Relating Product Line Context to Requirements Engineering Processes Using Design Rationale

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Abstract: The design of engineering processes is dependent on the context they are designed for. This paper presents the results of an action research study that used design rationale to discover a number of contextual factors that provide criteria for designing a requirements engineering process in a given product line environment. The presented context dimensions and process design argumentation provide a starting point for understanding product line context and how supporting engineering processes are designed, communicated, and evaluated.

Kewords: product lines, context, requirements engineering, process design, design rationale, action research

1 Introduction

Product line engineering is adopted by a number of companies as a means to increase product individualization, to reduce development costs, to enhance product quality, and to reduce time-to-market of products. These benefits are achieved by reusing domain artifacts and exploiting product line variability [PBL05]. The use of a product line approach, however, comes with a number of challenges. Compared to single-product development, product line engineering introduces a new level of complexity in designing artifacts and engineering processes.

The product line approach adds additional challenges when used in large and distributed organizations. Coordination and communication problems will occur, as distance plays a role [GF07]. Here, requirements engineering is in the focal point, as requirements are a key instrument for achieving coordination. Requirements specifications define agreements between stakeholders. Therein contained requirements capture objectives and expectations of these stakeholders.

Without requirements engineering processes that integrate product line development, complexity can hardly be mastered. Communication breakdowns happen and islands of development emerge that lead to a product line that consists of heterogeneous, rather than homogeneous, parts. Quality of the resulting product line is disastrous, as short-sighted decisions are taken to meet reasonable delivery dates with non-fitting parts. Ultimately, the company risks loss of customers and revenue.

We used action research [DMK04] to better understand the factors that influence the design of such requirements engineering processes. The research was carried out parallel to the development of a concrete process in an industrial environment. Design rationale [MC96] was used to relate objectives and product line context to the design of the requirements engineering process that was adopted by the company. Design rationale helped to recognize and express the interdependencies of context and design. The conceptualization of context influences the shape of the process, and questions in the process design were used to discover the facets of the context that were relevant.

The paper describes those facets of product line context that matter in the design of a supporting requirements engineering process. It shows how design decisions can be justified by a specific constellation of product line context. The results provide a starting point for moving from tacit, experience-based, and person-dependent process design towards a model for using concrete characteristics of product line context for guided design and evaluation of engineering processes.

The paper is structured as follows. Section 2 describes background and related work. Section 3 characterizes the case organization and outlines the research method. Section 4 describes the conceptualization of context that emerged from the research study and the use of design rationale for the design of a requirements engineering process. Section 5 discusses the research results. Section 6 concludes.

2 Background and Related Work

The behaviour of development organizations is often characterized by *process reference models*. A process reference model describes a number of process areas in terms of the goals that are pursued and the practices that are implemented to achieve these goals. A widely spread reference model of product line organizations is the framework for software product line engineering [PBL05]. The process areas primarily related to requirements engineering are product management [WBN06], domain requirements engineering, and application requirements engineering.

In addition to the pursued goals, a number of *contextual factors* influence the design of engineering processes. For example, organizational structure [Ha03], social and political concerns [ORS05], and distance [FG07] have an effect on how requirements engineering is performed. To construct requirements engineering processes for specific product line contexts, process engineers would greatly benefit from a framework for conceptualizing the relevant context and identifying optimal design decisions. The lack of such a framework forces such engineers to adopt a costly trial and error approach.

The process reference models and a specific organization were taken as a starting point towards establishing a *joint model* of product line context and requirements engineering processes. *Design rationale* was used to relate product line context to the design of a requirements engineering process. Design rationale captures the motivations for initiating design, the objectives and conditions that give rise to shape [MC96]. In the context of process design, such rationale is also called method rationale [RTRL00].

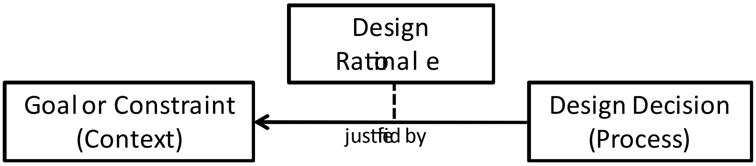

Figure 1. Design rationale relates process design to objectives and context.

Figure 1 describes the kind of design rationale used in this research. Process design is concerned of a number of design decisions such as which methods are used, how requirements are structured, and how stakeholders are involved. The process is designed to address a number of objectives and to fit contextual constraints. A specific combination of one design decision with its justifying goals and constraints is captured by a design rationale.

Design rationale captures design knowledge that emerges as a result of reflections during process design, independent of the process design method applied. It is useful to explaining the process, to support process evolution, and to advise other process designers in conceptualizing context and reusing design knowledge. The design rationale for a specific process can be generalized into a process pattern [HL05].

3 Research Method and Process

3.1 Studied Organization and Product Line

The research has been performed at ABB. ABB is a leader in power and automation technologies that help enable utility and industry customers to improve their performance while lowering environmental impact. The ABB group of companies operates in about 100 countries and employs more than 110,000 people. The research project took place in one of ABB's global organizations. The overall product line effort aimed at reducing hardware and software cost and at implementing new domain-specific standards. The organization had a tradition in product line engineering and performed at the product line maturity level [Bo02].

The first author of this paper was employed by ABB at the time of the study. Of the global organization a product management unit and a development unit, both located at two European sites, were involved in the project. The project client was senior management of the product management organization. A number of employees participated in the project: one process champion, two process developers, one information system engineer, two global product managers, half a dozen of local product managers from Europe and Asia, four product and domain architects, representatives from marketing, and three line managers. The researcher participated as a leader of the process development effort, as a requirements engineering expert, and as a facilitator. The project regularly reported to a steering committee that consisted of senior management from the product management and the development units.

3.2 Research Question and Method

Canonical action research [DMK04] was used as a research methodology to be able to contribute to knowledge, while providing results of immediate practical value. The general goal was to understand the context that is relevant for the design of requirements engineering processes in a product line environment. The project client was interested in establishing a company-wide homogeneous requirements engineering process. The success of the project was measured by the degree of process adoption, satisfaction of process performers and reported evidence of economic impact.

The launch-point of this research was the observation that it was hard to transfer requirements engineering processes from one organization to another. The aim of the research project, hence, was to explore the relationships between context and the design of suited requirements engineering processes. Of particular interest was understanding the kinds of contextual factors that influence process design decisions. The following research question was formulated: *which facets of product line context are relevant for the design of requirements engineering processes?*

The project followed the *cyclical process model* of canonical action research, which consists of diagnosis, action planning, intervention, evaluation, and reflection phases. The here reported research is based on one iteration in this cycle, which lasted one year. Subsequent iterations were started to adjust the requirements engineering process to other situations that can be described using the presented model of product line context. A description of these following iterations is out of scope of this paper, however.

The *diagnosis* phase established the objectives of process development and a first understanding of the product line context that was relevant for process development. Senior managers, a process champion, and a number of process performers were interviewed. Senior management appointed representative parts of the product line for process development, piloting and evaluation.

During *Action planning* a tentative requirements engineering process was designed. Requirements engineering concepts and methods that seemed to optimally suit given objectives and context were selected. The proposed process was then analyzed, debated, and adjusted by all involved members of the organizations. This negotiation ensured understanding and sharing of the rationale behind the process design, relevance of the process for the concerns of the process performers, feasibility with given tool support, practicability within time and resource constraints, and commitment to piloting the process.

During the *intervention* phase the agreed requirements engineering process was piloted. The IT infrastructure was adjusted to support the process. Training was provided to the process performers, by involving them into the definition of the requirements engineering process during the action planning phase.

Evaluation included monitoring the process and was performed concurrently to intervention. For this purpose, requirements and requirements specifications were regularly reviewed and experiences of performing the process discussed. Identified inconsistencies between process specification and actual practice got resolved as rapidly as possible. Hence the process was continuously adjusted to the context.

Reflection was performed both by the research and the practitioner side. The process champion, a product manager, wrote an experience report and recommended the adoption of the piloted process in the product management unit on a wider scale. One architect became a champion for adopting relevant parts of the process in the development unit. Global senior management decided to roll the piloted process out for the complete product line and to support further process development. This marked the start of a second action research iteration.

4 PL-RE Context

4.1 Product Line Context

Major design decisions for requirements engineering processes in a commercial product line company concern the structure, flow, lifecycle and storage of requirements and the definition of how and when different requirements engineering activities are performed. During the action research project the following major categories of product line context have emerged and affected the design of the requirements engineering process:

- **Technical context**: requirements provide the rationale for the design of the various parts of the product line; hence the structure of the product line influences the requirements engineering process.
- **Business context**: the people and organizations benefitting from the product line justify the effort and resources that are put into its development; hence the argumentation of benefits influences the requirements engineering process.
- **Organizational context**: the people and organizations managing and developing the product line aim at pursuing their objectives and interests; hence the organizational structure and behavior influences the requirements engineering process.
- **Geographical context**: different means for communication and coordination are used, depending on the distance between collaborators; hence geographical separation influences the requirements engineering process.
- **Historical context**: development is organized differently, depending on the lifecycle state of the product line and its various parts; hence the evolution of the product line influences the requirements engineering processes.

The following subsections discuss these categories in more detail.

4.1.1 Technical Context

The *technical context* concerned the structure of *engineering artifacts*. Such artifacts are the result of development projects and are recognizable stable entities in the overall product line. Every such project was a consumer of requirements and produced requirements for other artifacts as a result of negotiations with other projects. Two kinds of relationships between artifacts were of particular importance: the use hierarchy and the composition hierarchy.

The *use hierarchy*, Table 1, had the following implications on the requirements engineering process: an engineering artifact implements requirements posed by the next higher-level entity and provides interfaces for its use. It also uses interfaces and controls features of the lower-level artifacts, hence is subject to constraints imposed by these entities. The design of engineering artifacts requires understanding and negotiation of expectations, constraints, and interfaces along this use hierarchy.

Table 1. Use hierarchy. A higher-level entity acts on lower-level artifacts.

Entities	Definition
Users	Humans configure, monitor, and control lower-level artifacts through the use of software tools.
Software Tools	Software tools store, process, and present data and provide access to lower-level artifacts.
Secondary Equipment	Software-intensive equipment automates the control and protection of lower-level artifacts.
Primary Equipment	Electrical-mechanical equipment acts on the electrical grid and take measurements.

The *composition hierarchy*, Table 2, had the following implications on the requirements engineering process: requirements for contained artifacts are derived from design decisions for a containing artifact. The reuse of lower-level artifacts provides the efficiency and quality advantages that are expected from the product-line approach, but introduces constraints for higher-level engineering artifacts.

Table 2. Composition hierarchy. A higher-level artifact is composed of lower-level artifacts.

Entities	Definition
Systems	Specific arrangements of products to provide services and applications.
Products	Stable arrangements of components that provide a number of related functions. A product appears on a price list.
Components	Hardware or software that is systematically reused in the development of products.

4.1.2 Business Context

The *business context* concerned the objectives to be achieved by engineering artifacts. A number of abstraction levels were identified [GW06], with different kinds of benefits to be reached with the engineering artifact. Table 3 characterizes the four levels of the *benefit hierarchy*: strategy, economic factors, usage, and engineering artifact.

The business context provided the argumentation for justifying the concrete realization of the engineering artifact. The interactions between two abstraction levels were used for prioritizing and selecting requirements for releases of the artifact by exploring requirements refinement choices and evaluating requirements pertinence [HC88, Yue87, In04].

Table 3. Benefit hierarchy. Higher abstraction levels describe objectives of the company and lower levels how these objectives can be reached.

Abstraction Level	Definition
Strategy	Long and short-term company vision and goals pertaining to an engineering artifact and the market it addresses.
Economic Factors	Features that influence buying decisions and cost of the engineering artifact.
Usage	Requirements related to the usage of the engineering artifact, including functions and quality properties.
Engineering Artifact	Design decisions related to structure and behavior of the engineering artifact and utilized technologies.

4.1.3 Organizational Context

The *organizational context* concerned a number of *company functions* that acted on the engineering artifacts [Po85]. Every function has specific responsibilities and manages staff, knowledge, assets, and capabilities. The steering committee, consisting of senior managers, defined and managed the product line company. Product management steered the evolution of the engineering artifacts by coordinating marketing & sales, research & development, and production.

Negotiations between organizational units lead to a number of *contracts*. Every role had responsibilities and pursued objectives, which needed to be considered in the development of the engineering artifacts and balanced against each other. To speed up negotiation, product management and architects acted as principal agents and prepared contract proposals. A typical contract was a requirements specification for a release of an engineering artifact, which included expected benefits [GW06] and implementation proposals [FGM07].

4.1.4 Geographical Context

The *geographical context* concerned collaboration over distance. English was the language used for documentation as the organization was spread over the world. Instead of working in a document-based manner, requirements were stored in one common repository that was accessible from everywhere.

Specific tactics were used to adjust to local or remote collaboration. For example, while communication of requirements and domain knowledge are supported by frequent informal meetings in a collocated situation, a more structured, tool-based approach was needed to ensure requirements understanding with few meetings [FGM07].

4.1.5 Historical Context

The *historical context* concerned the evolution of engineering artifacts and the product line as a whole. Novelty of requirements played an important role; new requirements needed more effort and care to be analyzed, documented and communicated than requirements that were well known and understood. Compatibility of engineering artifacts over a number of versions yielded a number of constraints for development. Finally, the order of implementation defined the order of how requirements were fixed; early developed artifacts provided constraints for later artifacts.

4.2 Requirements Engineering Process and Its Design Rationale

The company decided to scope the process development project so that the requirements engineering process could be developed, piloted, and evaluated with given resources within one year. The process was developed according to the procedure described in section 3.2 by considering requirements engineering literature and by actively involving the process owners, participants and supporters. When consensus was reached, the process was piloted for two mission-critical products to gather lessons-learned.

The requirements engineering process addressed three *primary objectives*: continuous collection of needs, selection of requirements for a product releases, and communication of requirements to the development project team.

The *product line context* was fixed as follows:

- **Technical context**: requirements are engineered for one single control product (secondary equipment, product) that is part of a standardized control system and based on recently developed components. The product is operated through existing tools and controls well-established primary technology.
- **Business context**: product design needs to be justified by objectives from the whole benefit hierarchy.
- **Organizational context**: the requirements engineering process needs to be defined for the product management function. Product management acts towards research & development as a principal agent representing the steering committee, customers, marketing & sales and production.
- **Geographical context**: Product management is located at two sites in Europe, customers, marketing & sales, and production at various sites distributed over the whole world, and research & development at one of the two European sites.
- **Historical context**: the development adjusts an existing product to a new market and ports it on recently developed components. Hence, the majority of features

were well-known with a few quality attributes to be adjusted to the flavor of the new market. Compatibility concerns were defined as requirements.

Methods to address the three objectives in the given context were integrated into the overall *requirements engineering process* by basing the process on the lifecycle of market requirements [CR00]. To address need collection, the flow of needs towards product management was defined and responsibilities assigned to various roles working at a number of company sites. A globally accessible need database was established. Needs were collected from company management, marketing & sales, customers, and production. Requirements that were derived from the collected needs were structured according to the Requirements Abstraction Model [GW06]. Requirements selection was supported by informal goal [HC88, Yue87] and cost/value [KR97] analysis. The selected requirements were stored as a requirements specification in a globally shared requirements database. New requirements were specified in detail. Requirements related to reuse of features were specified by referring to the product line domain documentation. The requirements specifications for product releases were reviewed by important company-internal stakeholders of the product. Requirements communication was supported by handshaking with implementation proposals [FGM07]. Finally, a change management process was set up to manage change requests from product development.

A number of *design rationales*, summarized in Table 4, motivated the design of the requirements engineering process. These design rationales capture the reflections behind the process design and provide the motivation for both why the described contextual factors matter and why the process fits the specific context.

Table 4. Design decisions for the requirements engineering process and their rationales.

Design Decision	Rationale	Context
Backbone of process: market requirement lifecycle.	Engineering artifact: secondary equipment product.	Technical
	Process owner: product management.	Organizational
Need providers: steering committee, marketing & sales, customers, and production.	Product management acts as principal agent for these company functions.	Organizational
Globally accessible need database.	Globally distributed company.	Geographic
Distributed need collection responsibilities.	Globally distributed company.	Geographic
Requirements structure: Requirements Abstraction Model.	Justification of product design: argumentation using objectives from the whole benefit hierarchy.	Business
Goal analysis for requirements selection.	Justification of product design: argumentation using objectives from the whole benefit hierarchy.	Business
Cost/Value analysis for requirements selection.	Economic impact of development (implicit strategic objective).	Business

Design Decision	Rationale	Context
Varying requirements specification style.	Varied novelty of requirements.	Historical
Requirements specification reviewers: steering committee, marketing & sales, customers, and production.	Product management acts as principal agent for these company functions.	Organizational
Globally accessible requirements database.	Product management and research & development collaborate over distance.	Geographic
Requirements communication method: handshaking with implementation proposals.	Product management and research & development collaborate over distance.	Geographic
Change management process.	Stakeholders agreement required for changes to artifacts.	Organizational

5 Discussion

The requirements engineering process was developed and is in use in the described organization. Product management was satisfied with the *practical impact* of the process: "We get structure and quality in the work results and improve the communication about requirements. […] Because of the handshaking concept, research & development had significantly adjusted the scope of the development project and reconsidered one major decision about the components to be used in the product". Expressed was also, however, the early stage of process adoption: "Need collection is under start-up. Still to be addressed is that people assigned to the process also get the time needed for the work."

The positive results encouraged the continued use and further spread of the requirements engineering process. A second iteration of the research project was launched to extend the requirements engineering process for a more comprehensive coverage of the technical product line context.

The *research contribution* of the presented study is a conceptualization of product line context for the design of supporting requirements engineering processes. The role of design rationale for motivating relevance of contextual factors for process design was exemplified. The relationships between the requirements engineering process, the supported objectives, and the conceptualization of the contextual constraints provide the reasons that justify the process. With this understanding, process goals such as those of process reference frameworks [PBL05] can be achieved in a traceable manner.

Design rationale helps to split process development into manageable and foreseeable junks. Reusing design rationale helps to limit the scope of process development by limiting the context in which process design takes place. Further, design rationale can be used for designing a process in a constructive manner, rather than employing pure trial and error. Documented design rationale helps to share design knowledge for advising process developers confronted with contexts new to them with already-made experience.

Design rationale helps to communicate and train a requirements engineering process. Without design rationale, the process appears as a number of steps and records stored in databases. With design rationale, process stakeholders start to see interdependent pieces of the process that together make meaning in the context they are applied.

Other observations concern the *role of product line variability in process design*. The acquisition, analysis, explicit representation, and use of variability are differentiating factors of product line engineering. In the design of the requirements engineering process, however, these practices have played a less dominant role than expected. They were supported to some degree by the chosen requirements structuring mechanism, the Requirements Abstraction Model [GW06], and by spreadsheets that characterized product variants in the product requirements specifications.

The product line was not managed from a central authority using a comprehensive variability model. Instead, catalogues of available engineering artifacts were used at the different levels of the composition hierarchy. Constraints between the artifacts were negotiated between the organizational units as part of the requirements reviews and requirements communication activities. Hence, much of the understanding of variability and commonality of products was distributed in the organization and the knowledge of people that participated in product line engineering.

6 Summary and Conclusions

Product line engineering has great potential for enabling companies to increase individualization and quality of products, while at the same time increasing development efficiency. The adoption of a product line engineering approach, however, leads to a number of challenges related to the size and complexity of the product line. As a consequence, supporting engineering processes must be carefully designed to achieve their objectives in their given environment. Overcoming costly trial and error in constructing such a process requires access to knowledge of successful design.

This paper describes a successful action research study performed in a large global product line organization. Design rationale was used to capture how the product line context influences the design of requirements engineering processes. Five categories of context were of particular importance: technical, business, organizational, geographic, and historical context. The paper characterizes these categories and shows their use for explaining the design of a specific requirements engineering process.

The research results provide a starting point towards a general design framework for engineering processes in a product line context. Such a framework will help to reduce some of the challenges of process design, hence reducing process improvement cost and increasing the yield and acceptance of engineering processes. Future work includes studying how changes in product line context affect the design of supporting requirements engineering processes.

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