WHAT IS SUCCESSFUL PROTOTYPING? INSIGHTS FROM NOVICE DESIGNERS' SELF-EVALUATION OF PROTOTYPING SUCCESS

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ABSTRACT

Prototyping is essential for fuzzy front-end product development. The prototyping process answers questions about critical assumptions and supports design decisions, but it is often unstructured and context-dependent. Previously, we showed how to guide novice designers in early development stages with prototyping milestones. Here, we studied the prototyping success perceived by novice design teams. This was done in two steps: (1) teams were asked to assign each prototype to a milestone, a specific purpose, a fidelity level, and a human-centered design lens, and then evaluate the success using a predefined set of criteria. (2) Teams were interviewed about the success of the prototyping process, this time using self-chosen criteria. Results related to (1) show that teams perceived prototyping activities with respect to desirability and problem validation significantly less successful than prototyping activities towards feasibility and solution validation. Results related to (2) show that teams mostly chose success criteria related to how well prototypes supported communication, decision making, learning, and tangibility. This insight may be used to give priorities to further improvement of methods and guidance in these areas.

Keywords: Prototyping, Design process, New product development, Evaluation, Education

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1 INTRODUCTION

When prototypes are used well during product development processes, they have been found to increase both design performance (Camburn et al., 2013; Dow et al., 2009), feasibility of design concepts (Walker, 2010), and funding for startups (Nelson et al., 2019). Prototypes embody a product (or part of a product) that is being developed and are used by the design team to communicate, make decisions, and learn about the product during its development (Lauff et al., 2018). By using different types of prototypes, such as cardboard mockups, functional prototypes, or computer-based simulations, prototyping can create value in all phases of the product development process (Elverum and Welo, 2016; Menold et al., 2017). This makes prototypes powerful tools, but the many possibilities can also create uncertainties among designers about whether they are prototyping the 'right way' (Hansen and Özkil, 2020a). Especially the fuzzy front-end of innovation is defined by a degree of uncertainty and unpredictability that makes it challenging to decide what to do (Gassmann, 2014). Unsuccessful prototyping can lead to large sunk costs and little usable outcome (Viswanathan and Linsey, 2013). Guidance for prototyping in early-stage development is therefore especially relevant.

Prototyping heuristics and best practices guide designers on how to prototype in product development projects. 'Design the minimal model needed', 'use prototyping to answer specific design questions', and 'be especially purposeful with higher fidelity prototypes' are examples of guidance from the existing literature (Deininger et al., 2017; Tiong et al., 2019). However, it is possible to apply prototyping best practices and still get unsatisfactory results. Best practices contribute to successful prototyping, but they do not necessarily describe a prototype's value. The context-dependency of prototypes and a limited understanding of prototyping success reduces our ability to provide applicable guidance to designers on how to prototype well. Recent papers have shown how collecting prototyping-related data during development projects can teach us about the prototyping process (Erichsen et al., 2020). However, when such prototyping data cannot be connected to a prototyping outcome, its potential to be used in data-driven analyses diminishes (Hansen and Özkil, 2020b). In short, we cannot really say how to prototype, when we are not able to identify successful or failed prototyping.

In previous research, Tiong et al. (2019) quantified the value of prototyping by scoring the design information uncovered from prototypes on a scale of 1-4 depending on the newness of the information. Camburn et al. (2013) and Dow et al. (2009) measured the performance of prototypes to compare the effect of different prototyping strategies on design outcome. Finally, Nelson and Menold (2020) asked student teams to rate the value of their own prototypes as such: (1) likelihood of project success, (2) refining project requirements, (3) learning about the design problem, and (4) learning about fabrication methods. The value of prototyping is often balanced with the cost and resources that were spent on the prototype, and Nelson and Menold found that there was little correlation between the time and money spent on prototypes and their perceived value. Additionally, prototyping itself is sometimes used as a metric for good design processes (Camburn and Wood, 2018). As shown, different types of measures have been used to investigate the effect and value of prototyping, but we lack precise metrics to characterise successful prototyping (Nelson and Menold, 2020).

This study investigates how novice designers themselves define prototyping success and why some prototypes are perceived to be more successful than others. It explores how prototyping success can be measured during design projects and what can be learned from quantifying prototyping outcome. The research is based on data gathered through a university course where nine student teams evaluated the success of their own prototyping activities on a daily basis. The study demonstrates the value of measuring prototyping success and contributes to the establishment of metrics to measure the success of prototyping in the future. Thus, the research questions to be answered are:

- *RQ 1: Which prototypes do novice designers find most successful and unsuccessful?*
- *RQ 2: What are the reasons that novice designers consider some prototypes more successful than others?*

In Section II of this paper, the methodology of the study is outlined, followed by the results from quantitative and qualitative data collection in Section III. In Section IV insights are discussed.

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2 METHODOLOGY

This study uses the prototyping-centric course 'Think.Make.Start.' (TMS) as test setting for data collection. It is a 10-day makeathon for students from the Technical University of Munich to collaborate in teams. The goal is to create new mechatronic products by going through a prototyping process from problem to solution (Martins Pacheco et al., 2020). In total, 44 students participated in the course forming nine teams with 4-5 students each from various backgrounds (Design, Mechanical Engineering, Electrical Engineering, Informatics, Robotics, Business, etc.). Participants applied for a specific role: Business, Problem, or Tech. Each team consisted of one Problem role, one Business role, and two to three Tech roles.

This mixed methods research contains two distinct activities for data collection: (1) daily measurements of prototyping success during development projects and (2) interviews with design teams after the completion of the projects. Two different methods were used to analyse the data, as they are quantitative (questionnaire) and qualitative (interviews). The quantitative data was used to identify which types of prototypes were successful or unsuccessful and qualitative data was used to understand why.

2.1 Daily measurements of prototyping success during development projects

The student design teams documented their activities by planning and reflecting each time they prototyped. For this, the teams needed to fill out a questionnaire each time they concluded a prototyping cycle, consisting of planning, building, testing, and reflecting on the prototyping activity. The items from the questionnaire originated from a literature review (Blomkvist and Homlid, 2011; IDEO, 2015;
Martins Pacheco et al., 2021). The questionnaire included items as shown in Table 1. When planning a prototyping activity, the teams assigned a purpose and a milestone on which they wanted to work. After the prototyping cycle, the teams reflected by choosing a fidelity of the prototype, selecting a lens pointing at questions they answered, and evaluating their own prototyping success. In the questionnaire prototyping success was defined in terms of how much the team had learned from their prototyping activity. The prototyping process was guided through a number of prototyping milestones starting with a problem pretotype and ending with a minimum viable product (MVP).

Data from the daily questionnaire was used to compare the success of different groups of prototypes. We tested for significant differences in the level of prototyping success depending on team, purpose, milestone, level of fidelity, lens, and time in the course.

2.2 Interviews with design teams after completion of projects

At the end of the course, the answers to the questionnaires provided by the students were graphically depicted. Three weeks after the completion of the course, interviews were conducted with one person per team who was speaking as a representative for the team. The interviewee got to see the data of their prototyping process and were asked if the data represented their prototyping process. Afterwards the participants were asked the following questions: *Q1: What was a successful prototyping activity related to your teams prototyping process and why? Q2: What was an unsuccessful prototyping activity related to your teams prototyping process and why?*

For the qualitative analysis, interviews were transcribed to identify reasons for the success or failure of prototyping. The transcribed interviews were coded by means of open coding by two of the authors individually. The result of the open coding approach were two independent coding lists (Burnard, 1991). These two lists were compared and combined into a final list of codes consisting of 9 themes and 25 specific sub-codes for successful and unsuccessful prototyping. The developed coding manuscript was applied to the transcribed interviews by the authors independently to identify which of the codes applied to which teams. The agreement between the two coders was 0.92 for the 225 instances (40 instances of codes applied to a team by both coders, 168 instances of codes not applied by both coders, 17 instances of codes applied by one coder only). Discrepancies were discussed until consensus was achieved for all instances. The result is a definition of prototyping success and a list of indicators for successful or unsuccessful prototyping, presented in in Figure 4.

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Table 1. *Prototyping data submitted by students each day during the course.*

Category	Items	Descriptions
Team	Name	A unique name given by the team
Date	Timestamp	A timestamp assigns a point in time to the activity
Purpose	Exploration	Learning new insights while trying out possible alternatives
	Evaluation	Test explicit hypothesis and assumptions for specific design ideas
	Communication	Explaining, persuading or discussing a design with stakeholders, e.g. through user testing
Mile-stone	Problem Pretotype	Understanding the problem by illustrating complete representation of the problem with all possible complications considered
	Problem Prototype	Aims at defining the final set of problems that can be reasonably deduced to be solved through targeted user feedback
	Solution Pretotype	A partially mocked-up representation of the intended product that can be built in minutes, hours, or days instead of weeks or months
	Model Prototype	A looks-like representation of the solution without features deployed on the product, but in a presentable form
	Functional Prototype	A works-like version of the solution with a minimal set of features deployed on a product, mainly used as demo units
	Minimum Viable Product	Contains sufficient features to satisfy early adopters and convince them to invest in the product
Fidelity	Low	Rough, quick to build, easy to throw away
	Medium	Includes interactivity, but not all features work
	High	Increases in completeness and detail of the features deployed
Lens	Desirability	Solving a customer need and creating a positive customer experience
	Feasibility	Solving a key issue on functionality or technical feasibility
	Viability	Creating an economically viable solution people a willing to pay for
Success	Very unsuccessful (1)	Nothing was learned
	Unsuccessful (2)	Learnings did not fulfil expectations
	Ok (3)	Something was learned about what was wanted
	Successful (4)	Expected learnings were obtained
	Very successful (5)	Learnings exceeded expectations

3 RESULTS

In this section, we show the results of applying a success metric in product development projects and how student design teams evaluated the success of their own prototyping.

3.1 Measured success of different types of prototypes

Figure 1 shows the overall success rates for the 74 prototypes by the nine teams during the course. With an average success rate of 4.0, design teams perceived most prototyping activities to be successful. 23% of prototypes received the maximum success rating and no prototypes were evaluated to be completely

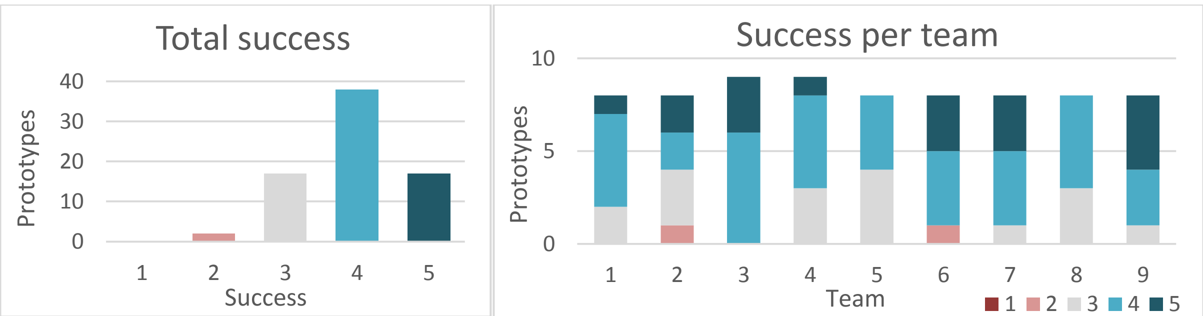

Figure 1. Total prototyping success (left) and success per team (right). Success is rated on a scale from 1: Very unsuccessful to 5: Very successful.

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unsuccessful, getting the rating 1. Yet, two activities were rated with a 2, which means that the teams did not learn what they expected from the prototype. The success differed between teams, where team 5 had the lowest average perceived success of 3.5, and team 9 had the highest average perceived success of 4.4.

Figure 2 shows the prototyping success for different groups of prototypes: purpose, lens, fidelity, milestone, and day of the project. Table 2 shows whether these differences are statistically significant. Prototypes used for exploration were perceived to be less successful than prototypes used for communication or evaluation (a). Feasibility prototypes were significantly more successful than desirability prototypes (b). The perceived success increased as the fidelity increased, and high-fidelity prototypes were significantly more successful than low-fidelity prototypes (c). Prototypes for the problem phase were significantly less successful than prototypes for the solution phase (d). Finally, the success of prototypes increased over time in the project, so prototypes made in the later part of the course were evaluated to be significantly more successful than prototypes made in the beginning (e). These factors influence each other, as problem prototypes were mostly made in the first part of the course and solution prototypes were made in the later part of the course. The quantitative data shows that some types of prototypes are more successful than others. However, this data alone cannot tell us *why*.

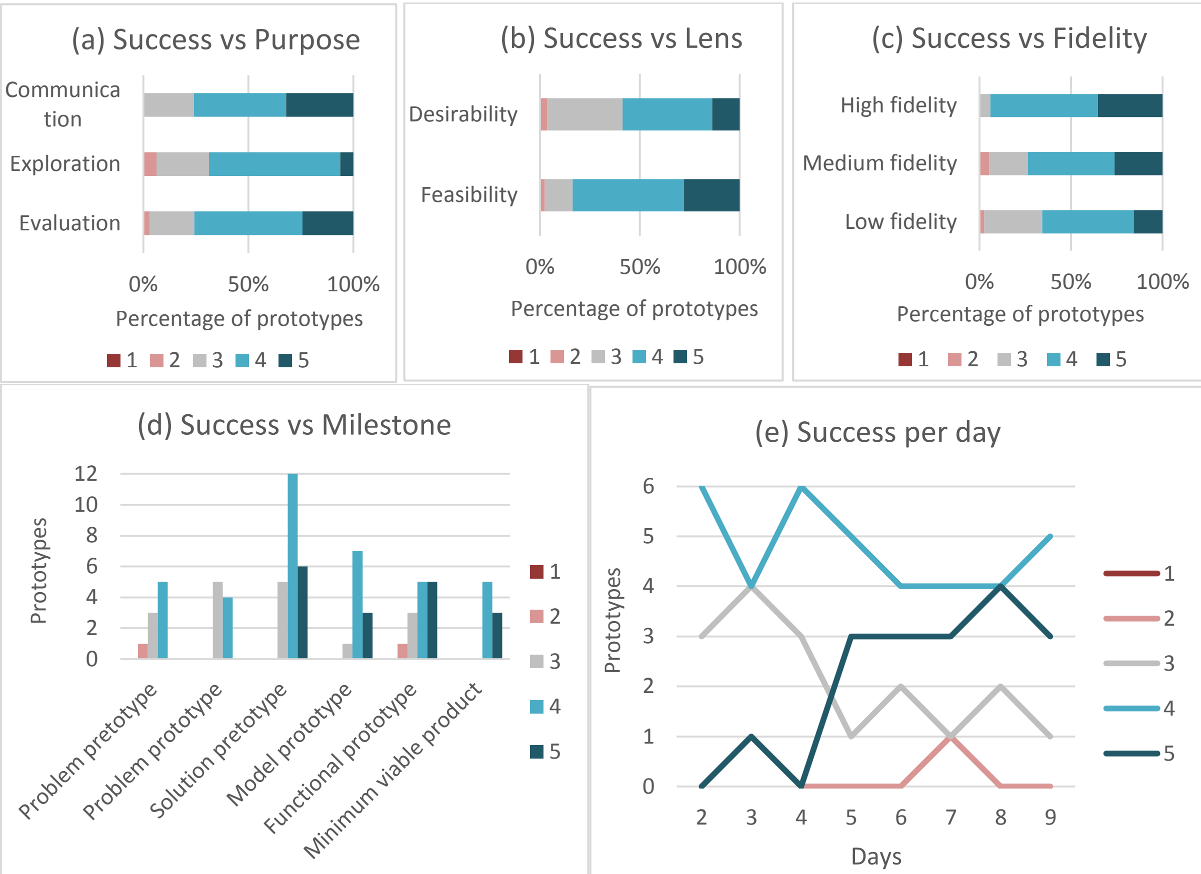

Figure 2: Comparison of the success of different groups of prototypes: (a) prototypes with different purposes, (b) prototypes with different lenses (Viability was excluded as there were only two prototypes for this lens), (c) prototypes with different fidelity levels, (d) different prototyping milestones, and (e) prototypes made at different days in the course.

3.2 Indicators for successful and unsuccessful prototyping

Figure 3 shows an example of a successful and unsuccessful prototype from two of the teams. Team 6 developed a game to teach young children basic programming skills and their most successful prototyping activity happened when they tested their idea at a kindergarten. This prototype was successful because they identified unanticipated challenges that made them adjust the design of the game. They would not have been able to identify and easily solve these challenges if they had not tested a prototype with users.

Table 2: Statistical differences between groups of prototypes. The Mann-Whitney test was

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*used to compare two groups of prototypes. Milestones were categorised into problem and solution phase and days categorised into beginning and end of course. The null hypothesis is that there is no difference in success between the groups. *) Null hypothesis is rejected and significant is found at alpha < 5%*

Factor		**Count**	**Avg. success**	**Var**	**p-value**
(a) Purpose	Communication	25	4.08	0.58	0.575
	Exploration	16	3.69	0.50	0.305
	Evaluation	33	3.97	0.59	0.952
(b) Lens	Feasibility	43	4.09	0.51	**0.023***
	Desirability	29	3.69	0.58	
(c) Fidelity	High	17	4.29	0.35	Low vs. medium = 0.654
	Medium	19	3.95	0.72	Medium vs. high = 0.194
	Low	38	3.79	0.55	**Low vs. high = 0.018***
(d) Milestones	Problem Phase	18	3.44	0.38	**0.001***
	Solution Phase	56	4.11	0.53	
(e) Days	Day 2-4	28	3.61	0.40	**0.002***
	Day 5-9	46	4.15	0.58	

Team 7 provides an example of an unsuccessful prototype in their development of a gaming device for bicycles. The prototypes they made to demonstrate attachments needed for the bicycle were deemed to be unsuccessful because they lacked a clear purpose. The prototypes were not valuable to the team as they neither provided any functionality to test nor communicated their idea well to others.

Figure 3: Examples of a successful prototype (left) and unsuccessful prototype (right)

These two examples illustrate 'learning' as an indicator for successful prototyping and 'mismatch between purpose and prototype' as an indicator for unsuccessful prototyping. Figure 4 presents nine overall indicators for successful and unsuccessful prototyping along with specific examples from the teams and the incidences of appearance. These are the reasons for a prototype being successful or failing and are based on interviews with the student teams after the completion of their projects.

Based on the indicators, we define successful prototyping as such: *A successful prototype has a clear outcome that enables the team to move the project forward faster, earlier, or with more confidence than if the prototype had not been used.* Thus, for a prototype to be successful, the team must be able to identify its outcome and how they can apply this outcome to progress the project. A key indicator for a prototype's success is its ability to help a team **learn** about their problem or solution or spark new ideas. Prototypes are especially successful when they provide insights quickly with the minimum use of resources. Success comes from acquiring desired information but also from learning something unexpected and important, as seen by Team 6. Prototypes are successful both when they prove that a solution works and when they show challenges for a given solution that need to be solved. Another important indicator for success is when prototypes enable the team to **communicate** and discuss ideas more concretely than what would otherwise have been possible. Communicating with external stakeholders such as customers and users is crucial to get early feedback. In addition, success comes from helping the development team build consensus with a common vision that enables internal decision-making. Another indicator for success is when prototypes increase the **tangibility** of the

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problem or solution. Prototypes can be successful by making the team agree on a common vision for the final product. By reaching different milestones, a solution becomes more tangible by knowing what path to go and what a solution might look like. The final indicator for successful prototypes is their ability to enable **decision-making** during the project. To evaluate if an idea is good, a prototype can be successful because it tests critical assumptions before too many resources are invested. Prototypes progress the project by validating the design direction or causing the team to change direction. Risk and uncertainty can be minimized and confidence in decisions increased if the teams test several different alternatives.

*Figure 4: Nine indicators for successful and unsuccessful prototyping. The numbers in the circles of the indicators show how many teams mentioned it in interviews. The bubbles contain specific examples of successful and unsuccessful prototyping. The colour coding shows the assigned indicator for the respective example. *) Not supported by literature*

Prototypes are unsuccessful when they fail to provide value to the development project or when the same value could have been achieved earlier, faster, and cheaper. An important indicator for unsuccessful

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prototypes is having a **mismatch between purpose and prototype**. This happens when a created artifact does not match its purpose and context for testing or when it lacks a purpose altogether. Unsuccessfulness comes from not achieving a useful outcome or spending too many resources on developing a prototype compared to the yield. **Prototyping the wrong way at the wrong time** can also result in unsuccessful prototypes. This happens when the prototype does not fit the current need of the development process. Sometimes prototypes can contribute to a premature solution focus where the problem phase is skipped too quickly. In addition, waiting too long before a first prototype is built and tested can result in postponed failures. Additionally, prototypes **built for demonstration without testing** are considered less successful. To get a useful outcome from the prototype, it is not enough to build something just for the sake of building - the prototype needs to be tested or applied to be successful. Technical **challenges in achieving expected prototypes** are also referred to as a cause for unsuccessful prototyping as it increases the effort of the prototyping activity but not its value. Finally, some teams also elaborated that **unsuccessful prototypes do not exist** or a least that they did not have any because you always learn something from prototyping.

4 DISCUSSION

From interviews with novice designers, we have identified nine indicators for prototyping success or failure. Additionally, we have compared the success rates for 74 prototyping activities made during a 10-day makeathon. Here, we discuss how this data answers the research questions.

4.1 Some prototypes are more successful than others

With an average success rating of 4 on a 5-point Likert scale, most prototypes were perceived to be successful by the design teams. This is supported by the opinion that unsuccessful prototypes do not exist because you can always learn something from a prototype, which was voiced by some of the teams. Still, the quantitative data shows that some types of prototypes were more successful than others. We found that feasibility, late stage, high fidelity, and solution focussed prototypes were more successful than desirability, early stage, low fidelity, and problem focussed prototypes. This indicates that it is more challenging for novice designers to use prototypes in the vague and uncertain first part of a project. During this phase it may be less obvious what they should build and test but also to identify clear outcomes from these prototypes. Once the teams decided on a solution, the use of prototypes became clearer and easier to them. While increased tangibility is related to prototyping success, teams did not specifically state that prototypes had to be highly detailed or solution oriented to be successful. Rather, they defined successful prototypes by their ability to provide a clear outcome that could move the project forward. This suggests that prototypes from the projects were unsuccessful, not because they were of low fidelity or problem oriented, but because the teams struggled in evaluating and using the outcome from these types of prototypes.

4.2 How to measure prototyping success

As shown in the results, there are several different ways that prototypes can successfully contribute to the progression of a project and several ways they can fail to do so. The difference between indicators show why it is difficult to measure prototyping success or value. Gained knowledge could be an obvious metric for measuring prototyping success, but the results show that there would be many reasons for success not included in this metric and that it needs to be balanced with the resources used for the prototype. Measuring perceived success allows us to capture all of these aspects in one metric, but also makes it less clear what is being measured. This research suggests evaluating overall prototyping success based on the clarity of prototyping outcome and usefulness for progressing the project. We also find that instead of measuring successful and unsuccessful prototyping, perhaps degrees of success should be measured. In the quantitative data, no prototypes were rated to be completely unsuccessful, while only 3% of prototypes were somewhat unsuccessful. Still, all teams were able to say why some prototypes were better than others. A more successful prototype could be one that provided better insights than another or it could be one that provided the same insights but quicker.

All the found indicators are described in existing literature as the role of prototypes (Lauff et al., 2018), best practices (Deininger et al., 2017), or heuristics (Tiong et al., 2019). However, in this study they show reasons why a prototype was successful or not. While novice designers have been shown to have a

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limited understanding of prototyping (Lauff et al., 2017), the interviews showed a mature understanding of prototyping value. For instance, several of the teams understood that prototypes are successful even when they disproof their assumptions. Furthermore, the indicators relate to different aspects of a prototype's purpose such as decision-making and learning instead of focussing mainly on feasibility and fabrication aspects as might have been expected. Concluding that the teams had a good understanding of prototyping value, perceived success becomes a good metric for prototyping success. However, one of the indicators for unsuccessful prototyping is not supported by the literature. A few teams stated that prototyping for communication and internal decision-making was less useful than building and testing something concrete. This shows a more limited understanding of prototyping and indicates that a difference exists in the maturity of novice designers' perception of prototypes.

4.3 Value of measuring success

A measurement of success in the data collection allowed us to identify areas of prototyping where teams struggled to be successful. Without this metric, we would only have been able to show which types of prototypes they used during the course. The success metric therefore allowed us to make better insights about their prototyping processes. From a short-term perspective, these insights can be used to improve support of novice designers. This research shows that novice designers need support in identifying outcomes from early-stage prototyping for desirability aspects and problem validation. We recommend always including a metric for prototyping success when gathering prototyping data. Making prototyping quantifiable and measurable in more studies has the potential to provide better insights and guidance not only for novice designers but also in the industry. Success measures can help expert designers improve their development processes by indicating how unsuccessful prototyping can be eliminated and successful prototyping increased in future projects.

4.4 Limitations and future work

In the qualitative analysis, conducted interviews were analysed using open coding. To ensure reliability, two different persons performed the coding in parallel and the results were combined. However, the question arises whether the same indicators could also result from other persons. It should be emphasized that this is always the case when evaluating interviews. In the quantitative analysis, the main question remains whether a good metric was used to measure the prototypes' success. While the 5-point scale for rating prototyping success was explained to the students, a risk remains that success rates were influenced by other factors such as the general feeling of progression in the project. The students received explanations of all the items in the questionnaire, but there is a possibility that they may have understood the words differently. Future research should address the evaluation of success by experts or observers. The results from this study were based on novice design teams and are therefore not generalizable to experts in the industry. Experienced practitioners may have different perceptions of prototyping success than novice designers.

This study compared success between different types of prototypes. The insights are somewhat limited as it is not fair to compare success between prototypes with a different purpose. Therefore, we need to look at levels of success within one group of prototypes that had the same purpose. For instance, what was the difference between the 13 desirability prototypes with a success rating of 2-3 and the 17 desirability prototypes with a rating of 4-5? Knowing this, we will be able to give better guidance on how to increase the success of desirability prototypes. Future prototyping research should begin to include metrics for prototyping success to allow for comparability and generalisability of prototyping insights. This paper is a beginning to measure prototyping success and the results should lead to the development of useful success metrics.

5 CONCLUSION

This paper contributes to the question of how the success of prototyping can be defined and measured. Specifically, this study investigated which prototypes were most successful during a mechatronic makeathon and in what sense they were successful. Nine student teams' daily success ratings were used to determine prototyping difficulties during fuzzy front-end development projects. The novice designers were significantly less successful with prototyping for desirability and problem validation than with prototyping for feasibility and solution validation. Based on interviews, nine indicators were derived that

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characterize successful or unsuccessful prototypes. Teams mostly chose success criteria related to how well prototypes supported (1) communication, (2) decision making, (3) learning, and (4) tangibility. The indicators show that the novice designers had a mature understanding of prototyping value similar to descriptions in prototyping literature. These indicators cover a large span of different aspects. Consequently, they are difficult to combine into one global indicator. However, it is understood that a successful prototype has a clear outcome that can be used to progress the project. Thanks to success measurement, we show where prototyping has a tendency to be less successful, i.e. in prototyping for desirability and problem validation.

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