Target-oriented prototyping in highly iterative product development

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Abstract
The realization of radical innovations is a critical success factor in today's markets. When traditional sequential development processes are employed the high degree of uncertainty connected to these innovations results in a long and costly development time, potentially leading to failure of the project. The paper at hand recommends highly iterative prototyping processes based on findings from the software industry where agile processes, mostly Scrum, are widely employed. In the development of physical products, prototyping is often unsystematic which is considered as a major obstacle to an efficient agile development process. This paper presents a systematic method of prototyping in the context of physical product development in order to gradually reduce the high degree of market and technological uncertainty associated with radical innovations. The prioritization of requirements is suggested to be the basis for the design of adequate prototypes. An analytical information-oriented approach is presented that continuously takes into account the amount of uncertainty in the dimensions market, product and process. The evaluation of the specific ratio of benefit and effort connected to the implementation of the requirements leads to their prioritization.

1. Introduction
Short product life cycles and continually increasing customer requirements characterize today's markets. The majority of established manufacturing companies have difficulties to launch radically innovative hardware products at high speed - an essential ability to succeed in this dynamic environment [1,2]. The dominant approach in physical product development, the sequential Stage-Gate process model, is overstrained with the realization of radical product innovation [3]. Companies must rethink and restructure their processes to meet the requirements for a successful development of radical products [4]. Based on these thoughts, in this paper, we present a prototyping approach suitable for a highly iterative product development processes.

1.1. The characteristics of radical innovations
Radical innovations are characterized by a high degree of both market and technological uncertainty [5]. This fact makes it harder to control them compared to evolutionary and incremental innovations with their medium and low degree of uncertainties, respectively. The high degree of market uncertainty of radical innovations results from a lack of clarity about the target market and the market potential. Customer requirements are unknown and the willingness to pay cannot be easily estimated [5,6]. Technological uncertainty can be classified in terms of product and process. Concerning the product, a lack of information regarding technical specifications and technical feasibility exists for radical innovations. Furthermore, technical challenges are often unclear and the cost of development is difficult to predict. Regarding the process, a variety of alternative production processes and unknown production costs are characteristic for
radical innovations [5,7]. In Figure 1 a) the three types of innovations mentioned above are positioned in a graph according to their specific level of uncertainty in the dimensions market, technology (product) and technology (process).

1.2. Development processes as a function of uncertainty

In his article What’s Next?: After Stage-Gate Cooper states that “one size should not fit all”: The product development process should be adjusted to the specific degree of uncertainty [8]. In the case of incremental innovations which are based on existing market knowledge and technological know-how, it is appropriate to make use of approaches which systemize the process of innovation. Therefore, Cooper developed the Stage-Gate model, which structures the innovation process into separate phases [9]. A further reduction of the time to market and the development costs could achieved by a parallelization and forward displacement of activities, as with Concurrent Engineering and Front-Loading [10,11]. In the case of radical innovations, however, a learning-oriented approach is recommended [12]. Contrary to the clear hierarchical structures that are commonly used to manage daily operations, a high degree of agility and flexibility is necessary to give development teams more creative freedom. Being open to new ideas, as well as working target-oriented rather than process-oriented, are the basic enablers for successful market innovations [4]. Concerning evolutionary innovations a mixture of agile and sequential processes is suggested. Figure 1 b) visualizes the suggested types of development processes for the specific types of innovation.

1.3. Prototyping in agile process structures (Scrum)

In the development of software, sequential approaches have been identified as too bureaucratic and “heavyweight” due to an extensive documentation and strict project role divisions [13]. For this reason, the popularity of agile development processes has increased significantly: A comprehensive assessment of industrial surveys of agile software development shows that the usage of agile methods worldwide is reported at about 55% [14]. Among various agile frameworks, Scrum is the most commonly used one. It structures the work in a development project along so called Sprints. These Sprints are of fixed duration and take place one after the other. Every Sprint starts with a Sprint Planning in which a cross-functional team selects the top-prioritizes items of the Product Backlog. The Product Backlog is a list of items containing short descriptions of all functionalities desired in the final product. The items can range from specifications and requirements, to use cases, epics, user stories, or even bugs and chores. The team commits to complete a specific amount of items by the end of the Sprint. During the Sprint, the chosen items and the overall aim do not change. At the end of it, the Product Increment, the sum of all the Product Backlog items completed, is reviewed with all stakeholder interested in the Sprint Review. The feedback obtained can be incorporated into the next Sprint, again in the form of items. [15]
Scrum emphasizes a functional product at the end of the Sprint that meets a predefined Definition of Done. Within the context of software, this means a code that is integrated, fully tested and potentially shippable [15]. Physical product development, however, is different from software development. As software consists of lines of code which can be arbitrarily broken down into software increments, it is almost infinitely divisible. The development of a physical product cannot be incrementalized this way, and thus the notion of short time-boxed Sprints has to be adjusted to the characteristics of physical developments [8]. In physical development with Scrum the deliverable of each Sprint should be something that can be demonstrated [8]: A prototype. Corresponding to the development of functional code in software development, the rapid implementation and testing of prototypes enables an agile development of physical products. With the help of prototypes the development team can learn and incorporate obtained information into the next development cycles. The potential customers and stakeholders can be integrated already in the early stages into the development process, in order to provide important information about their needs and requirements. Furthermore, prototypes represent milestones and act as a channel of communication between the various stakeholders in the development process [16].

2. Challenge

As shown in Figure 2 by the stepwise approach of a point of minimum market and technological uncertainty, the development process is a process of reducing uncertainty [17]. The construction and testing of prototypes within the Sprints is a key enabler in continuously reducing the high degree of uncertainty of radical innovations in a process of learning. However, approaches of selecting the most suitable prototype in the complex environment of physical products are mostly unsystematic. Prototyping has always been an established part of the product development cycle, but the underlying motivation is rarely explicitly formulated and therefore not taken into account when selecting prototypes [18]. With the

![Figure 2 - The Scrum framework in the context of physical product development](image)

![Figure 3 - Numerous possible prioritizations and selections of the top items to be implemented within the Sprints give rise to various development paths](image)
prototype being at the center of the agile development process as a means of interaction with the customer, this can be seen as a major obstacle to the implementation of this approach.

In the Scrum framework, the motivation for a specific prototype results from the top items to be implemented within the next Sprint as derived from the prioritized Product Backlog. The prioritization of the Product Backlog items and the selection of the top items should thus control the development and the prototyping strategy. In this context, the question of how to prioritize the items of the Product Backlog emerges. Different prioritizations of items lead to a different design of prototypes. The potential differences of the design of the second prototype (framed) based on a different prioritization and selection of items is portrayed in Figure 3. The effect is a difference in the remaining degree of uncertainty in the three dimensions. The result of the varying prototyping strategies are numerous possible paths along which prototypes are supposed to lead to the final target of a minimum amount of uncertainty remaining.

3. Methodical Approach

With the following methodical approach, we would like to propose a model of prioritizing the items of the Product Backlog in order to follow the most efficient development path in the development of radical products. This forms the foundation of a methodology aiming at a gradual reduction the high degree of market and technological uncertainty associated with radical physical innovations.

For a methodical and uncertainty-reducing prioritization the basis is a comparison between the systematically derived benefit (maximum output in terms of reduction of uncertainty) and effort (minimum input in terms of invested resources) connected to the potential implementation of each item. At the beginning of the development, in the case of radical innovations there is a high degree of uncertainty in all three dimensions mentioned above. Hence, a systematic prioritization of the Product Backlog items at a given point in time is suggested to be based on their specific ratio between this potential benefit and effort.

In our approach, the benefit of an item at a certain point depends on the specific amount of uncertainty reduction in the three dimensions through the item’s realization. The amount of reduction of uncertainty in the three dimensions is to be evaluated by team through the usage of key performance indicators (KPIs) for each dimension. The design of the indicators takes into account specific factors relevant for the reduction of market and technology uncertainty. For the market, uncertainty is described as a lack of information regarding the target market, its potential, and its requirements. For the assessment of the uncertainty of the technology regarding the product a lack of information concerning the technical feasibility, technical specifications and unknown technologies. In terms of the process, the production processes needed and their costs is are unknown. [5,7]

The effort of the implementation of an item has to be considered for a target-oriented prioritization, as well. Depending on the company’s capabilities, the implementation of an item needs a specific amount of effort which needs to be assessed individually. For this, a skill profile is to be developed that can be used to describes the specific abilities of a company concerning its major tasks. The profile is suggested to allow for the deduction of a specific effort for the realization of the requirements.

At specific points of the development process, the reduction of uncertainty in dimension can be of more interest than the reduction of uncertainty in the other two: For every given point in time the dimensions are proposed to be weighted. In this context, we suggest a target-oriented prioritization approach that addresses the three dimensions of uncertainties in specific sequences: Intuitively, as a first step, the development team should focus on the market to analyze its potential and needs to ensure that the product meets the market requirements. At this stage the principle of "Fail early and cheaply" applies – the aim should be the generation of the highest possible output information in form of the reduction of market uncertainty with the least possible resources. Often, cost-efficient prototypes can be used to integrate the customer in the development process to uncover their latent needs. The market information obtained serves as a framework for the further prototype development, which should focus on the reduction of the technological uncertainty in terms of the product. The customer needs must be systematically translated into technical specifications and be technically realized. Furthermore, the functionality of the product technology needs to be understood. In this step, the development and testing of prototypes can provide the development team with important information about the final product. Late prototypes should focus on reducing the technological uncertainty in terms designing the most efficient
and economic manufacturing process for the series product. Figure 4 shows the sequential reduction of uncertainties suggested in our approach.

The continuous analysis of benefit and effort for every item and the weighting of the factors along the development is the basis for a systematic prioritization of the Product Backlog: For each Sprint the information on the potential amount of reduction of uncertainty in the three dimensions, the effort connected to their implementation as well as the importance of the three dimensions according to their sequence as proposed above have to be updated.

The items that show the highest ratio are top priority and will thus be implemented in the upcoming Sprint and a prototype realized. The amount of these items depends on the pre-defined length of the upcoming Sprint.

4. Conclusion

Incremental innovations have been successfully developed for many years and, with the help of traditional sequential process structures. However, agile approaches that literature suggests for the realization of radical physical innovations still deserve thorough study. The approach presented in this paper is a contribution to existing research in this field. It serves as a basic framework for an efficient Sprint Planning within an adapted Scrum process. In Scrum, experiencable prototypes possess a crucial role. So far, however, prototyping often lacks a specific prototyping strategy in practice. Addressing this shortcoming, our approach follows a sequential reduction of the high uncertainties associated with radical innovations as a basis for a target-oriented prototyping strategy. This way, the most suitable prototypes for the various Sprints can be derived.

In the Sprint Planning, the items of the Product Backlog with the highest priority are implemented in the upcoming Sprint. The prioritization follows the assignment a specific benefit/effort ratio to each item of the Product Backlog. The sequential addressing of the uncertainties in the dimensions of market and technological uncertainty guarantees that the prototyping strategy focusses on the most beneficial items. At the same time, the effort for the implementation of the items is estimated on the basis of the team’s capabilities.

Future work must address various aspects of the models presented in this paper to permit their use in practice. For example, research is necessary in the context of the assessment of benefits connected to the items of the Product Backlog. On the one hand, an operationalization of the degree of uncertainty in the dimensions market and technology is necessary. The development of KPIs on the basis of aspects affecting the corresponding uncertainties is seen as suitable here. The development of a skill profile is another factor that needs further investigation.

The major amount of work is remains in a sound derivation of the model weighting the dimensions throughout the development process.

Acknowledgements

The new approach of “Target-oriented Prototyping in Highly Iterative Product Development” is being examined by the Laboratory of Machine Tools and Production Engineering (WZL) within the publicly funded (German Research Foundation, DFG) University graduate training program “Interdisciplinary Ramp-Up” (Graduiertenkolleg Anlaufmanagement).

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