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Integrating requirements engineering for different domains in system development – lessons learnt from industrial SME cases

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Abstract

There is a trending transition for companies from offering products to solutions in order to fulfill better customer needs and to reduce environmental impact by e.g. dematerialization. This solution-based development has an associated integration of intelligent devices that contributes to increasing system complexity. The ability of systems engineering processes, methods and tools to cope with these developments is a critical factor for manufacturing companies today. Still, in many cases it is hard to find adequately trained people and sufficiently integrated development tools for complex solutions, especially in the case of small and medium sized enterprises. Often, the tangible (hardware) part of the solution is primarily developed and the intangible parts (software and services) are added on top. However, key for a successful development is to adapt and integrate all parts according to the requirements set for the solution. Thus, it is essential how requirements are worked with during systems engineering and how they influence the development of the tangible and intangible parts of the solution. The objective of this paper is to study the approach of different industrial use cases for requirements engineering in system development. The aim is to identify how practices from domains like mechanical engineering, software or service engineering can be adapted for an integrated requirements engineering for complex systems, like product-service systems.

Keywords: Systems Engineering; Requirements Engineering; Product-Service Systems; Industrial Case Study

1. Introduction

Industrial companies are a set of human competencies, skills and machine technologies able to realise complex processes. In order to remain competitive on the market, a wide range of services is added to the physical product in order to deliver new personalized functions and other benefits as a holistic solution. This trend has originally been named as the “Servitization” of business [1] and led to the introduction of Product-Service Systems (PSS) as a promising framework describing the integrated development, realization and offering of specific product-service bundles as a solution for the customer [2]. Additionally, rapid technological changes combined with a highly competitive market have induced a need for e.g. implementing new processes and production methods for reducing “time to market” [3], waste and failures, as well as in order to be both appropriate in terms of quality and cost effective [4] and meet the customers’ expectation. PSS also enable the companies to meet higher environmental goals set by e.g. the United Nations [5]. As the PSS implies that instead of buying the actual product, the customer pays for the function there is a change of the right of disposition [6]. This change in ownership transfers the responsibility of care for the product to the provider instead of the customer, and moves the focus from consuming to using products. Therefore, PSS is often seen as a way toward a more resource efficient and effective solution with less environmental impact, as stated by e.g. Tukker and Tischner [7], Lindahl et.al [8] and Sundin and Bras [9].

Incorporating sustainability aspects can be a challenge for SMEs, regarding the amount of experience within the
The main prerequisite for successful systems engineering is understanding the underlying needs, and thus the requirements for a solution throughout its entire life cycle [14,15]. In this context, it is essential to investigate and identify the requirements of the system elements to design. For this reason, a suitable Requirements Engineering (RE), which aims to understand and capture stakeholders’ needs and related requirements, is the foundation to allow a successful change to holistic solutions in manufacturing industries. A major challenge in this process is the integration of the different domain perspectives. Berkovich et al. [16] identify product, software and service engineering as relevant domains for different PSS components. They list dedicated RE approaches in each domain and analyse their suitability for PSS. On this basis, the need for an integrated RE approach for PSS is justified. Continuous interaction between the systems engineering process and RE for all elements is inevitable for ensuring a consistent and traceable elicitation of requirements [17].

The objectives of this paper are to elaborate the specific challenges for complex systems engineering, focusing on the RE process; to understand the application of RE methods and tools from different domains in industrial cases; and finally to identify good practices towards an integrated RE approach. The next section (2) will first describe the research approach and will identify the main research questions. Section 3 contains the theoretical background, while section 4 presents the description of the industrial use cases. Section 5 summarizes the results, concludes the research and presents next steps.

2. Research Objective and Approach

The main question to be answered in this paper is what are the challenges of RE for complex systems and which methods and tools are applied by companies to successfully develop and offer such solutions? For this we first need to know what characterizes complex systems engineering and which characteristics are relevant for the RE process. Secondly, which methods and tools exist in the different domains and how are they applied in industry. Based upon such an analysis, we can identify the needs for an integrative approach for complex systems, such as PSS. This leads to our research objective:

To investigate how RE methods and tools are applied in industrial SMEs to design complex systems based on selected case studies.

In order to reach this objective, our methodology uses an exploratory approach, analyzing RE methods and tools for different domains described in literature and applied in several industrial use cases. Relevant literature has been identified based on previously published papers, mainly a literature review in Wiesner et al. [18]. This literature review has analysed 41 books, journal and conference papers in English and German language related to RE for PSS from the multidisciplinary SCOPUS database, complemented with papers from additional sources, such as Web of Science. Working with the industrial use cases, the researchers have been involved in the specification and development of the systems engineering scenarios during the last three years. More specifically, action research was applied [19], conducting multiple on-site workshops with representatives from different departments.

3. Theoretical Background

This section gives an overview on the theoretical background in the scope of this paper. First, the role of RE in systems engineering and approaches from the product, software and service domain are presented. Second, the challenges for PSS development in SMEs are discussed.

3.1. Requirements engineering

RE describes a process where the needs of one or many stakeholders and their environment are established to find the solution for a specific problem [20]. Thus, it is the key to success of every system development project. RE continues along the life cycle of a system and secures a consistent and traceable elicitation and management of requirements, e.g. depicted in the “V-Model” for systems engineering [17]. Usually, RE activities can be distinguished between requirements development (elicitation, analysis, specification and validation) and requirements management (traceability, change management and qualification) [21].

The purpose of RE is to understand the problem that arises from the needs of stakeholders, including, but not limited to, customers and end-users and transform it into requirements to define and design the related solution. This means that the RE focus is about the interaction of the solution with the problem, and not the behavior of the solution itself. For complex systems, the RE approaches applied must be able to develop requirements for a rising amount of tangible and intangible components, from both a growing number of distributed stakeholders and multiple disciplines. Furthermore, it must also be able to manage a high number of interrelated requirements that may dynamically change during the solution’s lifecycle. Several authors have proposed RE approaches for systems and different domains, which are described below.

For product development, RE approaches have already been implemented with a high degree of formalization. Structured fundamental models exist that provide a general development procedure including RE. However, they focus almost exclusively on requirements development as the main process, which is only conducted at the beginning of the development approach, e.g. by specifying the product requirements document [22]. Sometimes, also aspects of requirements management are adopted, but without explicit instructions for implementation [23]. For requirements
elicitation, first, the stakeholders are identified; however, procedures for the elicitation of requirements for product-related services are not described. Moreover, there are weaknesses in the derivation of requirements from the customer’s value chain processes, and cross-domain knowledge is not considered [16].

In the software sector, RE is widely recognized as a special discipline; RE “has begun to evolve from its traditional role, as a mere front-end in the software development lifecycle, towards becoming a key focus in the software development process” (p.11) [24]. In direct comparison with product and service development, RE is integrated deeper and more comprehensive into software development [23]. Customer-integration is emphasized in the software engineering approaches, but the focus is laid upon the software domain – interdisciplinary requirements are not considered. The procedures provided for the identification of conflicts focuses solely on the software domain; interdisciplinary conflicts are not discovered. Negotiation with stakeholders is suggested to resolve conflicts and find a compromise [16].

Models for the systematic development of services have been created [25]. However, no systematic procedures for the implementation of RE have been established, because the characteristics of a service, e.g. its complexity, pose greater challenges. Thus, service engineering procedures do not integrate a holistic RE until now, but focus more on methods like “trial and error” [26]. The elicitation process in service engineering comprises the tasks of identifying essential information – e.g. service ideas, possible customers and their expectations, and the sources of the requirements – and determining the goals, chances and risks. The procedures are service-domain specific; cross-domain knowledge is not considered. Furthermore, no precise methods for the elicitation are provided. Procedures for the requirements elicitation are described on a relatively general level [23].

Concerning RE in PSS development, a Business Use Case (BUC) analysis can be used to define the use-case model and a goal-oriented set of interactions between external actors and the PSS. It is proposed that hidden requirements can be elicited using Serious Games to investigate the PSS life-cycle [27]. Subsequently, a Design Structure Matrix (DSM) could be used to define the main functions of a PSS. Peruzzini et al. [28] propose a methodology to support the preliminary design of a sustainable PSS based on quality functional deployment (QFD). As the PSS business model is often used as an argument for lower environmental impact but despite this argument there is still missing methods how to incorporate environmental aspects within the system perspective PSS require [29].

However, the mentioned approaches are rarely used integratively in real complex system development. In the following section, several industrial case studies will be presented, which show the actual usage of methods and tools in such scenarios, as well as their drawbacks.

3.2. Small and Medium sized Enterprises

SMEs have a positive perception of adapting more innovative and new business ideas e.g. PSS to fulfill their customers’ needs [30]. Design process undervalued or not considered in SMEs [31]. Time spent on RE and truly understanding the customers’ needs will be recovered later in the development process [32]. As the Pareto principle could be used to argument that about 80% of the cost and environmental impact is determined by the first 20% of the activities in the development it is of high importance to not underestimate the affect RE has in the process. ICTs could be utilized as a mean for the provider to offer supplementary services to the already supplied solution, and facilitate operation and administration processes [30], while also helping to enable and improve communication with stakeholders, and increase social inclusiveness and empower the voice of the customer [33].

4. Industrial Case Studies

In order to investigate how RE methods and tools are applied in SMEs to design complex systems, five case studies from different sectors are presented in this paper. They use different approaches for RE without combining the viewpoints of all domains involved. Thus, these use cases can support the identification of the main challenges for integrated RE.

4.1. Use Case A

The company is a Spanish medium-sized tool manufacturer, which designs, manufactures and commercializes precision cutting tools and thread rolling tools, particularly for automotive and aviation. Although the individual tool is quite inexpensive, the clients are very cost-sensitive as usually a large batch is required. In addition, the development cycles are short, as the customer expects a fast solution to the manufacturing problem. Thus, a full service solution, where the customer needs are quickly identified and transformed into a specification, while the tools are delivered and billed to the customer as required provides a decisive competitive advantage. This has led to the decision to sell e.g. "holes" instead of individual milling tools.

As the company is coming from a product focused business and does not have much competence in service development, the RE methods and tools applied to develop such a result-oriented product-service system are still very traditional and product-focused. In a first step, the sales department contacts the customer to analyse the parts to thread, the machine and other necessary specifications. Based on this, customer’s needs are identified and transformed into product requirements that are documented on a paper template. This requirements specification is handed over to the engineering department, which designs the tools and calculate the production cost. In return, the sales department uses this information to create the individual product-service offer for the customer.

It can be noted that the RE process focuses on the tangible part of the solution, while requirements for the intangible parts (e.g. service level, payment models) are not systematically elicited and managed. In fact, the service offer is specified with the product already designed. This limits possible trade-offs between the tangible and intangible elements, e.g. enhanced tool lifetime with less frequent replacement services.
4.2. Use Case B

The company is a Spanish umbrella organisation for more than 500 associated companies from the wood and furniture sector. It performs research, technological development and provides innovation services to its associated members and customers. The solution provided to national and international companies as the final customer is the renovation of office spaces. The company plans the design, selects new furniture together with the customer, and then executes the renovation project. In this case, it is essential for competitiveness to match the design and functionality of the new office furniture to the customer requirements as good as possible.

Being primarily focused on service provision, the RE process is not very structured and only a few tools are used. The customer contacts the company to discuss the requirements of the renovation with the service department in order to develop the new decoration project. After identifying the main requirements and examining different possibilities in workshops, several offers are created, including specific alternative options. Proposals are evaluated by the customer, considering design, corporative colours and other parameters. After several iterations, one proposal is accepted. Only then, a furniture producer is contacted to manufacture the furniture according to the already fixed requirements.

In this case, the RE process focuses on the intangible part of the solution (the renovation design), while requirements for the tangible part (the furniture) are only derived from the final service offer. Therefore, only standard furniture or limited adaptations can be included into the project. More individual customer needs require time and cost-intensive coordination efforts.

4.3. Use Case C

The company is a German SME vendor for the aviation sector. It offers fully integrated solutions for surveillance systems, certified according to aviation standards. Customers are airlines, which retrofit their aircraft with the buyer furnished surveillance solutions from the vendor. It generates video streams, which are stored on a memory cartridge within a central video recording unit. As the system is certified, it cannot easily be changed to offer additional functionalities for a competitive advantage. Instead, the company is moving towards offering solutions integrating services, such as video archiving or analysis.

As a system integrator, the company’s RE methods and tools are focused on the hardware and software elements of the system. The customer contacts the sales team of the company and communicates the needs for a surveillance solution in an unstructured way. The engineering department checks the technical feasibility and creates a first lightweight specification to be validated by the customer. These tasks are supported neither by tools nor by a standardized method. After this, the requirements definition takes place. Functional requirements, as well as those describing the performance, handling or integration of the solution to be developed are defined and documented thoroughly by the engineering staff. An iterative approach is followed here in order to gather all requirements.

The task it is mainly done without the customer based on spreadsheets, which do not support all issues of requirements management, requiring a lot of manual work especially for the change management.

While the RE process is well structured for the technical part of the solution, still adequate tools for requirements management and stronger customer involvement are missing. Furthermore, requirements for services beyond mere software functionality are not considered in system development, thus payment and maintenance models offered to the customer might not be aligned to the final system.

4.4. Use Case D

The company is an Italian medium-sized manufacturer of fine woollen fabrics. It provides the fabrics as a solution for the fashion industry, designing raw material choice, style, and colour together with the customer. A great variety of products (about 1000 fabrics) is designed each year, for which physical prototypes are realized. While cost is not the main competitive factor for the clothing industry, the wide choice and newness of fabric designs is very important. Only few of the original prototypes are selected for production, which makes the process highly cost intensive.

During RE, first requirements for the new collection are derived from previous year sales, since they provide ideas on the most asked fibres weaves and colours. Designers use this information to create a collection of different fabric styles, for which a physical prototype is produced for every variant. The customers from the clothing industry, according to their specific requirements, indicate those variants they are interested in or ask for other variants not included in those presented. Based on this feedback, the final collection of fabrics is specified.

The RE process is conducted in a “trial and error” style in this case. The main methods used are extrapolations from previous sales, and physical prototypes are the main tool to collect requirements from the customer. There is no requirements take up for the design service itself, where the physical fabric is only the result of the interaction with the designer.

4.5. Use case E

The company is a Swedish medium-sized manufacturer and supplier of complete grinding and maintenance systems for floors. Their systems include a complete concept that takes into account economy, ergonomics and ecology. The business concept is to develop, manufacture and sell professional flooring solutions, e.g. grinding and cleaning. The company aims to fulfill not only the buying customers’ needs but also in turn their customers’ customers’ (or final users’) needs, e.g. architects, cleaning companies or property users. The company sells solutions that might be higher investments but lowers the cost over time thanks to e.g. reduced maintenance costs. The head office is based in Sweden, and subsidiaries operate in USA, Germany, UK and France to have a closer connection to their markets.
Requirements usually originate from the marketing department whom represent the customers voice and the product manager compiles the requirement specification by using regular word processor e.g. word (no specific RE tool or method is used). Requirements may also come from internal stock, installation or purchase. The requirement specification is used as a list in order to be able to check whether developed solutions fulfil the requirements or not.

There is a lot of focus put on market requirements, specific functional requirements and effects of the product. Legal requirements are of course always considered. The identification of requirements can come from performed market surveys and internal requirements are often based on finance but can also be based on what seem to be a logical solution. Specific requirements for the products can be set by different kinds of certifications such as CE for the European market and UL required for the US market. Requirements can also originate from issues with complaint products.

5. Use Case Findings

The following table presents an overview of the analyzed use cases and their characteristics:

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Sector</th>
<th>RE Focus</th>
<th>Meth. and Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Spanish SME)</td>
<td>Tools</td>
<td>Product</td>
<td>Paper Temp.</td>
</tr>
<tr>
<td>B (Spanish Organization)</td>
<td>Furniture</td>
<td>Service</td>
<td>Notes</td>
</tr>
<tr>
<td>C (German SME)</td>
<td>Aviation</td>
<td>Hardware</td>
<td>Catalogue Opt.</td>
</tr>
<tr>
<td>D (Italian SME)</td>
<td>Fabrics</td>
<td>Product</td>
<td>Extrapolation</td>
</tr>
<tr>
<td>E (Swedish SME)</td>
<td>Floor solutions</td>
<td>Product</td>
<td>Lists</td>
</tr>
</tbody>
</table>

Based on the findings, it can be stated that the RE process in the cases mainly uses methods and tools from the traditional field of business of the company, e.g. product development for manufacturing companies, service design for service providers, and hardware and software engineering for system integrators. Requirements for newly integrated elements of the solution from other domains are only provisionally included in this process. This can be explained with a hesitation to replace established practices that yielded good results in the past, but also with a lack of expertise beyond the core business domain in SMEs. As a result, elicitation and traceability of requirements for other domains or integration between the solution elements is limited, jeopardizing functionality and quality of the offer.

Additionally, it could be observed that the predominantly medium-sized companies do not follow a strictly formalized RE process. In most cases, some pre-defined activities are performed, but they stem from good practice rather than a developed methodology. This may enhance flexibility and delivery time, but has a negative impact on the quality of requirements specification. In connection with the less formalized processes, dedicated RE tools are seldom used by the companies. Apart from paper documentation and spreadsheets, (CAD) drawings or prototypes are applied. The functionality and pricing of dedicated RE tools is perceived to target larger companies and often the benefit is not immediately clear. Instead, during our work with the use cases, some basic actions to improve RE were taken, which are described below.

In use case A, it has become clear that the paper-based documentation of customer requirements often neglects service needs and hampers the comparison with existing tools and thus for a faster and cost-effective solution. Therefore, an electronic selling tool has been proposed and is currently being implemented that on the one hand guides the elicitation of requirements for all involved domains and on the other hand enables to immediately quote e.g. full-service costs per “hole” to the customer. For use case B, the unstructured RE process and the late involvement of standardized product (furniture) components limits the possible solutions and thus the degree of fulfilment for customer requirements. Based on the findings, the organization develops a tool to collect customer feedback on a proposed office design, including the possibility to adapt furniture early to the requirements. The tools used in use case C provide no possibility to document service requirements and estimate the effects of changed requirements to other domains. In order to better integrate services into solution design, the company has decided to develop a requirements management software suitable for SMEs, which enables the traceability of requirements between hardware, software and service elements. In use case D, the RE process depends on the availability of visual and haptic prototypes to collect feedback from the customer. In order to reduce time and cost, it has been decided to create virtual prototypes that can present different designs on the same physical material. For use case E, more stakeholders need to be included into the elicitation process. E.g., the design department, and market and sales are currently excluded. Therefore, far into the development process new demands and requirements raised by design or the customer cannot be considered. The tools used today also miss support for cross-domain validation and traceability of the included requirements to set a necessary common ground for the development.

6. Summary and Conclusions

Systems engineering is evolving from a centralized development process for individual systems and components towards the orchestration of distributed product, software and service processes as an integrated solution. The scale and complexity of the objects targeted by systems engineering is constantly growing, reflected by the emergence of PSS. Requirements from additional domains have to be considered and integrated. Companies aiming to provide such offers have to adapt and apply suitable RE processes, methods and tools accordingly. SMEs with their limited resources and competences seem especially challenged here.

Thus, five SME use cases have been analyzed for the RE processes, methods and tools applied. It could be shown that integrated approaches are seldom used. Most of the time, non-formalized approaches from the original business domain of the company are used for RE, neglecting part of the requirements and requiring additional integration in the end. The analysis further shows that the benefit of current dedicated
RE tools for SMEs is questioned or misses integrated support for complex system development. The main points identified are a greater number of requirements, multiple distributed stakeholders and the involvement of several disciplines with their own formalisms and models, such as product, software and service engineering. For the individual cases, some supportive action have been proposed and implemented.

However, research in this paper has been limited to a small sample of SMEs that move from isolated offerings in different domains to integrated PSS solutions. Thus, the challenges might only be representative for similar companies. RE processes, methods and tools used in larger companies and companies that are already mature in offering PSS should be analysed in addition and may provide insights to support SMEs in this regard. Nevertheless it can be stated that SMEs need more guidance to formalize their RE processes and integrate domains beyond their traditional business. This requires the implementation of appropriate interfaces or translation between domain specific and common requirement activities. Furthermore RE tools are needed that specifically satisfy SME demand on functionality and pricing, while still offering cross-domain support for complex systems. Addressing the identified challenges with an integrated RE framework would help to make the development of such complex systems more cost effective and faster, while retaining a high system quality.

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