The use of prototypes within agile product development

Explorative Case Study of a Makeathon

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***Abstract*— Due to rapid technology change and increased innovation dynamic, product development is related with high uncertainty and complexity [2]. As a consequence of the shortened product life-cycles, agile development becomes more important. It fosters cross-functional project work and enables a team to react fast and flexible to a continuously changing environment. Central aspect of the agile approach within physical product development is prototyping. This work identifies criteria to analyze the use of physical prototypes within an agile set up. Therefore, a Makeathon has been analyzed. In contrast to plan-driven development, prototypes are used to explore, design, verify, test the usability or communicate product aspects. They support the learning process by providing important insights about the solution space on which the planning of the next iteration is based. The data also support the assumption that there is not "one" approach in agile product development. It is much more likely to be unique to each product, which is also one of the strengths of agile product development, as it allows you to react flexibly to changes.**

Keywords— Agile Development, Physical Product Development; Prototyping; Makeathon

I. Introduction

Innovation is a hardly understood and highly complex system [1]. Especially the early phases of innovation processes are characterized by a high uncertainty about the problem and solution space. Agile approaches such as design thinking are of importance in these early stages. The focus on customer or user needs facilitates the iterative concretization of the problem-solution fit by emphasizing with the user [2]. Insights are gained by creating various prototypes that enable interactive user tests. Based on the specific situation, different kind of prototypes are used. They vary from very simple paper or cardboard models, mock-ups, function patterns to fully functional designs. These variations are dependent on certain decision to be made. For each decision, a certain type of prototype is used, pursing different objectives.

Creating various prototypes the product becomes more concrete with every iteration. The fuzziness of the project becomes more clear and the requirements more specific. At the same time, however, the project becomes more immobile [3]. With each iteration, the team's range of options decreases along with the depth and breadth of its decision tree. The initially planned solution may change due to gain in knowledge or insights. Overall, the lack of knowledge and fuzziness decreases as the project progresses [1].

II. Background

A. *Agile Product Development*

In product development, agile signifies the outcome of the development, which is not entirely clear, but in some way "fuzzy" [3]. Agile project aim to react flexible and fast in case of a continuously changing environment [4]. One important element of agile product development is the iterative, cyclical approach [5]. Meaning, a continuous realization of product

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elements in specific intervals (iterations). Each iteration of agile product development includes the following steps: set-up requirements; set-up, realization and test of design; acceptance by customer [5]. Each iteration comprises all steps and ideally emerges a certain product element. Finishing one iteration, the created product element is analyzed. If the current version of the product element is a completed feature implementation of the final product, it is named an increment. The current product development status is reviewed by the team and with the customer. Based on the findings, the target may be refocused for the next iteration.

Agile product development has its origin in software development and specifically in the agile manifest, written by Beck et al. in 2001 [6]. Being a user-centered approach, the customer is in focus. He is actively involved during the entire development, which also allows to adapt the product according to his needs.

B. *Prototypes within Agile Product Development*

Lim [7] describes Prototypes as "purposefully formed manifestations of design ideas". The objective is to explore the solution space and to generate findings towards a final design. Furthermore, he describes a prototype by "manifestation dimensions" (material, level of detail, considered area) and "filtering dimensions". These "filtering dimensions" describe the designers approach to consider only specific areas of the final product with one prototype. Thereby prototypes can be "incomplete" regarding the final design and should be used in the easiest and most efficient way, while still producing the required findings. Ulrich & Eppinger [8] defines a prototype in a similar way. It is an approximation towards the final product along one or more dimensions. A prototype must display at least one aspect of the developed product. Each prototype represents both, the knowledge and findings by the team within a physical or virtual model [22].

Prototypes in agile development are not only functionally reduced experimental models of later series products, but also deliver the confirmation of the question addressed to them as required [24]. They are simplified abstractions of the final product developed specifically for defined test purposes in the agile development process [25]. Prototypes are used for learning, communication, integration or demonstration [26].

This paper aims to clarify various types of prototypes as well as their use during product development. For this research a prototype is defined as everything that constitutes a figure of the product to develop, whereby it is not relevant whether the product is constituted entirely or just partially.

"Prototyping is the activity of making and utilizing prototypes in design" [7]. It is important, that utilizing means not only verifying an idea, but conveying ideas, creating user interaction or exploring design concepts [1]. According to Vetter [9], the actual value of a prototype comes through direct interaction. As a consequence, it is important to make use of prototypes as early as possible within product development [10].

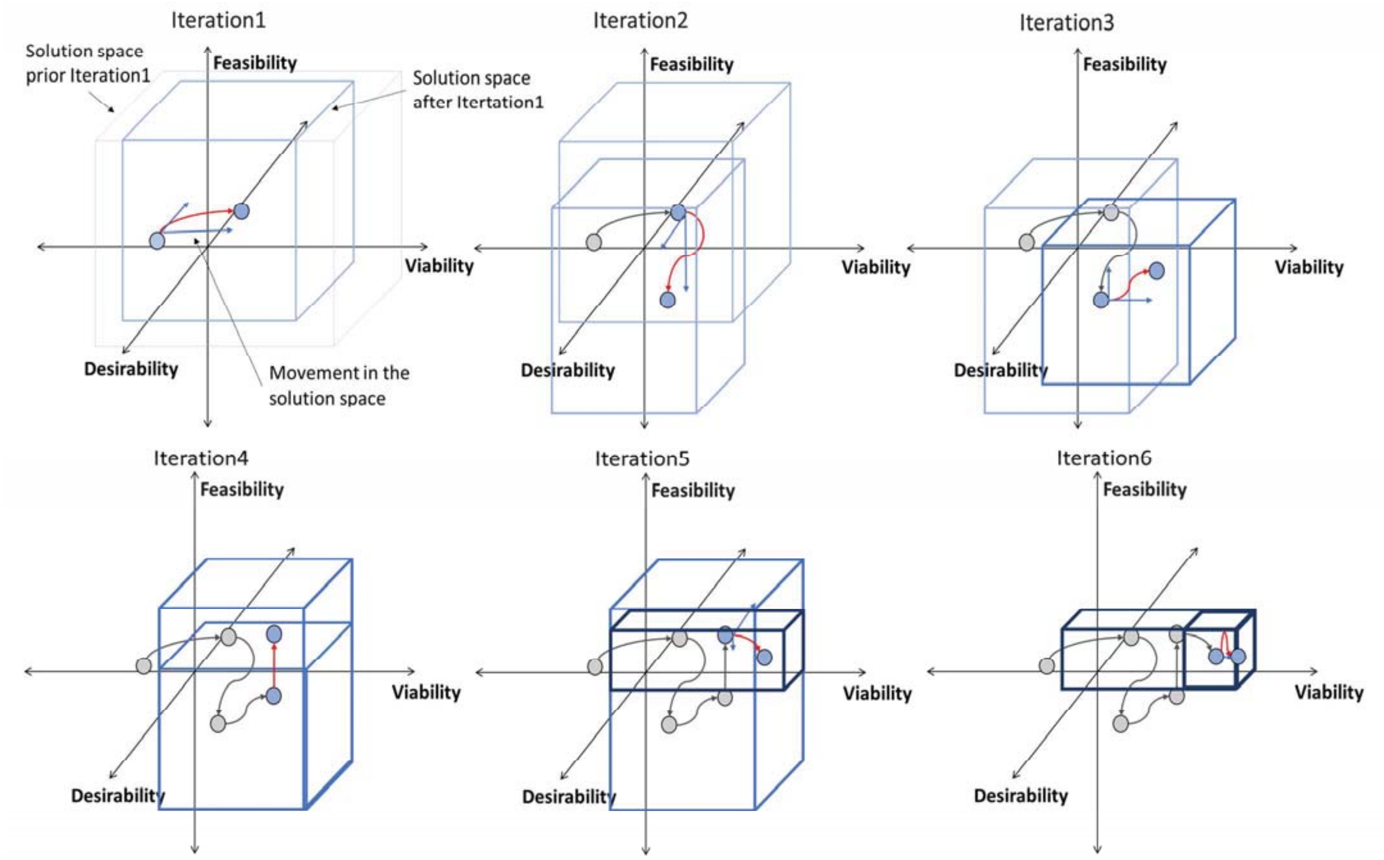

Fig. 1: Iterative exploring of the solution space according to [3, 11, 23, 24].

Thereby the first prototypes may be quite simple, fast-build models, which will get more detailed with progress in development [10]. The main reason for prototyping within agile product development is to reduce uncertainties as early as possible. According to Hallgrimsson [23], prototyping is part of an iterative learning process. He classifies the prototypes objectives into four main categories: exploration, communication, usability and design, and verification [23]. Möller [27] differentiates four prototyping categories within product development: concept models, geometrical prototypes, functional prototypes and technical prototypes. Prototypes are used to test feasibility (technology perspective), viability (business perspective) and desirability aspects (customer perspective) [11].

C. Agile Product Development Model

For the fundamental description of an iterative approach, the "Fuzzy-model" by Oestereich and Weiss [3] is used. It assumes, that the outcome of the development at the beginning of the project is fuzzy and follows a clear vision without specifying it in detail. Initial assumptions are made and tested with the user within the first iteration. Afterwards the findings will be analyzed and compared to the assumptions. Subsequent to this review, new assumptions are defined. Due to the findings, the outcome of the development becomes more clear.

In this paper, the model will be supplemented by the feasibility, desirability and viability model, introduced by Menold et al. [11]. Feasibility measures the technical functionality, desirability its value for the customer as well as the likelihood of purchase, and viability the ability of the designs to fit into time- and budget constraints. Using these three variables a three-dimensional space is created, illustrated in Figure 1. The solution space of the final product will be explored iteratively with regards to feasibility, viability and desirability during the development of a new product. The aim is to explore the solution space in a way that combines all three variables in order to make the new product an innovation by definition.

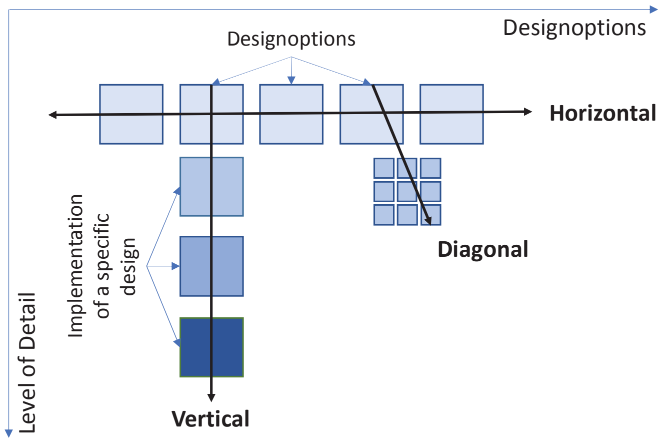

Fig. 1: Horizontal, Vertical & Diagonal Prototyping accoring to [12, 13]

Further, the model of horizontal and vertical prototyping will be used to analyze the focus within an iteration. It combines the works of Beaudouin-Lafon & Mackay [12] and Elverum & Welo [13]. Horizontal prototypes are used for testing and exploring the design. They are used to compare various designs and gather information to select the best possible solution. Vertical prototypes are used to refine, specify, and optimize the chosen design. They are focused on the implementation of a specific design variant. Further, prototypes can affect both directions. Those are called diagonal prototypes (see Figure 2).

Furthermore, a specific purpose can be assigned to every prototype. Those purposes are categorized into explorative, usability, communicative and technical verification [14]. Explorative prototypes are used to determine whether a specific idea should be pursued further. They help to gain knowledge, explore the solution space and generate new ideas. These prototypes do not have to be highly complex or precise. They are experimental and fast build designs. Prototypes for usability purposes are creating an interaction between the customer and the product. Using them, the developer generates data and feedback about how the customer uses the product. Communicative prototypes are getting more important due to the increasing interdisciplinary nature of product development. They facilitate to communicate design ideas throughout the team and visualize the status and the vision. Another important application of these prototypes are the presentation of the product to customers or management. They can be highly precise, when communicating a possible final design. According to Hallgrimsson [14], prototypes for technical verification are used to verify bought-in components prior to their usage. In this work, the purpose of technical verification is extended by the usage for testing and optimizing a design. These prototypes may be high-fidelity prototype (corresponds to final product) or low-fidelity prototypes.

III. Research Design

A. Think.Make.Start. – An Agile Framework

Think.Make.Start. (TMS) is a interdiscilpinary course at the TUM in cooperation with UnternehmerTUM. Each semester 50 master students take part and develop their ideas to create a potential business around them within just 14 days. TMS brings together students from different backgrounds, such as Mechanical Engineering, Informatics, Computer and Electrical Engineering, School of Management as well as others (Medicine, Communication Management, etc.). The students allocate themselves into teams under the constraint that each team must represent at least three different faculties.

The projects' topic is freely chosen, but limited to a budget of ~400 EUR. The teams are supported by coaches of the corresponding faculties and have free access to the MakerSpace. TMS is characterized by time pressure, competition and an open community. The students learn agile and traditional methods and principles, but the team- or time-specific application is not predefined. The resulting agile product development approach is inspired, by integrating knowledge and methods from different disciplines, using a real synthesis of approaches. The research focuses on the application of elements or rather methods the following agile frameworks: Makeathon, Scrum, Kanban, Design Thinking as well as Lean Startup. The central aspect of the agile product development is the Munich Procedural Model (MPM) by Lindemann [15].

B. Data Collection

Data was collected throughout the course and repeatedly from same students along the lines of a longitudinal study. To obtain objectivity, the data is acquired using six different approaches and focuses on four different aspects (see Fig. 3). The data collection focuses on the prototyping characteristics of an agile product development. For transparent data acquisition, each team created an online database for project work. Besides the daily progress of each team, the generated prototype status and the retrospective project path was gathered. At the end of each day, the teams presented their daily progress, covering their achieved goals, new insights, and lessons learned. The created prototypes, their purpose, and the findings, were recorded. The sequence and the links between the prototypes were documented. Data, describing the prototypes, the hypotheses tested with them as well as the gained findings were documented. In discussions with the team members, missing information and additional prototypes were queried.

Aspect	Data Collection Method				
Daily Progress	Interviews and Observation	Data Base	Daily Progress Presentation		
Generated Artefacts	Interviews and Observation	Questionnaire	Data Base		
Prototyping Roadmap	Interviews and Observation	UTUM Pad			
Overall Project Path	Team Essay / Reflection	Questionnaire	UTUM Pad	Data Base	Daily Progress Presentation

Fig. 3: Used methods for data collection and related analysis aspects

To gain knowledge about the team compositions, the experience with agile product development and an assessment of the importance of prototypes for product development, a questionnaire was completed by the students on the first day of the course. In the same way, data on the participants' satisfaction with their prototypes and overall progress were gathered on the final day of TMS. Further the students were asked about their approach for creating prototypes, the reason for using them and again an assessment of the importance of prototypes for product development. To be able to compare the data, pre-formulated answers were used.

C. Research Question and Data Used

Based on the outlined state of the art, the data collected will be processed and analyzed by the following aspects: the purpose of the prototypes (exploratory, usability, communicative and technical verification), the alignment (horizontal or vertical), the nature of these, as well as the insights gained (feasibility, desirability and viability). In addition, the prototypes were assigned to several iterations to examine the progress of development during the course. The analysis follows the fuzzy-illustration of an agile project development path of [16].

According to [19] the data collected is classified to one of the three categories: feasibility, viability and desirability. These categories help to gather the most important attributes a new product should combine and where there is uncertainty with regards to the solution space [17]. Next, the type of prototype is classified to the certain purposes of the prototype: explorative, usability, communication, and technical with regards to [18].

Both classifications are independent of geometry and quality of the prototype and therefore allow a clear identification of the purpose of prototype. Subsequently, the prototypes were divided into iterations, for comparing the development process across all teams (compare Table 1). To compare the various products, the prototypes where analyzed based on the components and the development progress. Further, the iterations were not divided by time or sum of components, but by objective and focus of the prototypes. Therefore, an iteration ends, the moment the objective, pursued with a prototype, changes. Each iteration of the diagram is complemented by horizontal and vertical prototypes [20, 21]. Thus, the focus of the prototyping effort is illustrated with regards to exploration of various solutions or rather the validation of a specific solution.

TABLE I. TEAMS OF THINK.MAKE.START. #4

Team	*Product*
Bikorsa	Modern, stylish bike bag with safety functions
DroneTag	Real-life shooting game with drones and virtual reality
FanCam	Camera and streaming platform for amateurclubs
Furnewture	Transformable, flexible furneture
IntelliSleep	Smart matraze for aldery homes
LongShoard	Foldable longboard with detachable trucks
MiMero	Pen for the therapy of people with writing difficulties
Oasis	Automat for flauvored water
MyScreen	Portable beamer
Solos	Smart-mirror for gyms

To prevent a falsification of the data due to variance in number of prototypes for each iteration, the numbers within an iteration were standardized towards the overall number. Finally, the categories focus (horizontal / vertical), purpose (explorative, usability, communicative, technical verification) and solution space (feasibility, desirability, viability) were analyzed to find similarities and dependencies. From the gathered data, answers towards the following research questions were derived:

1. What kind of prototypes were used during TMS?
2. Are there common prototyping approaches?
3. What influence have the purpose of prototypes on the insights gained regarding solution space (F, D, V)?
4. How is the interrelation of purpose and focus of a prototype?
5. What effect does the selected focus of a prototype have on the insights gained regarding the solution space?
6. In what manner do the prototypes fulfill the intended purpose with regards to the learning process of an agile product development?

IV. RESULTS

A. Types of Prototypes

A total of 162 Prototypes were built during TMS. Thereof the pursued purpose had been explorative in 54%, technical verification in 30%, Usability in 27% and communicative in 36% of the prototypes. Prototypes were counted more than once, if a prototype combined two or more purposes. In total, 42% of the prototypes combined at least two purposes, especially usability was only used twice as a single purpose. A combination of explorative and technical verification did not occur [see Figure 4].

That explorative accounted for the highest share, could be explained with the early stage of the development. At the beginning, the search for a design is one of the main objectives of prototyping. In contrast, technical verification occurs only later in the process and is used after selecting a design. It could be assumed, that usability can be easily combined with other purposes. The lack of prototypes with a combination of explorative and technical purpose underlines the assumption of a separation between these purposes. Because of the high share of combined purposes, the assumption is made, that the teams seem to combine them intuitively.

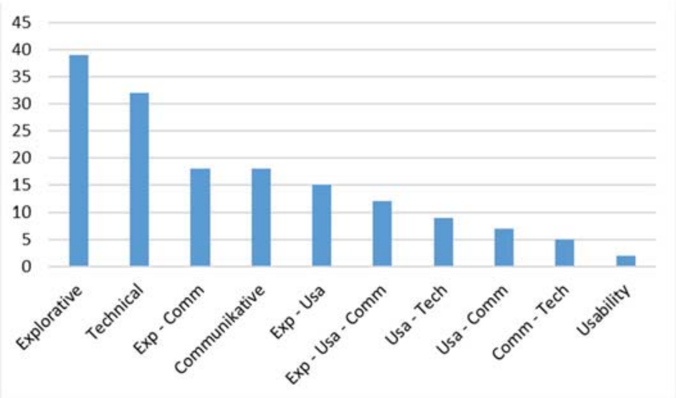

Fig. 4: Combination of purposes of the build prototypes

In a next step, the prototypes were analyzed by their form (quality and material). Therefore, the following categories were defined: "simple material" signifies a not a final material, with the focus on a fast and simple implementation. Prototypes made of "final material" already use the intended end material. The category "3D Modelling" combines all electronical models, like graphical designs or CAD models. They are often highly precise. "external subsystems" are products, bought from other suppliers, or systems analyzed to understand a specific solution. "own subsystems" on the other hand are self-produced parts, with none or very little connection to an already existing solution. "Software" collects the not transparent software prototypes into one category. Each prototype is counted to more than one category (Figure 5).

There were high shares of "simple material" (40%) and "external subsystems" (33%) found. This shows, it is reasonable to build simplified models or use existing products to generate solutions for the own product, especially at the beginning of the development. By consideration of the horizontal and vertical focus, a share of 70% for horizontal focus and 48% for vertical focus was determined.

This supports the thesis, that at the beginning of the development, prototypes are used to explore the solution space and for finding the best design. Further, it displays the different use of prototypes in agile and traditional product development. For the traditional approaches, prototypes are primarily used for verification of a function or to test the final design. This would be counted as vertical prototyping in this analysis. Whereas in the agile product development during TMS, more horizontal prototypes were build, showing a focus towards finding the right design.

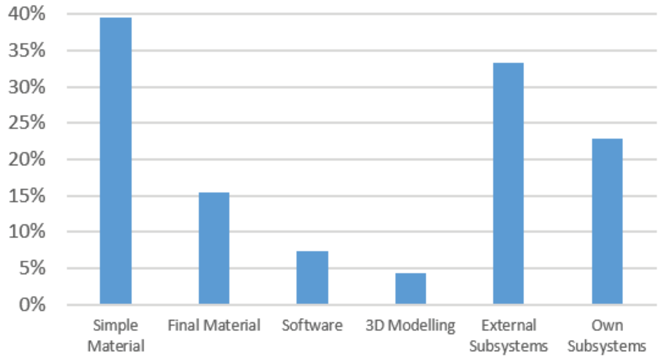

Fig. 5: Form (quality and material) of prototypes build.

B. *Prototyping Approach*

To start this section, the prototypes, which had been assigned to a specific iteration, were divided according to horizontal and vertical focus. While analyzing the focus of the build prototypes, it was determined that the focus shifted from horizontal to vertical while the development process. Prototypes, build in the first two iterations, all had a horizontal component. Afterwards, the share decreased within every iteration. In iteration 6 and 7, 20% of the prototypes showed a horizontal focus. The other way around it occurred with the vertical prototypes. While in iteration 1 only 4% of the prototypes were vertical, in iteration 6 and 7 every prototype possessed a vertical focus (Figure 6).

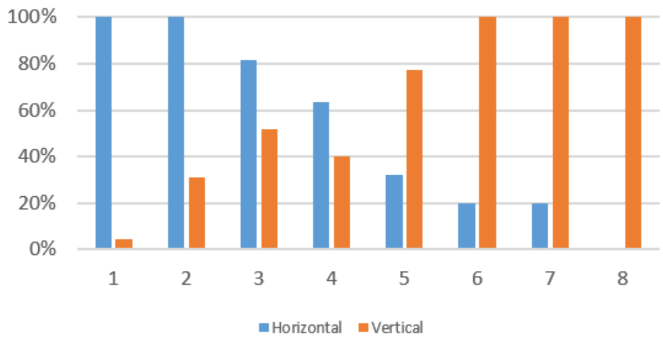

Fig. 6: Shares of horizontal and vertical focus during the development process

The shift from a horizontal to a vertical focus shows the changing use of prototypes within the development process. The further the development is proceeded, the less design exploration must be done, and the more the focus shifts towards a detailed implementation of the design. Simultaneous the data also show the importance of horizontal prototyping even in later stages, as still 20% of the prototypes build in iteration 6 & 7 showed a horizontal focus. This could be explained by the need of the development team to correct or change a chosen design because of new arisen findings. Therefore, they again need to open the solution space and use horizontal prototypes to do so. Although a horizontal share still exists in those iterations, it is always a combination with vertical and thus diagonal prototyping. Hence it seems to be possible, to combine the exploration of possible solutions and the increase of details, once a certain level of design fixation is reached. Thus, from a certain point in time, it is tried to build a more precise version of the design with every prototype.

In the next step, the same analysis was done for two single teams: Bikorsa and MyScreen (see Figure 7). In the first iteration, only horizontal prototypes were build. In iteration 2 the focus was again on horizontal prototyping and furthermore the most prototypes were built in this phase. In Iteration 3 there were no patterns recognized. Thereafter, the focus shifted once again towards horizontal prototyping. With the start of iteration 5, vertical prototyping dominated throughout the teams.

The use of only horizontal prototyping in iteration 1 can be explained by the necessity to communicate the idea and objective within the team. The actual development started with iteration 2. Thereby the solution space was opened wide, to search for the best design to implement the primary functions. The different focuses in iteration 3 can be explained by the different outcomes of the second iteration. Teams which already found a fitting solution, are more focused on building a more precise elaborated version, while teams, which had to cancel their first solution, are again opening the solution space, to find a better approach to implement the main functions. The high share of horizontal prototypes in iteration 4 seems to be caused by the search for solutions for the secondary functions. Thereafter, the basic design is set and the teams start to concentrate on further developing the chosen solutions.

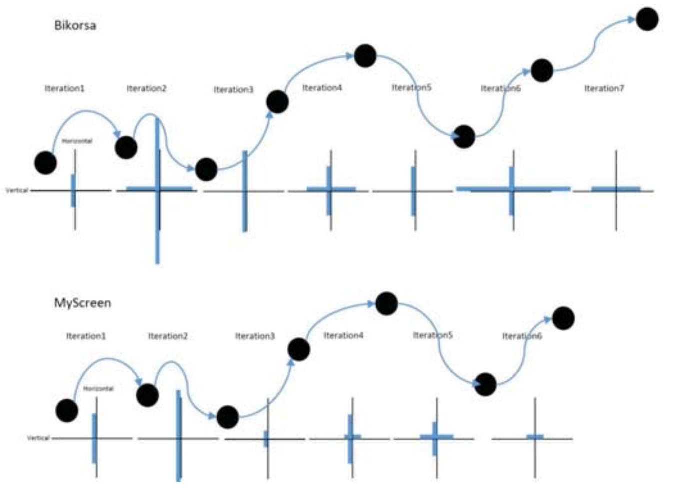

Fig. 7: Iteration course of the teams Bikorsa and MyScreen with vertical and horizontal prototypes

The following provides a consideration of the form of the prototypes in the individual iterations. In the first iteration, a share of 78% of the prototypes was built with simple material. This number declined in the following iterations, but stayed between 20 and 40%. Further, an increase of prototypes build with the final material, as well as own subsystems, was noticed.

The high share of prototypes build with simple material supports the thesis, of using the first iteration for communicating the idea within the team. Therefore, prototypes built of paper and cardboard are sufficient, because they should only help to visualize the idea. The fact, that the share of simple material does not fall under 28% until and included iteration 6, shows the use of those prototypes throughout the entire development. The teams tried to visualize their idea with simple material first and only changed to the more expensive final material, once the design was set.

The findings of the previous paragraph suggest a relation between the horizontal focus and the use of simple material. To prove this assumption, the material and quantity categories were analyzed regarding the focus of the assigned prototypes. Thereby, a domination of horizontal prototypes in the category "simple material" was determined. Further, the category "final material" shows a clear majority of vertical prototypes.

This proves the interconnection between simple material and horizontal focus, as well as between final material and vertical prototypes.

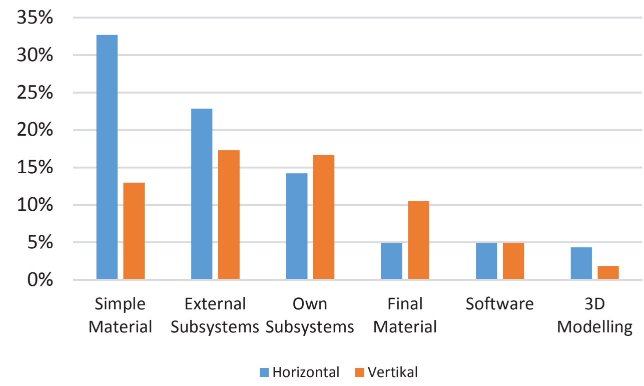

Fig. 8: Horizontal and vertical focus of a prototype build with a specific material category

In the following, the distribution of the four purposes to the single iterations will be analyzed. In figure 9 the percentage distribution towards the total number is displayed. The analyzation shows, that the explorative share decreased over the iterations, while the purpose of technical verification shows a rising trend. Noticeable are the iterations 4 and 7, were an interim decrease of the technical verification prototypes was detected. By considering the communicative purpose, a significantly higher share in the first and last iteration was recognized. The same increase in the last iteration can also be seen by usability prototypes. Over the remaining iterations, the share of those prototypes remained with a variation of 7% relatively constant.

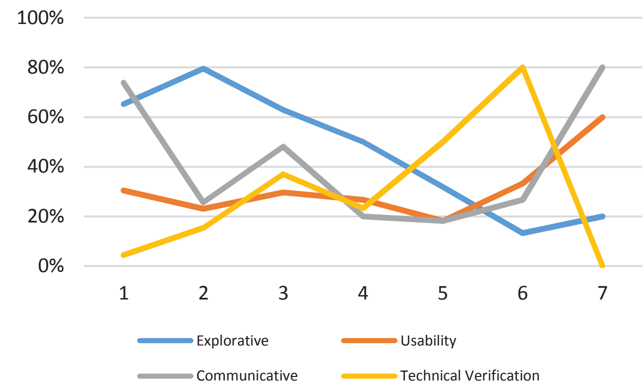

Fig. 9: Analysis of the purpose of prototypes

By looking at the purposes divided by the teams, no clear patterns were recognized, the composition variates from team to team. But the Usability share was lowest for six teams and the explorative share highest for eight. For the categories, communicative and technical verification, large fluctuations were determined. The share of communicative prototypes laid between 12 and 41% for technical verification between 6 and 41% (see Figure 10).

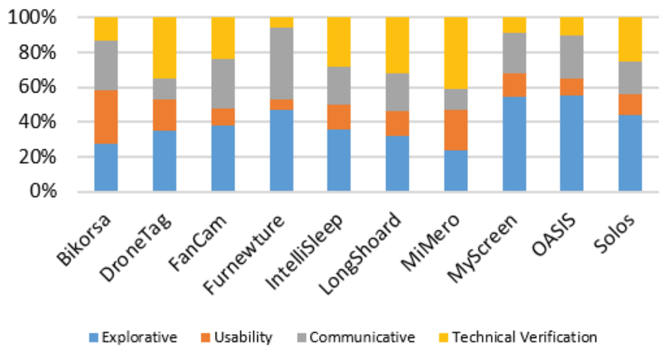

Fig. 10: Distribution of the purposes in the teams

Once again, the decrease of explorative prototypes over the iterations shows, that with progressed development, less designs were tested and the target shifts towards further development of a specific design. This is also confirmed by the increase of prototypes for technical verification. There, the decrease in iteration 7 can be explained by the preparation of the teams for the final "Demo-Day" (= teams presenting final state of product). Thus, the focus was more towards preparing the prototype for the presentation, than on further technical development. This hypothesis is supported by the course of the shares of communicative and usability prototypes. The assumption, that the first iteration is mainly used for communicating the idea within the team is supported by the increased share of communicative prototypes. An explanation for the differences in the categories, determined while analyzing the teams, is the difference of the developed products. It seems that different products need different approaches. For example, a product with high novelty grade has to be developed more exploratively, while other teams, who try to develop more customized products, need more usability prototypes.

In the next step, we considered the distribution of the findings on the solution space in the individual iterations. In figure 11 an increase of the feasibility share from iteration 1 to 4 was detected. Afterwards the share stayed constant at 87%, ere in iteration 7 a decrease to 60% was registered. Desirability as well as viability show no clear pattern during the development. Prototypes, added to the category "no findings", gained insights, which could not be assigned to one of the other three categories. The share of this category was with 30% relatively high in iteration 1, but dropped afterwards till only 5% remained in iteration 5. In the last two iterations, it again increased towards a percentage of 20 in the last iteration.

The decrease of feasibility and the highest share of desirability in iteration 7, as well as the increase of prototypes with "no findings", again points towards the preparation of the teams for the "Demo-day". The high share of prototypes that did not gain findings in iteration 1 supports the thesis, that prototypes in this phase were used for communicating ideas and thereby have no effects on the solution space. The fluctuation concerning the viability share can be explained by the different products the teams were developing as well as on different approaches towards the gathering of information on for example production costs. While some teams tend to prioritize that information early in the process, some other postponed the gathering of such information towards later stages of the development.

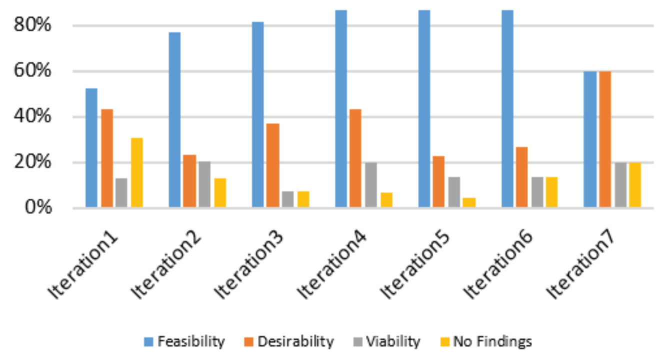

Fig. 11: Findings gained with the prototypes in the single iterations, as percentage from the total number of build prototypes in that iteration

To finish the analysis of the prototyping approach, we looked at the approach, the teams pursued for creating prototypes. Thereby was to recognize, that 52% used a progressive approach, with planning from one prototype to the next. Additional 15% also build on a previous prototype, but followed a predefined plan. Only 11% created prototypes just when they needed to verify a function. The forth category, building and testing as many prototypes as possible, included 22% (see Figure 12).

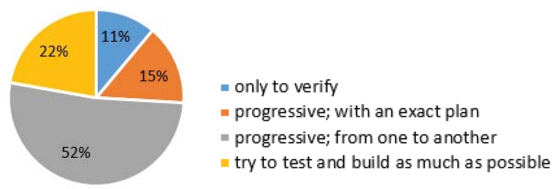

Fig. 12: Approach of the teams for the creation of prototypes

These data show, that the majority of the teams used an iterative approach. The case, were they build upon a previous prototype and planned from one to the next, displays the ideal iterative development. In addition, the category "try to test and build as many as possible" can be counted towards the agile approach at least partially.

C. *Impact of Prototype Focus and Prototype Purpose on the Solution Space*

In this section, we analyze the dependencies between the chosen purpose or the chosen focus and the findings derived from a prototype. Initially the variation of the different purposes and findings in all iterations have been compared (see Fig. 13). The data reveal again a constant high share of feasibility (more than 80%). Furthermore, the feasibility is mostly independent of changes in purposes. Usability, communicative and desirability behave in a similar way, whereas viability seems to be independent from the chosen purpose.

Again, the data support the assumption that findings concerning feasibility have highest priority over the entire development process. The constant feasibility share after the shift from explorative prototypes to technical verification can be explained by the corresponding change of the type of feasibility. Thus, in the course of the development the findings become more detailed and accurate but remain constant in number and can still be assigned to feasibility. Usability and communicative are related to desirability. Both purposes aim at presenting the product to generate feedback. The apparent independency of viability is due to the high complexity of this category. Viability depends on many other factors like budget, type of product and competitors and not only on the purpose.

We also analyzed the relationship between purposes and findings. Thereby combinations of purposes and findings were treated separately. It is remarkable that for any combination of purposes no more than three combinations of findings stand out. Furthermore, all prototypes not leading to any finding are communicative (Figure 13).

The data allow the conclusion that by choosing certain combinations of purposes the findings from a prototype become predictable. Findings would not be achieved accidentally but could be rather systematically planned. Prototyping could be structured to achieve certain findings. The evaluation further supports the assumption that findings from communicative prototypes cannot be captured by the used model.

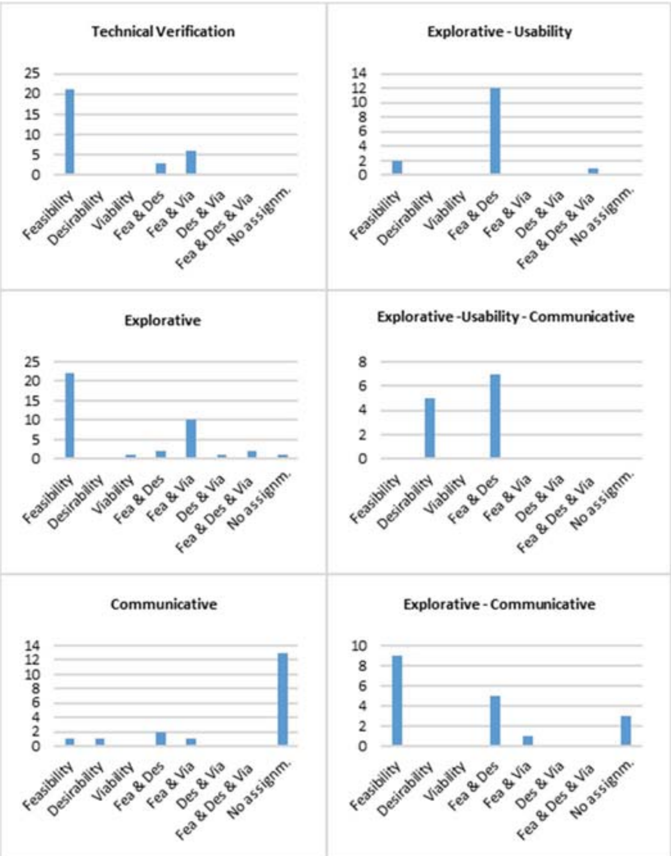

Fig. 13: Findings gained from a specific purpose combination

In the following we investigate the relation between focus of a prototype and findings about the solution space. No direct connection between focus and findings of a prototype could be found. As the shares of horizontal and vertical prototypes reverts during the development the shares of the feasibility, desirability, and viability remain unaffected.

As the solution space is continuously investigated in all three categories and only the focus of the prototypes shifts from horizontal to vertical during the development, findings are independent from the focus.

D. Impact of Prototype Purpose on Prototype Focus

Finally, we analyzed the relationship between purpose of a prototype and intended focus. Whereas the number of horizontal and explorative prototypes continuously decrease with the number of iterations, vertical prototyping and technical verification become increasingly important. Horizontal and explorative seem to occur jointly as well as vertical and technical verification. For communicative and usability purposes, no clear relationship to the focus of the prototypes could be observed.

This analysis confirms the hypothesis, that horizontal prototyping is mainly explorative, i.e. it is used to test different solutions in order to investigate the broad solution space with the aim to find a design. However, vertical prototypes are related to the technical verification. Usability and communicative purposes seem independent from the focus and are being used in both horizontal and vertical prototyping.

V. Discussion and Outlook

A. Limits and Potential of Prototypes within Agile Product Development

The study confirms, that a prototype may be incomplete and is a model, representing at least one dimension of the final product. In the context of agile product development, a prototype is of primary importance. In contrast to plan-driven development, the team is dependent on iterative (re-)planning and reorientation. Therefore, a prototype is central aspect combining and representing the insights and experience gained by the team. This allows a target-oriented development process being not specified and detailed in advance. Moreover, it promotes the transparency of knowledge within the team and facilitates the speed of reaction or rather adaption.

The evaluation of the data has shown that most of the prototypes have an explorative purpose. This means that the search for a suitable design has priority. This was also confirmed by examining the focus of the prototypes. During the development, a change from horizontal to vertical focus was observed. The focus shifted from design research to design optimization. At the same time, however, the data also show that even in the later iterations a share of 20% of the prototypes still have a horizontal orientation. The possibility to explore the solution space with prototypes will continue to be used in later phases as well.

It was found that only a small number of combinations of knowledge arise from a certain combination of prototype purposes. This shows that the use of the prototypes can be planned and the insights are not randomly gained.

Furthermore, a dependency between horizontal and exploratory as well as vertical and technical prototyping has been determined. Likewise, the following relationship for the state of prototype has been determined: vertical and final material, as well as horizontal and prototypes from simple material. Thus, a transition from exploratory, simply produced prototypes, to technical prototypes from final material is identified.

The data also support the assumption that there is not "one" approach in agile product development. It is much more likely to be unique to each product, which is also one of the strengths of agile product development, as it allows you to react flexibly to changes. Horizontal prototypes are used for explorative manners, whereas vertical prototypes pursue technical aspects. The purpose of communication and usability is dependent on both vertical and horizontal prototypes.

Summing up, most prototypes (52%) were generated from one to another and just about 15% were built with an exact plan in beforehand. This confirms an agile approach and confirms the cloudy model, where the final product is developed iteratively by gaining insights and experience.

In conclusion, prototypes are an important part of agile product development. They support the learning process by providing important insights about the solution space on which the planning of the next iteration is based. Different types of prototypes and the several purposes of prototypes support the exploration of the solution space.

B. Further Research

Subsequent to this analysis the study was done for the same course done with three teams of an OEM within automotive industry. This second study aims to put the findings into a more complex setting and to obtain more data on the role of prototype within a corporation. Observations for more complex products developed by interdisciplinary teams are used to investigate the impact of this result-driven development on the traditional innovation process. Fostering an agile product development model, it is interesting to analyze, the aim of multiple prototypes with regards to speed and flexibility of highly complex products. A dedicated investigation on the role of communicative prototypes as well as their impact on the corporate culture is performed as well. Finally, the complete development cycle from initial idea to an early market entry is considered with regards to product innovation. It shall enable a corporate team to act like a startup, pursuing various purposes with different types of prototypes.

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