Minimum Viable Products in Mechatronic System Engineering: Approach for Early and Continuous Validation

Valentin Zimmermann[1], Jonas Heimicke[2], Tobias Schnurr[3], Nikola Bursac[4], Albert Albers[5]

[1]Karlsruher Institute of Technology (KIT), IPEK – Institute of Product Engineering, valentin.zimmermann@partner.kit.edu
[2]Karlsruher Institute of Technology (KIT), IPEK – Institute of Product Engineering, jonas.heimicke@kit.edu
[3]Hekatron Vertriebs GmbH (HVG), SHT@hekatron.de
[4]TRUMPF Werkzeugmaschinen GmbH + Co. KG, nikola.bursac@trumpf.com
[5]Karlsruher Institute of Technology (KIT), IPEK – Institute of Product Engineering, albert.albers@kit.edu

Abstract: Minimum Viable Products (MVPs) are products created with little effort, in which experienceable properties are made available to customers and users without the product having to be developed, thus enabling early validation in terms of customer and user benefit. Due to increasing uncertainties for developing companies and the fact that there is a discrepancy between the importance of validation as a central activity for reducing uncertainty and the importance in the research environment, the integration of MVPs into the development process was supported. For this purpose, a portfolio for the selection of MVPs within the framework of the SPALTEN was created. This portfolio contains 17 different MVPs, which are selected according to the objective for validation and the stage of development. Finally, two MVPs were selected in a development project, set up and made available to customers and users in the course of a product validation. This helped to reduce the uncertainty regarding two objectives and identify a false objective, which was then removed from the product system of objectives.

1. Motivation

In 2014, the JUICERO a "smart-juicer" was launched, promising its customers a new experience in preparing and drinking juice. The JUICERO only worked with suitable juice pouches and needed an internet connection to evaluate the expiration date printed on the pouches. It quickly became apparent that the JUICERO did not represent the future of drinking juice, as the functions did not offer any relevant added value for customers and users. Thus, first the product and since 2017 also the startup disappeared, as the assumptions regarding the added value for customers and users turned out to be wrong [1]. This example demonstrates clearly the challenge for developing companies to define the right products from the customers' and users' point of view, since there are many uncertainties due to the assumptions made. The early and continuous validation of the assumptions stated in the system of objectives regarding the actual needs of customers and users enables companies to reduce market uncertainties and thus increases the innovation potential. Nevertheless, this alignment only takes place to a limited extent in mechatronic system engineering (MSE), as companies have difficulties with prototypical realization, especially at an early stage, due to the constraints of physical product development [2]. Thus, it can be observed that companies in MSE do not adequately validate the requirements regarding the needs of customers and users. As a result, they launch products on the market that do not adequately meet those needs.

2. State of the Art

2.1. The Model of Product Generation Engineering and the integrated Product engineering Model

Since products are developed in successive generations, the model of PGE - Product Generation Engineering is suitable for modelling product development [3]. According to this model, the development of each product generation is based on a reference system that includes existing products, their subsystems, products and subsystems of the competition, discarded or realized solutions from past development projects, or products and findings from other industries or research [4]. These reference system elements are used to realize a new product generation G_n using three types of variation: carryover variation, embodiment variation and principle variation [3]. Solutions that are transferred to the next product generation with exclusive adaptation of their interfaces are called carryover variations. In the case of embodiment variation, a solution is transferred to the next generation by adapting its embodiment and retaining its operating principle, while principle variation describes the realization of new functions by adapting the underlying operating principle. The shares of systems that are transferred to the next product generation by embodiment and principle variations describe the share of new development. By taking this into account, potential development risks can be identified at an early stage and validation efforts can be planned in a targeted manner [3].

In this context, by using the integrated Product engineering Model (iPeM) product development can be modelled integrated in interaction with the development of a validation and production system as well as a higher-level organizational strategy [5]. Thus, dependencies of goals and resources as well as emerging objects can be represented cross-organizationally. In this context, the iPeM also displays all activities that are carried out in the course of a product life cycle for the continuous synthesis and analysis of the product [5]. These activities are modelled as a problem-solving process using the universal problem-solving technique SPALTEN, so that a method selection for the individual SPALTEN activities within each product development activity can be made according to the situation and requirements. SPALTEN is a German acronym which means “to split” and therefore the 7 letter represents the 7 problem-solving activities **situation analysis** (S), **problem containment** (P), **alternative solutions** (A), **selection of solutions** (L), **analysis of consequences** (T), **deciding and implementing** (E), and **recapitulation and learning** (N), thus structuring the continuous generation and condensation of information [6]. SPALTEN supports both the selection and the implementation of methods.

2.2. Uncertainties in product development

According to DE WECK et al. [7], uncertainties in product development include not only the probability that assumptions made before will be proven wrong, but also the occurrence of completely unknown facts, which again will influence the product, its development and its success on the market. Thereby, the impact of uncertainty can be both positive and negative. MCMANUNS and HASTINGS [8] describe the impact of uncertainty through opportunities and risks, thus picking up on the understanding of the positive and negative influence of uncertainty on development. According to their understanding, uncertainty can be described either by the difference between available and necessary knowledge (knowledge gaps) or by pending decisions or specifications (definition gaps). In the context of product development, a distinction is often made between technology and market uncertainties. Technology uncertainty refers to knowledge or definition gaps with regard to the technical feasibility or the manufacturability of a product, whereas market uncertainty primarily comprises knowledge or definition gaps regarding the market, customer needs [9] or the willingness to pay [10]. According to ALBERS [11], validation is the central activity to gain knowledge and thus reducing knowledge gaps. In this context, validation is set to confirm that the right product is to be developed [12].

2.3. Minimum Viable Products

The approach of Minimum Viable Products (MVPs) has established in order to generate an early insight into customer needs. As a study by LENARDUZZI and TAIBI [13] shows, the term MVP itself is not clearly defined, rather it varies according to the context of consideration. The original term goes back to ROBINSON [14], who considers an MVP not as a product, but rather as a strategy for creating a product and selling it. RIES [15], on the other hand, describes MVP as a product that allows developers to generate the maximum amount of knowledge regarding customers with minimal effort. According to BLANK [16] view, a MVP is a product that has only those features that are necessary for use. Following LENARDUZZI and TAIBI [13], further definitions published usually build on at least one of those definitions. Some authors add that an MVP should generate cash flows [17] or should be profitable [18].

The term minimum is considered very controversial in the definitions. While some definitions are based on the understanding according to BLANK [16] and set the focus with regard to the functionality of the product, which should only be minimum [19], others only include the use of resources [20]. In this context, RIES [21] expands the objective of MVPs to the effect that assumptions which influence the success of the product on the market should be validated with as little effort as possible, whereby the focus is primarily not on experimenting with technologies and materials or checking the manufacturability of the product, but on validating customer requirements and checking the associated benefit and growth hypotheses. In this case, it is important to avoid efforts that do not provide any prospect of knowledge gain with regard to the hypotheses set [21]. A well-known example for a MVP is Dropbox, where a video was presented to potential customers, who could then enter their contact data on a landing page if they were interested. Thus, no technical solution had to be developed to validate the demand [22].

3. Research Design

The increasing complexity in MSE, caused for example by an increasing number of domains involved, leads to an increase of uncertainty in the form of definition and knowledge gaps in the associated product development projects. According to ALBERS, validation is the central activity in product development to generate knowledge and thus to reduce uncertainty [11]. In software development startups, the MVP approach has been established to generate early insights into customer needs. In this context, products that focus on the most relevant functionalities are provided to customers and users in order to obtain their feedback. Thereby, often the willingness to pay is determined directly by a real sale. However, this approach cannot be easily transferred to the development of physical products, since it is not possible to sell non-finished products to customers, especially in the context of approval-relevant products and since the constraints of physical product development [2]. Therefore, the following research questions are to be answered:

1. What is the importance of early validation to reduce knowledge gaps regarding market uncertainty in the development of fire-safety-systems?
2. How to integrate MVPs in the sense of the model of PGE into the MSE in order to promote the early and continuous knowledge gain with regard to reduce market uncertainties?

3. What change with regard to the subjectively estimated uncertainty results from the integration of MVPs in the sense of the model of PGE in a development project?

The research was organized in a three-stage research design according to the Design Research Methodology [23]. In the Descriptive Study 1 two development projects of Hekatron Brandschutz were analyzed in workshops, with the responsible project manager and product manager to determine the importance of validation in the environment of investigation. For this purpose, the activities carried out were recorded using the modeling technique according to ALBERS et al. [24]. In the subsequent Prescriptive Study, it was derived how MVPs can be transferred to the MSE. Therefore, MVPs identified in the literature were characterized and a process for the selection MVPs was derived. Finally, in the Descriptive Study 2, the contribution regarding the reduction of the uncertainties was evaluated in the environment of Hekatron Brandschutz. For this purpose, MVPs were created in a development project at an early stage and were provided to customers and users. Based on this, the use of the MVPs and the results of the associated validation were evaluated by 15 employees from the development and product management departments of Hekatron Brandschutz. Thereby, two business unit managers, seven project managers, three department heads and three product developers evaluated the change of the present uncertainty with regard to the fulfilment of customer and user needs.

4. Relevance of early validation in the development of technical fire-safety systems

In a first step, the activities carried out in two development projects were recorded retrospectively in workshops. For this purpose, the conducted activities and their interactions were recorded using the modeling technique according to ALBERS et al. [24]. To ensure comparability, the activities were subsequently transferred to the iPeM. The results are shown in Figure 1.

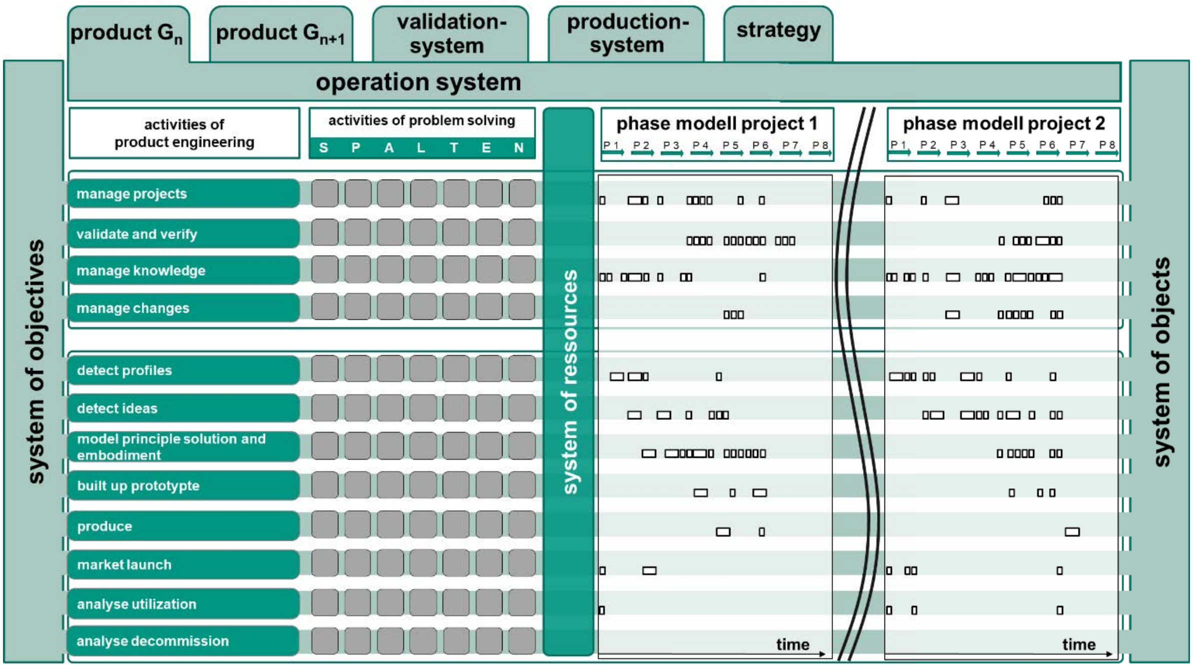

Fig. 1 Recorded process of two development projects modeled in iPeM; Phase 2 - Creation of the specifications, Phase 4 - Creation of the requirements specification, Phase 8 - Pilot Series.

It can be stated that both analyzed projects have a fundamentally very similar process in terms of the activities carried out. It should be pointed out, that activities recorded regarding the activity Validate & Verify, were carried out quite late in the two projects under review. Thus, there are no activities of this kind before the fourth defined phase of the projects. Furthermore, when looking at the contents of those activities it can be seen that they are primarily verification steps. For example, activities were recorded such as: verification of the firmware concept, mechanical tests, tests regarding the reliability and sensitivity of the sensor technology, or tests for electromagnetic compatibility. It can be seen that these activities are primarily carried out to verify whether the products in development meet the requirements, rather than checking the validity of the requirements. Only usability studies and studies in which design samples were provided to customers were recorded as actual validation activities.

In order to achieve a better understanding of the approach of the product developers with regard to the validation activities carried out, inquiries were made during the workshops. Of particular interest in the course of this publication are the reasons why validation activities, only take place at a late stage or often do not take place at all. This revealed that it seems to be a matter of course for the workshop participants that validation activities to reduce market uncertainties are only carried out at the end of the development project. In general, it was stated that validation activities take a lot of time and are therefore rarely carried out. This is accompanied by the fear that a validation step, especially if carried out late, can result in significant additional expense, as it may be discovered that the developed product does not meet customer and user requirements and must therefore be modified subsequently. However, all of the interviewees stated that they consider it useful to validate earlier and more, especially in order to reduce market uncertainties and to launch the right products from the customers' and users' point of view. However, there is a certain inhibition to approach customers with immature, unapproved products. In addition, it was stated that validation methods that enable early targeted alignment with customers and users are not known. Consequently, a discrepancy can be derived between the importance of validation for the success of product development [11] and the relevance of validation in the investigated projects, which is rather low. In the following prescriptive study, this discrepancy will be addressed by the use of MVPs.

5. Approach to integrate MVPs in the development of mechatronic systems

In order to support product developers to systematically reduce market uncertainties it is investigated how MVPs can be used in MSE to perform early validation. The goal of an MVP is to validate assumptions such as goals or their justifications, which relate to the customer and/or user benefits and are thus market uncertainty drivers, with little effort. The realization required to fulfill the function does not have to correspond to the intended realization of the final product. Rather, the functions or properties of the product to be validated can also be realized by components of the validation environment, since developing the product and modifying it on the basis of the findings collected during validation in particular require a lot of effort. Nevertheless, the MVP should be designed in such a way that the properties of the product can be experienced by customers and users within the relevant use cases. In accordance with the model of PGE, subsystems that are not to be validated, but also the environment of the system to be developed, should be taken from reference system elements. In order to support product developers during validation, the SPALTEN process of validation [25] was extended by supporting questions and by a portfolio. Thus, the selection of suitable MVPs and the execution of the validation is supported. Therefore, 17 approaches to create MVPs were identified in the literature and characterized according to their purpose (suitability for physical or digital product), necessary effort, objective for validation [25] and suitable time of application in the product development process. Further, profiles of the MVPs were created to support their implementation. The process and the associated MVP portfolio are presented below:

3. **Situation Analysis**: First, the existing knowledge gap and development situation is analysed regarding the development stage, available resources, and the type of uncertainty.
2. **Problem Containment**: The previously gathered information is condensed and decision criteria for MVP selection are further specified. In particular, it is relevant to know the stakeholders to be considered the objective, and boundary conditions of the validation.
3. **Alternative Solutions**: According to the decision criteria, a pre-selection regarding the potentially suitable MVPs is made. For this purpose, two portfolios were developed, one for MVPs that can be used for digital products and the other for physical products (See Fig. 2). A selection of suitable MVPs can be made via the objective for validation, and the corresponding development stage, which is determined by an assessment of the developers and is not to be regarded absolutely. With regard to the objective for validation, a distinction can be made, according to ALBERS et al. (2016c), as to whether a single (quantified) requirement - usability and design -, a sub-function, the overall function or the fulfilment of needs - customer benefit, user benefit, willingness to pay - is to be validated. The colouring of the bars in the diagram gives method users an indication of how much effort is required to design the MVP and was created based on information given in the literature.

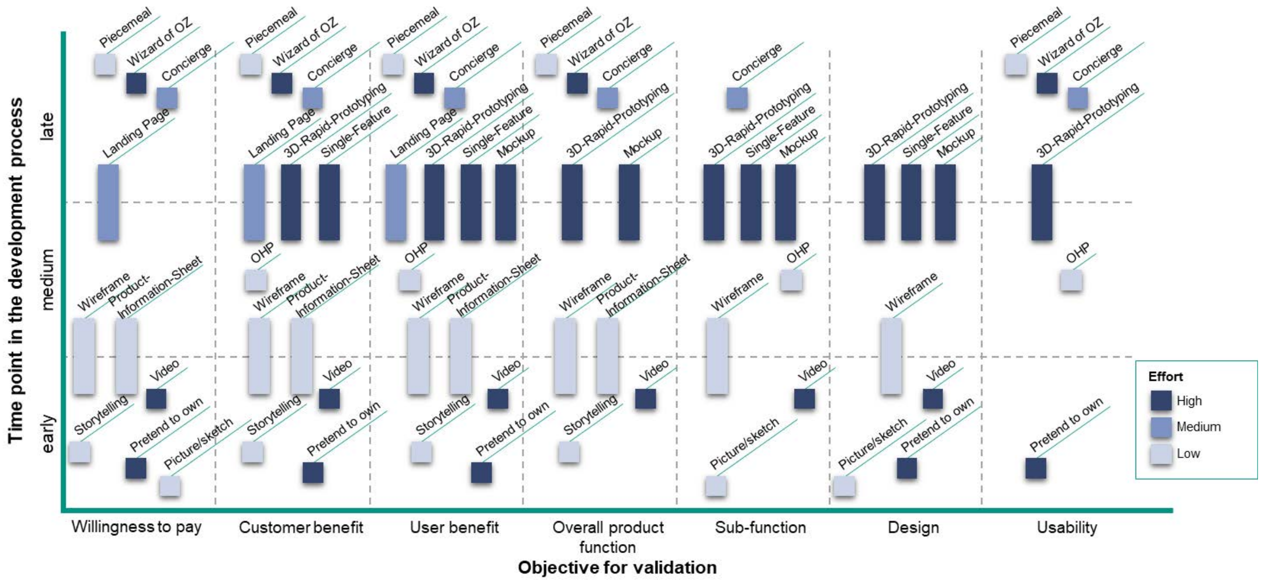

Fig. 2 Portfolio supporting MVP selection for physical products

By looking at the portfolio, it can be seen that MVPs can appear multiple times, or go across the boundaries of the portfolio, as they are appropriate with respect to different time-points and objectives for validation.

4. **Selection of Solutions**: The actual selection of the most suitable MVP is carried out. For this purpose, profiles (See Fig. 3) have been created that provide detailed information. For example, the resources required are listed, e.g. 3-D printer, or the time and costs to be expected.

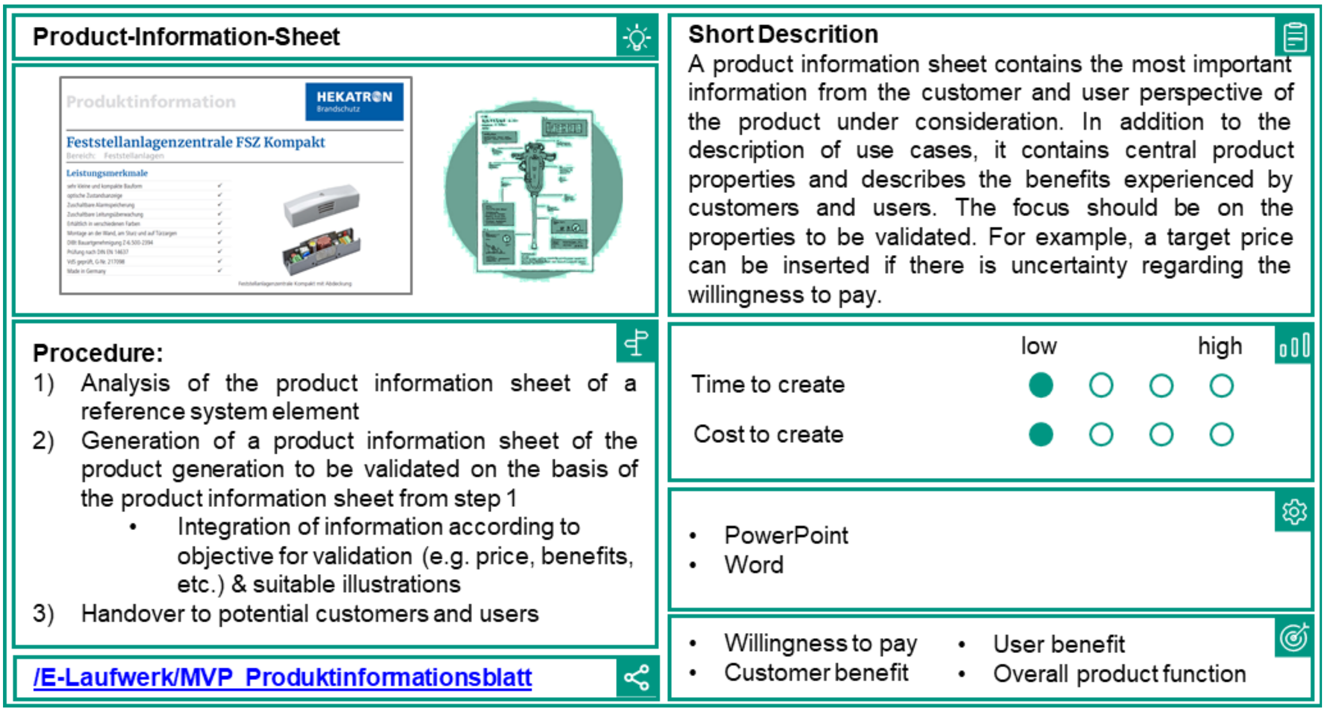

Fig. 3 MVP-Profile for Prduct-Information-Sheet

5. **Analysis of Consequences**: The preferred solution is evaluated in terms of opportunities and risks.
6. **Deciding and Implementing**: In this step the execution of the validation method takes place. According to the fractality of SPALTEN, the execution of the validation can be described by SPALTEN again. The knowledge gained from the validation is then used to identify further knowledge and definition gaps.
7. **Recapitulation and Learning**: Experiences gained through the use of the applied MVP are documented and linked to the profiles.

6. Contribution of MVPs in the context of the development of fire-safety-systems

In order to determine the contribution of MVPs in the context of fire-safety-systems, developers in a development project of Hekatron Brandschutz were supported by creating MVPs for early validation. The objective of the development project was to simplify a documentation task by integrating a human-machine-interface into a testing-device. In the run-up to the application of the method, three elements of the system of objectives (ESO) or the assumptions behind them were identified as being affected by market uncertainty. It was found that there are two different objectives for validation. So the objective was to evaluate the new sub-product function, which concerns the digital interface from the user's point of view and also to evaluate the customers' willingness to pay. Therefore, it was decided to create two MVPs: a wireframe - for the users to experience new sub-product function - and a Product-Information-Sheet - for the customers to assess the financial value of the feature.

Figure 3 schematically shows both the predecessor product generation G_{n-1} and the planned product generation G_n.

Fig. 4 Schematic illustration of the structure of the predecessor product generation (left) and the planned product generation G_n (right)

Component (b) was the main focus by creating the wireframe. Actually, component (a) and the components (c) and (d) (See Fig. 4), which are part of the product environment need to be modified in order to fulfill function of the wireframe, but since this would involve a lot of development work and users cannot verify whether communication really takes place via these components, component (a) was taken over from G_{n-1}. Instead, the necessary communication was triggered via remote control (see. Fig. 4 - step 2). In concrete terms, a mockup was programmed on component (b), which the user could control by using communication commands (1). However, there was no communication with component (a), but rather a command was now triggered by a developer via remote control and thus the rest of the communication chain was simulated. Thus, the function could be experienced by the user. Figure 4 additionally shows the integration of the component to be developed into the overall system. Subsystem (d) is located in a different room in practice. Therefore, it was omitted in the course of the MVP.

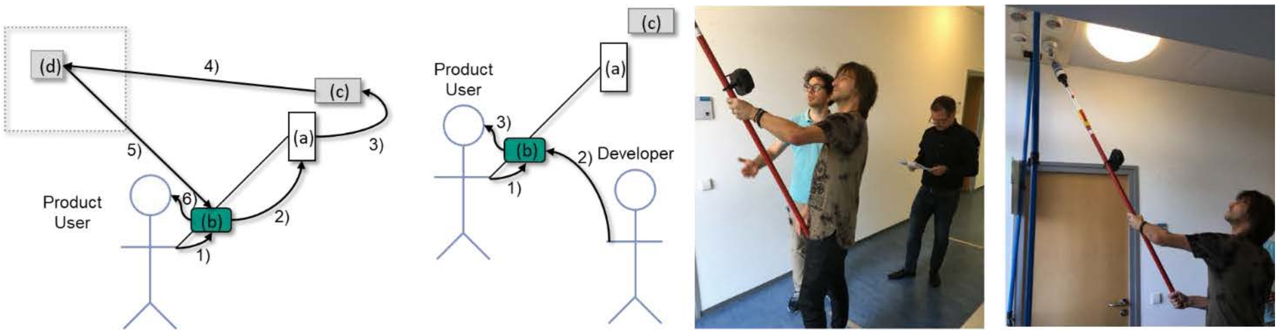

Fig. 5 From left to right: Systematic illustration of how G_n works; Systematic illustration of how the MVP works; Validation workshop; Users during testing

In order to test the willingness to pay, a Product-Information-Sheet was created. Therefore, the data sheet of the G_{n-1} was used as a starting point and only the new function to be tested and the resulting benefit were added. Furthermore, a field to place an order was added. On this, customers could indicate whether they would like to buy the new product generation at a specified price. The validation was carried out with four different groups, each consisting of a customer or sales employee and one to three technicians (product users). None of the participants questioned how the function was implemented in the wireframe. Only at the end of the validation all participants were informed about this.

After the method was carried out, 15 experts were shown the results of the validation in order to evaluate the method. For this purpose, they evaluated the uncertainty with respect to the three critical ESO before and after the method application. A high level of certainty means being confident that the implementation of that ESO will contribute to the success of the product in the market. A low level of certainty means that this ESO is not thought to contribute to the success. In addition, the participants evaluated how they perceived the validation to have changed the certainty that the product generation will be successful on the market. (See Fig. 5)

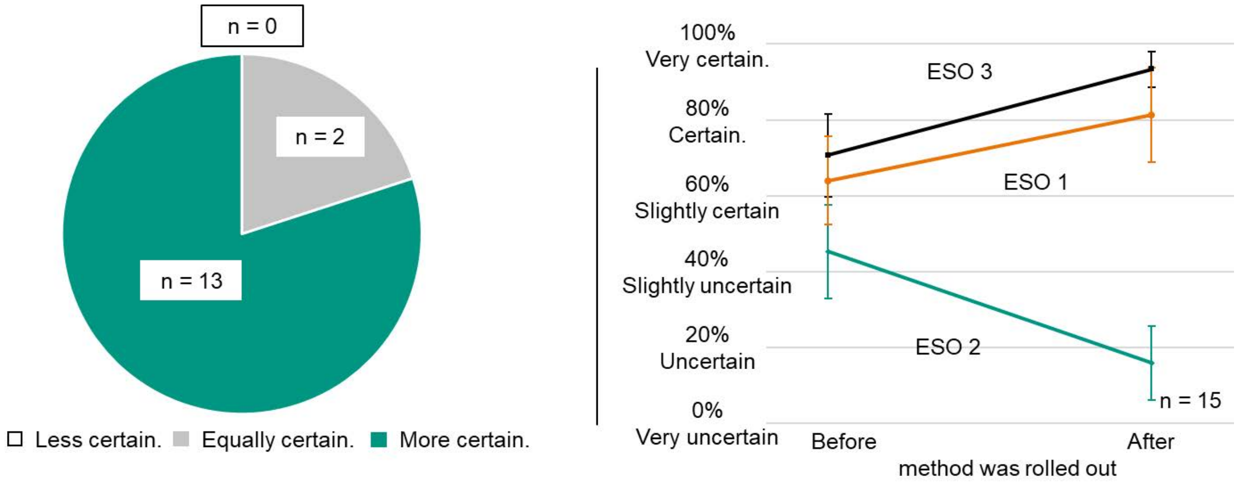

Fig. 6 Left hand side: Change in subjectively perceived uncertainty due to method application; Right hand side: Perceived uncertainty regarding three different ESOs before and after validation

It can be observed that 13 of the 15 interviewees indicated that the knowledge gathered in the validation process increased their certainty that the G_n will be successful in the market compared to the time before the method was carried out. None of the respondents were more uncertain. With respect to the three ESOs, it can be stated that before the method was carried out, the certainty lies between 45.3 and 70.7%. The certainty for ESO 1 and 3 increases to 81.3 and 93.3% due to the method implementation. This means that the experts were much more certain afterwards that the customers or users want a product that meets ESO 1 and 3. The level of certainty for ESO 2 dropped clearly. This was due to the fact that the associated assumptions regarding customer and user benefits were proved to be incorrect. Based on the results of the validation, it was subsequently deleted from the system of objectives.

7. Discussion and Outlook

As part of the evaluation, 15 domain experts indicated their personally perceived certainty with regard to three ESOs and thus assessed whether these contribute to developing the right product from the customer and user perspective. It can be observed that before the method implementation, all feedbacks were in a range between 45.3% and 70.7%, where a high certainty signals that one is certain that the implementation of this target system element contributes to the increase of customer and user satisfaction. In the evaluation, after the method had been implemented, the experts rated on average significantly closer to the extreme values of 0% and 100%. The conclusion to be drawn from this is that by using the MVPs, the initially vague statements made by the experts became more substantiated. Thus, goals and a non-goal of product generation could be identified. Furthermore, the experts stated that the perceived uncertainty that the right product is being developed has decreased as a result of the use of MVPs. However, it cannot be reconstructed to what extent the reduction of uncertainty can be attributed to the actual application of MVPs. Furthermore, no study has been conducted with other approaches to uncertainty reduction. Thus, it can currently only be assessed that uncertainty is reduced, but not how the MVPs stand in relation to other approaches.

Subsequently, the approach described must be applied in other development projects in order to further evaluate the MVPs. The aim is to gain more knowledge, especially about the suitability of MVPs, and thus to optimize the selection process. Since MVPs originate from startups, the integration of these into the development processes of smaller, flexible companies seems to be much easier. Therefore, the integration of MVPs into large companies with rigid processes should be analyzed.

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