enabling flexible Requirements Engineering.

Keywords: Requirements, Uncertainty, Risk management, User centred design

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1 INTRODUCTION

Every development project with a high degree of innovation is initially based on a knowledge deficit (Neumann, 2017). **Innovation projects** like developing complex interdisciplinary systems are characterized by numerous uncertainties (Ehrlenspiel, 2007). These occur in all phases of the development process and can affect the entire product life cycle. Uncertainty which is introduced by, for instance, insufficient knowledge of customer requirements, increases the risk of **requirement changes**. Studies show that requirements changes are unavoidable and they occur in all phases of a development project; more than half of all system requirements are subject to a high probability of change (Hein *et al.*, 2018). Handling and implementation of these changes lead to an additional cost and time expenditure, which can also lead to a failure of the development project (Pohl, 2010). In **managing requirement changes**, purely reactive measures in terms of damage limitation are not sufficient to cope with the potential impact of uncertainties in developing projects (Neumann, 2017). In scientific literature, there are already numerous recommendations for the procedure in innovation projects as well as various methods and modelling approaches in the field of risk management (Gräßler and Oleff, 2019). However, there is a **lack of support** for product development that addresses the specific problem of uncertainty and risk in the context of requirement changes (Neumann, 2017; Gräßler and Oleff, 2019; Hein *et al.*, 2018). One of the most fundamental deficits is the fact that methodological support has so far almost exclusively shown partial views of risk and uncertainty specific countermeasures (Neumann, 2017). The **aim** of this contribution is to enhance the efficient development of complex, interdisciplinary systems by enabling uncertainty handling in requirements change management. The following research questions are answered: *"How can uncertainty be differentiated in requirements engineering (RE) to enable uncertainty specific and proactive risk management?"* (RQ1) and *"What are uncertainty-specific countermeasures in requirement change management for the development of complex, interdisciplinary systems?"* (RQ2). The intention is to enable engineers in handling uncertainty proactively und utilizing knowledge about uncertainty as a positive and useful factor in requirements analysis.

2 METHODOLOGY

A **literature study** is conducted to clarify the research objective. To set a clear goal, approaches of risk management in development projects as well as approaches for requirement change management are reviewed and tasks in RE are identified (documented in section 3). Based on the findings of the literature study, **uncertainty in RE tasks** is categorized (see section 4). Building on this, the method for selecting risk specific countermeasures is developed (see section 5). To integrate the practical perspective in the development of the method, **three industry workshops** (duration: two hours each) were conducted with a large automotive engineering service provider. Uncertainties in RE were discussed with regard to their existence and their significance in practice. The questions *"what risk management measures do I apply in my job?"* and *"what risk management measures do I use proactively?"* were asked. Industrial practices were analysed on how uncertainties and risks are managed in general as well as in the context of requirements. The results are conformant with literature and show that there is no risk management approach for requirement changes in place so far. Counter measures cannot be validated regarding usefulness, but are discussed in terms of usability and applicability. **Four different industry representatives** (a requirements engineer, a project manager, a development engineer and a head of department) evaluate whether the proposed measures are appropriate for a practical handling of risks of requirement changes.

3 STATE OF RESEARCH

For the purpose of research clarification, approaches of risk management in development projects, uncertainty types and their implications in RE are analysed. The aim is to **identify approaches for considering uncertainty on requirement-level** to facilitate a better risk management in development projects. Since no risk management approaches exist for a differentiated view on the requirement-level, requirement engineering tasks are investigated to **create a better understanding of uncertainty in requirements**. Requirement change management approaches are analysed for identifying means to handle these uncertainty-based requirement changes.

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3.1 Risk Management in development projects

Traditional literature on risk management classifies decision-making situations into three categories: certainty, risk and uncertainty (Mousavi and Gigerenzer, 2014). Under certainty, every action leads to a specific outcome. In this domain, **decisions under risk** are understood as decisions for which the probabilities of each outcome are known. Under **uncertainty**, not all probabilities of the outcomes are known. While classical risk management approaches are adapted to product development (Vanini, 2012), **Systems Engineering** is an engineering approach that emphasizes and supports risk management as part of the development effort (Neumann, 2017; Walden *et al.*, 2015). As an interdisciplinary methodology, Systems Engineering aims at the goal-oriented transfer of complex problems into holistic problem solutions (Walden *et al.*, 2015). To manage risks, Neumann subsumes **different approaches of risk management into four phases** (Neumann, 2017): a) identification of uncertainties in the development process, b) analysis of the uncertainties, evaluation of the probability of occurrence and effects, c) formulation of solution plans for risk reduction, initiation of countermeasures and d) continuous analysis of risk development, monitoring of countermeasures. Current risk management approaches do not differentiate between uncertainty types in the context of requirements.

3.2 Uncertainty in development projects

Uncertainty applies in any case to situations in which the **information required for a task** is not completely available, the **information quality cannot be fully evaluated** and/or the **effects of a decision cannot be predicted**. It can be differentiated in all cases a) completely missing information from b) partially quantified, c) sufficiently quantified as well as d) complete information. Also the effect of aleatoric uncertainty can at least be estimated by information and probabilities. Following Kreye et al. (Kreye *et al.*, 2011) and Eifler (Eifler, 2015), data and model uncertainty are defined. Data is considered as input into product development, seized initially or in following iterations. **Data quality** (Wang and Strong, 1996) contributes to uncertainty mainly in **the form of 'imprecision'**. This is based on **data incompleteness**, **data correctness** and **data variance**. Models are the result of modelling, i. e., of a decisive development processes. According to Stachowiak (Stachowiak, 1973) mapping, reduction and pragmatism must be taken into account. These lead to a) **conceptual vagueness**, which includes programming errors, b) **approximation vagueness** and c) **calculation vagueness** (see (Thunnissen, 2003) and (Kreye *et al.*, 2011)). Both in terms of illustration and design, **developmental uncertainty** and **interaction inaccuracy** (acc. to (Thunnissen, 2003)) as well as **contextual inaccuracy** (acc. to (Kreye *et al.*, 2011)) can come into play. Besides semantic conceptualisation of uncertainty targeted in the paper at hand, some approaches exist that incorporate semantic enrichment into system models. For software models, Troya et al. present results of literature survey with different types of model integration (Troya *et al.*, 2021). Bandyszak et al. propose an "orthogonal uncertainty model" to enable the documentation of uncertainties in a dedicated model with tracelinks to engineering artifacts like requirements (Bandyszak *et al.*, 2020).

3.3 Requirements Engineering

Following the terminological definition of IEEE 610.12-1990 ("IEEE Standard Glossary of Software Engineering Terminology", 1990), requirements are always solution-oriented. In contrast to that, the term **'needs'** is used to describe problem-oriented statements (Walden *et al.*, 2015). **User requirements** (solution independent) can be distinguished from **system requirements** (solution specific resp. restricting the solution space) (Hoffmann *et al.*, 2013). **Main activities** of RE are elicitation, documentation, validation and negotiation as well as management (Pohl, 2010). In the contribution at hand, the analysis is seen as a follow-up to the elicitation to emphasize that the elicited requirements must be analysed in order to understand the development task. None of these activities explicitly include uncertainty or risk management activities in the context of requirement changes. Still, the **identification (and reduction) of uncertainty is part of all of them**. Uncertainty is inherent in requirements, because requirements cannot be described completely and precisely as information might be missing or incorrect (Pohl, 2010; Ehrlenspiel, 2007). Uncertainty in requirements lead to requirement changes (Pottebaum and Gräßler, 2020). Proactive risk management regarding requirement changes mostly occurs in the task management, but includes activities from all other main tasks. In requirements change management, different approaches are proposed for handling these uncertainty-based changes.

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3.4 Requirements Change Management

The requirements change management **process consist of three phases: identification, analysis and cost/effort estimation** (Jayatilleke and Lai, 2018). Activities within change identification are change elicitation and change representation. Changes need to be further analysed to understand the impact. Based on the impact of the change, costs and efforts to implement changes are estimated, which are based on expert judgements (P. Abrahamsson *et al.*, 2011). Causes for changes in requirements are categorized into five areas (Jayatilleke and Lai, 2018): changes to requirements are triggered by events that occur in the external market (1), customer organization (2), a better understanding of the problem and application space from the customers (3) or developers (4) point-of-view and solution space (5). **Uncertainties that lead to these changes** are, for instance, changes in government policy regulations (1), strategic changes within customer organization (2), involvement of stakeholders (3), quality of communication with the development team (4), and increased understanding of the technical solution (5). Decisions on the use of preventive measures in particular require a profound knowledge of the risk of change (Gräßler and Oleff, 2019). To assess the risk, the two assessment criteria of impact and likelihood of occurrence of a change in requirements are used (Clarkson *et al.*, 2004; Diederichs, 2012). Literature on requirements change management indicates requirements changes causes (João Fernandes *et al.*, 2018) and provides methods to assess their impacts (Jayatilleke and Lai, 2018). This information is used for the development of an uncertainty specific management of requirement changes.

4 UNCERTAINTY IN REQUIREMENTS ENGINEERING

To differentiate uncertainties in the context of requirements, a more detailed understanding of activities related to elicitation, specification and verification/validation of needs and requirements is needed. The information of section 3 is used to specify activities and artefacts in RE as well their uncertainties.

4.1 Requirements Engineering tasks to determine a valid product specification

Developing a product, multiple RE tasks have to be executed to determine a valid product specification. Hence, the main activities of RE are further detailed based on section 3.2. The backbone is defined by Product Development (Ehrlenspiel, 2007) and Systems Engineering (Walden *et al.*, 2015) in Figure 1. These foundations determine the interrelationships between an application space (also known as problem space) and the solution space. Background from RE (see section 3.2) is used to detail the interaction between engineers and actors having needs (upper part of Figure 1) as well as verification and validation (bottom part).

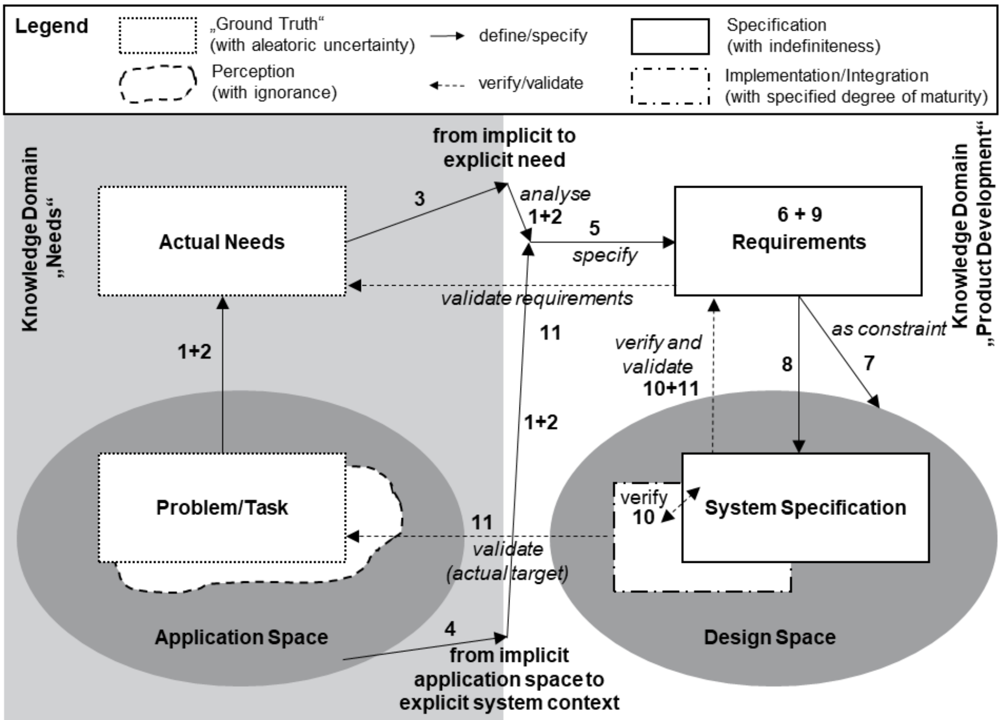

Figure 1. Tasks to determine a valid product specification including uncertainty

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To understand the causes of uncertainty in RE, concepts of knowledge externalisation and socialisation are used to differentiate between implicit and explicit knowledge (Nonaka and Takeuchi, 1995). The difference between ideally 'ground truth' (like actual user needs), which by nature cannot be externalised completely, and the perception of humans is introduced (cf. (Casakin and Badke-Schaub, 2017)). Consolidating these backgrounds, **ten specific tasks** are identified which can be assigned to the main activities. Uncertainty types identified in section 3.1 are reflected from the perspective of these activities. Starting with a problem to be solved or a task to be optimized, needs of users have to be understood and knowledge has to be socialized (1). At the same time, the application space of the problem has to be identified (2). Implicit knowledge of stakeholders needs to be externalized to document explicit needs (3). Comparably, the application context must be made explicit (4). Analysing explicit needs and application context, user requirements are specified (5). User requirements need to be transformed to system requirements (6). Specifically, constraints need to be determined which restrict the design space (7). System requirements are transformed into a system specification, detailing a specific solution to be realised (8). Changes in requirements need to be managed (9). Verification ensures that the system specification is compliant with system requirements resp. an implemented version of the system is conformant with its specification (10). Validation is conducted to ensure that the system resp. the system specification is compliant with actual needs (11). Tasks to determine a valid system specification including uncertainty are visualized in Figure 1.

4.2 Detailed description of uncertainty in requirements engineering

Treating RE as a knowledge-intense process, requirement engineers need to **understand** the application resp. problem space. This is typically tackled by methods like observation, interviews and data analysis. Needs are explicated either directly by those who are in need because of a certain problem to solve resp. a task to perform or indirectly by requirements engineers as observers or interviewers. With respect to uncertainties, it is essential to accept that all involved people can only **explicate** (a) what they perceive and (b) what they are able to communicate in the interaction. Needs are typically explicated by natural language. Changing the perspective into solution-oriented yet solution-neutral requirements, **mapping** of needs into user requirements is supported by templates and modelling languages.

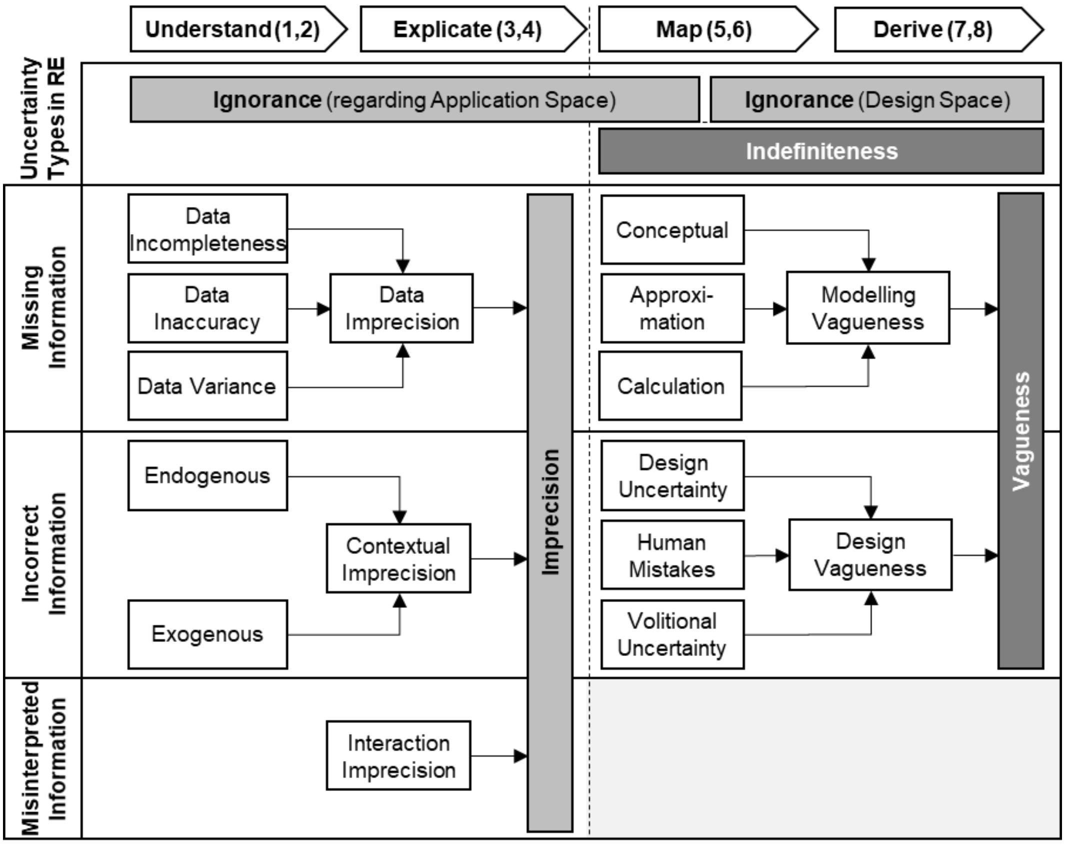

Figure 2. Uncertainty in RE: ignorance and imprecision, indefiniteness and vagueness

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From user requirements, the targeted step in RE is to **derive** system requirements. Thus, understanding and explicating needs are influenced by ignorance regarding the application space. Representing and deriving requirements are influenced by this ignorance of the application space. This uncertainty is complemented by both ignorance regarding the design space. For instance, engineers might not know about full potentials of technologies like 3D printing; they perceive a design space which is smaller than the actual one. The detailed uncertainty types are mapped to the tasks of RE (see Figure 2).

5 MANAGING UNCERTAINTY IN REQUIREMENT CHANGES

Based on this understanding of activities and uncertainty in RE, the process of four phases of uncertainty specific risk management by Neumann (Section 3.1) is adapted. First, uncertainties are considered in tasks in RE (1). Measures for the identification of uncertainties are applied and results are represented in models. Afterwards, risk factors for estimating the probability of occurrence and impact of uncertainty are presented (2). Based on risk assessment, uncertainty-specific counter measures are introduced (3). An ongoing activity is to monitor effectiveness, validity of assumptions as well as risk evolution (4). This is not part of the contribution at hand and therefore not discussed in detail. The overall process to manage uncertainty in requirement changes is illustrated in Figure 3.

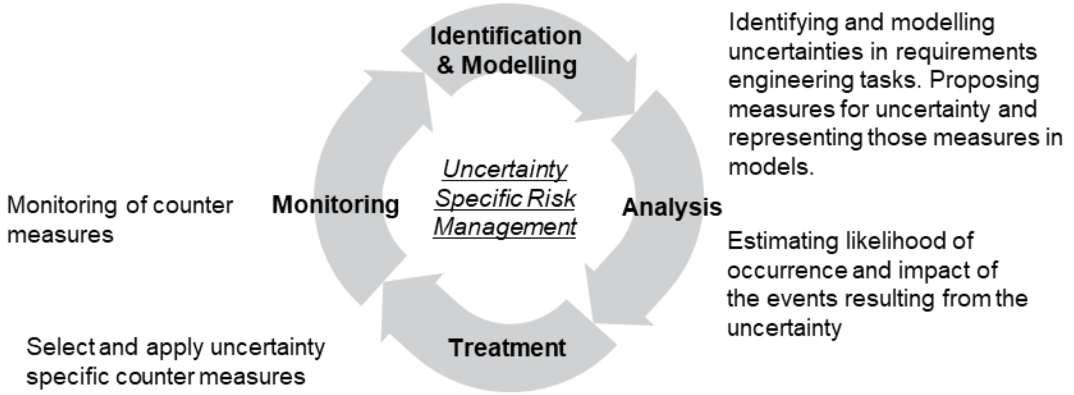

Figure 3. Uncertainty specific risk management of requirement changes. Adapted from (Neumann, 2017).

5.1 Identification & Modelling of Uncertainties

Using the insights from different types of uncertainty in RE tasks (section 4.2), means are applied to identify these in the project development process. Multiple means are describes in literature to identify uncertainties in RE tasks (Gräßler and Oleff, 2019; Pottebaum and Gräßler, 2020; Neumann, 2017; Vanini, 2012) These are mapped to specific types of uncertainty and enriched by findings from industry workshops. Those means aim to identify uncertainty.

5.1.1 Uncertainty Identification

Although application of those means aims to identify uncertainties in the first place, they also trigger frequently the reduction of uncertainty. For instance, applying questioning techniques to elicit missing requirements not only leads to the information that requirements are missing, it quite often also reveals those missing requirements right away. Therefore, the means to identify uncertainty are already defined as part of the uncertainty specific countermeasures. Workshop findings indicate that until now, they constitute the major part of risk management for requirement changes in industrial practice. Nevertheless, many uncertainties are still present after the initial identification stage and should be made transparent by modelling them.

5.1.2 Uncertainty Modelling

The knowledge about the uncertainty behind development decisions can become relevant, e.g. if the manufacturing technology is questioned in the later development process or in the product life. This can happen, for example, in the course of an economic efficiency calculation as part of a value analysis. Requirements must be mapped in a model-based manner. They can be set in relation to other requirements by means of description languages such as SysML and can be linked to system elements

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that meet the respective requirements. For this purpose, uncertainty must be explicitly integrated into the digital representation of a product and visualized in a task-related manner. It has to be recognized in the respective current product specification, understood and handled in a development-methodical way with access to the underlying product model. Means to identify uncertainty in RE tasks are visualized in Table 1.

Table 1. Means to identify uncertainty in RE tasks

Uncertainty	Means to identify uncertainty
data incompleteness	• within a requirement: software for automatic quality assurance • missing requirement: requirement elicitation techniques (questioning techniques, creativity techniques, document centered techniques, observation techniques, supporting techniques)
data inaccuracy	• initial elicitation: documentation guidelines/tools: templates, quality criteria for requirements and -sets • review and improvement: software for automatic quality assurance
data variance	• initial elicitation: reflection by complementary stakeholder groups • within a requirement: approximation by stochastic assertions
context inaccuracy	• simulations (e. g., in VR), customer reviews, prototyping, use cases, mock-ups, system delimitation/context delimitation, stakeholder analysis, user stories, personas, scenario technique • requirement elicitation techniques
interaction inaccuracy	• interaction with stakeholders: compare context inaccuracy • interaction with development team: communication strategies, modelling of the SoI/objective (structure and behaviour), glossary
development uncertainty	• application of process models, methods and tools from design methodology • check for inconsistencies • agile approach, rapid product development, experience design • Testing (Feasibility or degree of fulfilment)
modelling uncertainty	• using modelling methods (e.g. SYSMOD or OOSEM) • using modelling languages (UML, SysML) • using modelling tools (inconsistency detection, status representation, timeliness ...)

5.2 Analysis of Uncertainties

Analysis of uncertainties aims to assess likelihood and impact of an uncertainty related event to occur. After assessments regarding these two risk dimensions were made, an uncertainty related event is defined as a risk and can be treated accordingly. Available approaches to assess likelihood and impact depend on the application context. Due to interdependencies between requirements, changes might propagate (Gräßler *et al.*, 2020). Therefore, the two risk dimensions need to be further detailed to increase accuracy of assessment and subsequent risk treatment (Gräßler and Oleff, 2019). Likelihood of a requirement change to occur is based on exogenous and endogenous change causes. Exogenous change causes trigger an initial requirement change and originate outside the requirement set. Endogenous changes come from change propagation in a requirements set and can only occur after the initial change. To assess change likelihood both, exogenous change causes as well as requirement dependencies need to be analysed. Accordingly, the overall impact of a requirement change depends on the local change impact of a single requirement and the subsequent changes from propagation (Graessler *et al.*, 2020).

5.3 Risk Treatment

To treat the risk of requirement changes, information on likelihood and impact is crucial. One the one hand, it enables to compare, classify and order risks based on their importance for risk treatment. On the other hand, it enables to select and implement risk specific action strategies. Those strategies are structured by four main categories: avoidance, reduction, transfer and acceptance die (Diederichs, 2012; Gleißner and Wolfrum, 2019). Each category contains counter measures with certain effects on risk likelihood and impact. **Avoidance** is a preventive strategy that aims to eliminate the likelihood of an

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incident even occurring by removing the cause (Song *et al.*, 2019). In the project initiation stage this can be to reject the development project, for instance due to a high number of risks with high likelihood and impact. In later stages avoidance can mean to decline a change request or the usage of high-risk technologies or to eliminate requirements. **Reduction** strategy aims to reduce or mitigate the risk towards an acceptable degree. Counter measure within this category reduce likelihood and/or impact of the incident. Exemplary counter measure to reduce the impact of a requirement change are: freezing of specification (E. Fricke *et al.*, 2000), limiting the amount of working hours to implement the change [based on (Diederichs, 2012)] or increase the budget buffer. Counter measure to reduce the likelihood of a change are described in section 5.1. Risk **transfer** aims to sharing risks or transferring them to other stakeholders or insurances (Gericke, 2011). Counter measures depend on whether the risk is insurable. Against a fee, insurable risks can be transferred towards an insurance provider. **Acceptance** means to not apply counter measures against the remaining risks.

As an example to illustrate application of the method and risk treatment, the development of a new **electric formula student racing car** is used. High degree of innovation leads to extensive uncertainties. One uncertainty and resulting change was, that an unexperienced team member defined the wrong connection type requirement from inverters of electric motors and their control units to the electric motor. Besides changing the connection type, it caused change propagation in a way that the inverter housing requirements needed to be redefined as well. First, using the overview of uncertainty types (Figure 2) and uncertainty measures (Table 1) as part of initial requirement elicitation phase could have helped to be aware of high uncertainty from "human mistakes" due to low experienced part time students as team members for self-defined requirements (e. g., connection type). As a countermeasure for such requirements "check for inconsistency" could have helped to avoid this change. Otherwise, uncertainty modelling and systematic risk analysis (section 5.2) would have indicated high risk from such human mistakes and enable the selection of appropriate risk measures. Exemplary seeing the change of requirement "connection type" as risk "B" (Figure 4): **risk reduction** could be pairing of students, **avoidance** could be reuse of proven parts from the fuel car and **transfer** could be outsourcing.

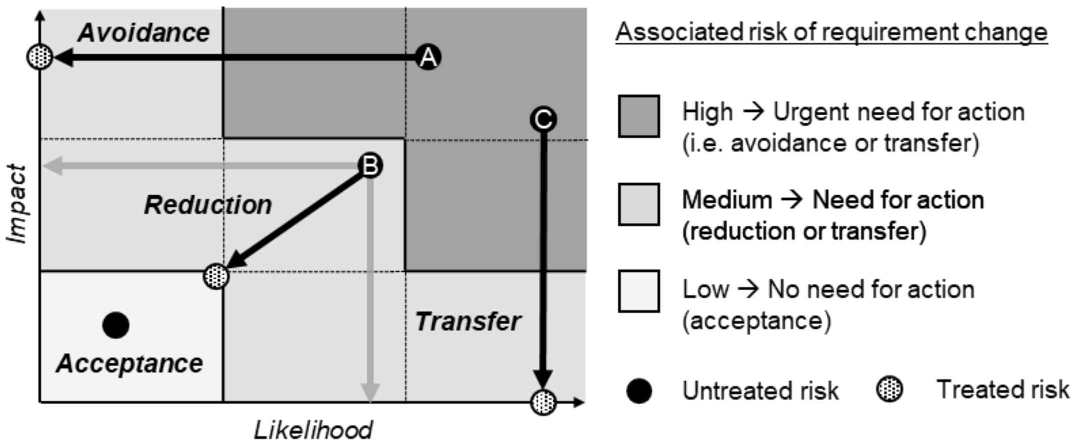

Figure 4. Portfolio of risks of requirements changes

Besides the risk strategy, counter measures can be differentiated by other criteria, like more specific risk factors (cf. section 5.3), timing or individual aspects. **Risk factors** like endogenous and exogenous change likelihood enable more accurate actions. For instance, modularization to reduce requirement dependencies and therefore the endogenous change likelihood or in process validation with the customer based on mock-ups to reduce exogenous change likelihood (Gräßler *et al.*, 2019). Looking at the **timing**, preventive, proactive and reactive actions can be differentiated. Preventive as well as proactive counter measures are initiated before a change request exists (for instance, pre-defined design freeze) whereas reactive counter measure are initiated afterwards (for instance, adjustment of development order) (Diederichs, 2012; Gericke, 2011). Reactive counter measure therefore might not be seen as part of risk management, but fire-fighting (Gericke, 2011). **Individual aspects** related to companies' organizational structure (i. e., roles and responsibilities), best practice or system characteristics might be added.

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6 SUMMARY AND OUTLOOK

A lack of research regarding uncertainties and risk management for requirement changes is elaborated and uncertainty related RE tasks are derived. Based on those tasks, related uncertainties are specified and assigned to individual uncertainty types. These are fundamentals to develop a risk management method that helps to identify and to model specific uncertainty types, to indicate risk factors for the analysis of uncertainty induced risks and to show specific risk management counter measures for handling them. The risk management method is based on results regarding both research questions: A detailed classification of uncertainty types which are relevant for RE tasks is presented in the paper at hand (RQ1). Uncertainty specific control measures for handling requirement changes are combined for the development of complex, interdisciplinary systems (RQ2). Application of the introduced method for selecting risk specific countermeasures provides a novel support that considers explicitly requirement specific uncertainties and, consequently, measures. This will help to reduce negative effects from requirement changes by supporting the selection of targeted measures to avoid requirement changes proactively or reduce their likelihood of occurrence and impact. Future research targets the detailed validation based on an integration of the risk management process into the product development process.

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