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Bridging Uncertainty Management and Requirements Engineering in R&D projects: a case in the e-mobility sector

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Abstract

Complex systems R&D projects aim to explore innovative solution alternatives characterized by multiple uncertainties, requiring open specification in the early development stages. At the same time, complex systems development relies on detailed requirements management. In such projects, it may be necessary to monitor uncertainties evolution along with requirements management to balance innovation potential with implementation feasibility. This paper presents an approach to bridging uncertainty management and requirements engineering in R&D projects. The proposed approach has been applied in developing an electric vehicle charging robot. The paper contributes to the literature on the intersection between requirements engineering and innovation management.

Keywords: Innovation Management; Requirements; Uncertainty; Mechatronic System; Electric Vehicle

1. Introduction

Research and Development (R&D) intensive projects aim to generate innovative solutions. Thus, R&D efforts are related to uncertainties in various categories, including technology, market, organization, and resources [1]. Concurrently, R&D projects are generally based on detailed requirements to guide the development [2,3]. While innovation requires openness, especially in earlier project phases, requirements engineering is typically rooted in rigid normative procedures, thus possibly resulting in perspectives that are necessary but not simple to align. Indeed, Rice et al. note that "*Companies try to cope with the multidimensional uncertainties associated with breakthrough innovation by imposing managerial discipline and an array of planning approaches*" (…) "*but breakthroughs, which are fraught with high degrees of uncertainty on many dimensions, require a different approach*" [1].

The literature on requirements engineering is well established [2,4,5]. However, works on the intersection between requirements engineering and innovation management focusing on uncertainty management are scarce in the literature, with a few exceptions – one example is given by the work of Salay et al. [6].

This work aims to propose an approach to bridging uncertainty management and requirements engineering in R&D projects for complex systems. Therefore, a Design Science Research (DSR) methodology is employed, including problem identification, solution development, demonstration, and evaluation [7]. The proposed approach has been initially applied in developing an electric vehicle charging robot. The initial application provided empirical evidence for the evaluation of the proposed approach.

This paper is structured into six sections. Section 2 presents the literature background on requirements engineering, uncertainty management, and the relationship between the two

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areas, indicating the knowledge gap. Section 3 discusses the DSR research method employed. Section 4 details the proposed approach integrating uncertainty management and requirements engineering. Section 5 presents an application case and discusses the theoretical and practical implications. Finally, Section 6 summarizes the main conclusions and provides directions for further research opportunities.

2. Literature background

This section summarizes the literature on requirements engineering and uncertainty management and the integration between these two theoretical streams. A synthesis of the literature summarizes the knowledge gaps and opportunities for further development.

2.1. Requirement engineering fundamentals and trends

Identifying and documenting requirements typically provide the basis for engineering development projects. The CIRP Encyclopedia of Production Engineering defines a requirement as a "*singular documented need of what a particular product or service should be or perform*" [8]. Based on this understanding, requirements engineering can be stated as "*the subset of systems engineering concerned with discovering, developing, tracing, analyzing, qualifying, communicating and managing requirements that define the system at successive levels of abstraction*" [2].

Requirements may be functional or non-functional [9], including quality requirements related to performance [10]. Requirements are gathered from various sources and users, with a strong focus on customers [11], also considering other stakeholders. Typical requirements engineering process phases are elicitation (identification, gathering, understanding), analysis (consistency checking), specification (documentation), and validation [8]. Usually, this process results in a requirements specification document.

Requirements engineering for complex hardware products, such as in the automotive industry, has been historically based on rigid processes to meet safety-critical requirements and enable the integration of several parts [3]. Nevertheless, the typical rigid process also has limitations, such as forcing early decisions [3], which may be challenging to arise in more innovative settings.

Recently, there has been a growing perception of the need to evolve requirements engineering approaches to consider software-intensive solutions and cope with increasing partner coordination, complexity and safety issues [3]. Therefore, late research has proposed process enhancements for requirements engineering. A growing stream of research, especially on software development, focuses on Agile approaches. This includes methods for prioritizing requirements [12]. However, the fit of Agile approaches originated from software development for complex hardware-based solutions has still not been entirely resolved. From the hardware-development perspective, Loucopoulos et al. propose using a capability-oriented paradigm emphasizing early requirements for mechatronic Cyber-Physical Production Systems (CPPS). The proposal has been exemplified in two cases in the automotive industry [13]. Ågren et al., also focusing on the automotive industry, suggests a series of improvements, including, for instance, combining lightweight upfront requirements engineering with later detailed specifications [3]. In an earlier study, Aurum and Wohlin examine requirements engineering from the decision-making perspective along the development process [14]. In common, these studies deal with the need to streamline requirements engineering while maintaining rigorous attention to quality and security in highly complex and innovative settings.

2.2. Uncertainty management in innovation projects

Uncertainty is considered the lack of sufficient information to support decisions and select alternatives. High levels of uncertainty are typically present in radical innovation projects, addressing new emergent customer markets or new technology competencies [15,16]. Thus, uncertainties may also be related to lower Technology Readiness Levels (TRL) dealing with novel technologies [17].

Uncertainty may be classified into different categories, including technology, market, organization, and resources. Technical uncertainties refer to the availability and understanding of the necessary scientific knowledge to result in a technically viable and scalable solution. Market uncertainties refer to the project team's understanding of user needs, market readiness, and competitors' positions. Organizational uncertainties relate to how the involved institutions can respond to the innovation challenges, including organizational resistance, lack of continuity, and potential changes in strategic commitment. Finally, resource uncertainties refer to potential gaps in critical competencies and guaranteeing the necessary funding for the project evolution [15].

In order to deal with uncertainties, new approaches are necessary. In this vein, Engelhardt et al. present a model to describe uncertainties based on different levels of abstraction [18]. Maes et al. analyze uncertainty linked to project work packages at the task level for work planning and management purposes [19]. Rice et al. propose the Learning Plan methodology and template to support project teams in systematically assessing uncertainties and learning from their evolution [1]. Although these approaches are useful, they do not directly address the relationship between uncertainty and requirements engineering.

2.3. Relationship between uncertainty management and requirements engineering

Works that explore the intersection between requirements engineering and innovation management, focusing on uncertainty management, are scarce in the literature, with few exceptions. Table 1 presents a summary of the related literature.

The two earlier studies in Table 1, from 2005 and 2008, have an exploratory nature. The first work presents the perception and practices of 16 companies regarding requirements change due to uncertainties [20]. The second study discusses uncertainties related to requirements engineering from a teaching perspective [21]. The two most recent studies propose solutions to the problem. Salay et al. use partial models to represent uncertainties in requirements [6]. Heimes et al. offer an approach for identifying uncertainties based on the product structure and requirements [22].

Table 1. Literature relating uncertainty management and requirements engineering.

Authors / reference	Main results
Sillitti et al. (2005) [20]	Survey 16 companies' perceptions and practices regarding requirements change due to uncertainties.
	Compare companies applying Agile-based processes (8 companies) and companies relying on document-based requirements engineering (8 companies).
Barnes et al. (2008) [21]	Discuss the teaching perspective for uncertainties related to requirements engineering.
	Present a critical assessment of the teaching experience.
Salay et al. (2013) [6]	Propose the use of partial models to represent uncertainties in requirements.
	Present the proposal implementation and exemplifies the application.
	Focus on software development.
Heimes et al. (2020) [22]	Present an approach for identifying uncertainties based on the product structure and related requirements.
	Describe the approach application.
	Focus on battery development for electric mobility.

The two most recent studies (Table 1) focus on dynamic markets – software development and battery development for electromobility.

2.4. Synthesis of the literature

The literature and practice on requirements engineering are well established [2,5]. Nevertheless, there is a recent stream of studies focusing on streamlining requirements engineering [3,13], especially in highly innovative settings, which are also characterized by high levels of uncertainty [15].

Innovative projects with a high level of uncertainty require specific approaches [1,15]. However, the intersection between requirements engineering and innovation management is still underexplored in the literature. The existing works contribute to clarifying the problem and offer the first solution approaches [6,22]. They also indicate further development opportunities. Beyond identifying uncertainties, it is also necessary to support acting on them. Building on existing knowledge, novel approaches are needed to track uncertainties evolution linked to requirements management.

3. Method

This research applies Design Science Research (DSR) methodology in order to propose and assess an approach to bridging uncertainty management and requirements engineering in R&D projects. The DSR is indicated when the research goal involves generating new artifacts such as constructs, models, methods, and instantiations to address a given problem [7]. For instance, Benfell applied DSR to propose and assess a UML-based modeling approach for functional requirements [23].

The DSR methodology involves six steps: 1) problem identification, 2) objectives definition, 3) design and development, 4) demonstration, 5) evaluation, and 6) communication [7].

This research is motivated by the need to monitor uncertainties evolution along with requirements engineering in innovation projects with higher levels of uncertainty. The literature research discussed in Section 2 indicates an opportunity to explore further the relationship between uncertainty management and requirements engineering by actionable approaches for the project teams. The research is also motivated by the authors' practical experience in a highly innovative R&D project facing uncertainties related to some important requirements.

Based on the opportunity identified in the literature and practice, the research goal is to develop an approach to bridging uncertainty management and requirements engineering in R&D projects.

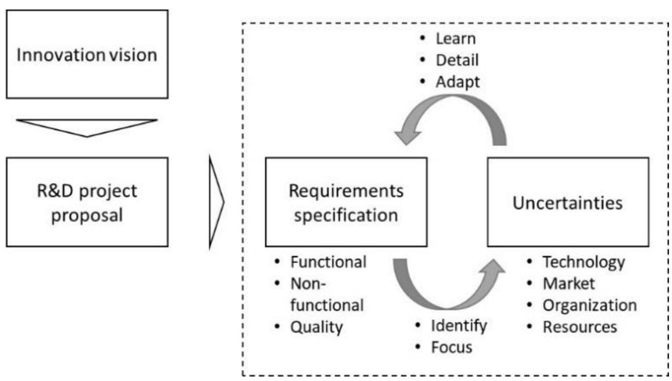
Following the DSR methodology steps, given the problem identification and objectives definition, the design and development of the solution are summarized in Section 4. The demonstration and evaluation are discussed in Section 5. The communication is achieved by means of this publication.

4. Proposal

The proposed approach is presented in Figures 1 and 2. Figure 1 provides an overview of the approach boundaries and course of action. Figure 2 details the approach procedure and related databank.

In order to solve the identified problem, the approach considers the requirements specification as a source for identifying uncertainty. Based on each requirement, the project team can discuss the existing uncertainties by asking what is known and what is unknown in every category – technology, market, organization, and resources. In this way, the requirements documentation, considering functional and non-functional requirements, provides the basis for identifying critical uncertainties. Identifying uncertainties based on requirements supports the project team in focusing efforts on solving uncertainties that are directly related to the final solution. At the same time, recognizing uncertainty levels in critical requirements allows the project team to further detail the understanding of selected critical requirements (Figure 1).

Fig. 1. Approach overview and boundaries



In order to operationalize the approach, amendments are proposed to the requirements documentation and respective databank. In addition to the typical requirements identification, description, and classification, novel data fields are necessary to specify the requirements-related uncertainties and the prototype planning (Figure 2).

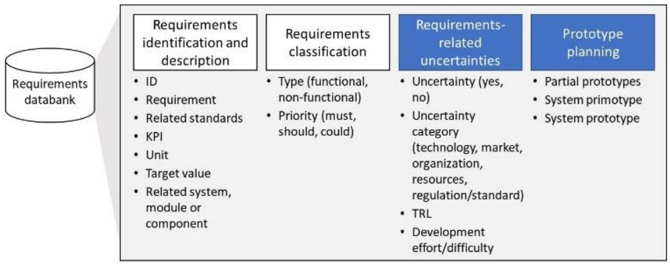


Fig. 2. Requirements databank and information for the proposed approach

The description of the requirements-related uncertainties should indicate, for each requirement, if there are uncertainties for requirements fulfillment. The uncertainties are considered at the project organization level – unknown to the project team – and categorized (technology, market, organization, and resources). Besides, especially for technology-related uncertainties, it might be useful to assess the state of the art in terms of the Technology Readiness Level. Finally, the team can estimate the necessary effort in order to overcome the existing uncertainties. The prototype planning allocates requirements and respective uncertainties to specific prototypes to be constructed to support learning and uncertainty mitigation (Figure 2).

The requirements-oriented identification of uncertainties is expected to support the project team in identifying the most relevant uncertainties and directing the necessary efforts to overcome them. One application of the proposed approach is described in the following section.

5. Demonstration and initial evaluation

This section presents the demonstration and evaluation of the proposed approach. Section 5.1 details the case application context. Section 5.2 describes the application. Section 5.3 discusses the initial evaluation and implications for theory and practice.

5.1. Case application context

The proposed approach has been applied in developing an electric vehicle charging robot. The solution is intended to provide mobile and flexible charging infrastructure to complement the traditional stationary electric vehicle charging points. The solution builds upon a light electric robot platform designed for logistics applications. Mechanically, electrically and electronically, the vehicle must be heavily modified to fulfill its new utilization. The vehicle platform will transport the loading battery and the required power electronics. The solution also has a user interface and a communication display. Figure 3 presents an overview of the solution concept.

The solution is considered highly innovative due to its features, including high-voltage, high-capacity battery, battery-to-battery charging (from the robot to the electric vehicle), and fast charging capability. Due to the high novelty level, the project involves uncertainties. This is expected in this type of project (as discussed in Section 2).

Due to its complexity and multidisciplinary nature, the project consortium is composed of two research institutes (one lead) and four partner companies. The overall project duration is three years.

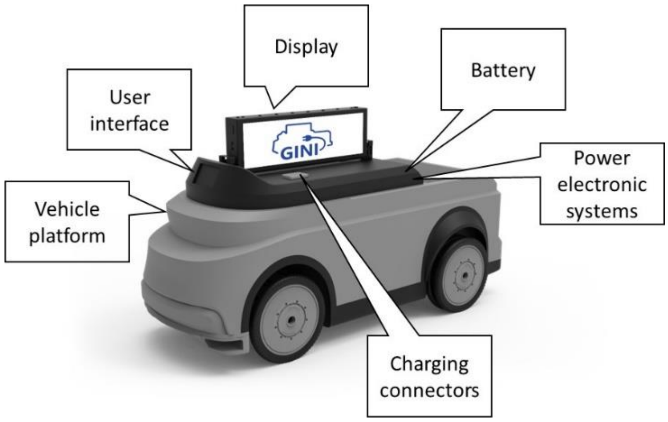


Fig. 3. Case application overview

The project will result in two main system-level prototypes – one preliminary partially functional prototype, called primotype, and a final completely functional prototype. The primotype serves as a testbed for technology development. It allows the team to anticipate critical uncertainties, learn from them and evolve the solution for the final prototype.

5.2. Application

The proposed approach was applied (pilot application) during the project execution, yet in the initial phases, just after the identification of the project requirements. The project team, faced with innovation challenges, considered applying a structured approach to identify and tackle uncertainties.

In the pilot application of the proposed approach, the requirements document specification was transferred to a database following the defined structure (Figure 2). In total, 277 requirements were registered. Thereafter, the requirements served as the basis for uncertainty identification. Moreover, along with project evolution and team activities, requirements-related uncertainties were continuously registered in the databank.

During the process, the need to extend the uncertainty category types was identified. Beyond the four categories defined in the literature – technology, market, organization, and resources – a fifth category related to standards and regulation was included. As rapidly evolving areas, electric vehicle charging and autonomous driving face evolving standards and regulations that must be continuously followed.

In order to illustrate the application, five examples of requirements and related uncertainties are described:

- The converter topology must be able to work with overlapping voltage levels. However, typical high-voltage (HV) DC-DC converters, even if they are bidirectional, need a minimum voltage difference. In order to mitigate the identified uncertainty, the team was enhanced with additional members to provide the necessary knowledge and support further development.
- Considering the charging from a mobile battery, the need for galvanic isolation was unclear. This uncertainty was mitigated by extensive research and information gathering with potential suppliers.
- The inductive charging function was required to allow bi-directional charging (robot to station and station to robot). However, existing inductive charging solutions are mostly unidirectional. The gap demanded further development efforts in partnership with a supplier.
- The follow-me autonomous driving function was under development for the desired application of the platform vehicle. Considering the necessary development effort, this function was foreseen for the second most mature prototype round.
- The overall system weight was restricted to the maximum load capacity of the vehicle platform. However, due to the high-power charging requirements and related power electronics, the system weight was at a critical level. The total system potential weight started being monitored continuously, and the weight was considered a critical parameter for the selection of every component and module.

Hence, based on the solution's requirements, the proposed approach supported the systematic identification of existing uncertainties. Moreover, uncertainties were documented and classified, providing the basis for mitigation actions. The pilot application provided the necessary inputs for the evaluation discussed in the following section.

5.3. Discussion

The evaluation of the proposed approach indicated strengths and limitations. Regarding strengths, applying the proposed approach increased project management's awareness of uncertainties (unknowns). Requirements also demonstrated to be a meaningful starting point for uncertainty identification in an early project phase providing necessary focus and supporting early action. Another strength is related to the relatively simple but effective documentation of identified uncertainties.

In terms of limitations, continuously maintaining the requirements databank was challenging, as also observed with similar tools. This challenge is especially critical in smaller project teams. A responsible must be assigned to track requirements and related uncertainties. Another challenge refers to the information distribution among the team members and project partners. The mindset brought by the approach supported project management. However, disseminating attention to uncertainty to the whole team could not be guaranteed by the proposed approach alone. This might require additional organizational actions.

The proposed approach contributes to the literature and practice. In theoretical terms, the proposed approach adds to the literature on the intersection between requirements engineering and innovation management focusing on uncertainty management [6,20–22]. It also differentiates from the Learning Plan [1] by directly relating uncertainty identification to project requirements.

In practical terms, it offers a novel way to identify and act upon uncertainties that may be relevant for engineering teams working on innovative projects. Relating uncertainties to widely disseminated requirements engineering may also support increasing awareness of uncertainty management at project level.

6. Conclusion

This paper presents a novel approach to bridging uncertainty management and requirements engineering in R&D projects. More specifically, the approach considers that requirements may serve as the basis for uncertainty identification and the definition of the necessary actions.

The proposed approach has been applied in developing an electric vehicle charging robot. The pilot application supported the initial evaluation, as discussed in this paper.

This research has some intrinsic limitations. The proposed approach was first applied in only one project. The pilot project was still underway at the time of preparing this paper. Nevertheless, the pilot application was able to provide insights into the approach's strengths and limitations.

Building on the current work, future research efforts may detail the related procedures, such as the periodicity for reviewing and updating uncertainties and the abstraction level of the documentation. Future work may also expand the approach assessment to other projects. Further research is needed to extend the approach to explore uncertainties beyond the defined project requirements. Moreover, evaluating the approach's effectiveness in relation to other existing methodologies, such as the Learning Plan, can be relevant for theory and practice.

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