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FOSTERING PROTOTYPING MINDSETS IN NOVICE DESIGNERS WITH THE PROTOTYPING PLANNER

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Abstract

Prototyping is an essential activity in product development, but novice designers lack awareness and purpose when they prototype. To foster prototyping mindsets in novice designers, we introduce a prototyping support tool that structures prototyping activities. This paper outlines the Prototyping Planner's development, evolution, and evaluation by 125 novice designers. The majority of novice designers' experienced that the Prototyping Planner helped them create purposeful prototypes and evaluate results from prototyping.

Keywords: prototyping, design learning, design tools, design methods, product development

1. Introduction

In today's globalised markets, products and their associated business models are becoming ever more complex. This complexity feeds back into the product development process, where designers are required to understand a wider context of needs and requirements than the ones concerning technical feasibility alone. In this regard, prototyping is one of the most valuable tools available for designers to gain insights and make informed decisions throughout the development process. Prototyping is part of an iterative learning process that aims at reducing uncertainties as early as possible by approximating the features of a product, service, or system (Hallgrimsson, 2012; Otto and Wood, 2001).

Recent years have witnessed a vast development and increased availability of digital desktop fabrication tools for prototyping (Jensen et al., 2016). Tools such as 3D printers and laser cutters introduce new opportunities but also create a more omniscient role of the designer. The knowledge and skills of fabricators are diminished and decision-making is becoming centralized around the designer (Wall et al., 1992). However, the iterative process and the uncertainty associated with it seem to be partly perplexing as the full benefits from prototyping are not always achieved (Drezner and Huang, 2009). This calls for the design community to study prototyping and support designers as they work to utilize prototyping technologies efficiently and effectively during product development.

Interest in research focused at prototyping has been sparked, and beginning prototyping frameworks and methods are being proposed to support designers with their prototyping activities (Camburn et al., 2017; Menold et al., 2017). This study continues these works with the introduction and evaluation of a process focussed design tool, the 'Prototyping Planner', dedicated towards novice designers.

1.1. Novice designers in product development and prototyping

In engineering design literature, a range of studies has investigated differences in the behaviour and performance of expert and novice designers. These studies share the overall finding that experienced designers are superior in employing design strategies. By reviewing the existing literature, we highlight specific competencies within product development and prototyping that are underdeveloped among novice designers, see Table 1.

Table 1. Development competences of novice designers vs. expert designers

Design aspect	Novice designers	Expert designer	Reference
General product development competencies			
Problem scoping	Spend less time in problem scoping and information gathering	Spend more time in problem scoping and information gathering	(Atman et al., 2007)
Design decisions	Trial and error with immediate implementations, omitting preliminary evaluation. Are unaware of design strategies	Makes preliminary evalua-tions of their design decisions prior to implementation. Uses particular design strategies	(Ahmed et al., 2003)
Design performance in non-routine situations	If support is available, perfor-mance is comparable to expert	"Benchmark performance"	(Daalhuizen and Badke-Schaub, 2011)
Competencies of particular relevance to prototyping			
Role of prototypes	Physical models created in the later phases of the development process with the objective to evaluate a chosen design	Dynamic tools of various forms to help refine or explore ideas throughout the whole development process	(Deininger et al., 2017; Lauff et al., 2017)
Awareness	Not always aware of own broad range of prototype usage	Prototypes used to aid in making decisions, and a tool to learn about unknowns	(Deininger et al., 2017; Lauff et al., 2017)
Prototyping approach	Lack specificity in prototyping practice	N/A	(Deininger et al., 2017)
Sub-system isolation and reduction of uncertainty	Incrementally approaching envisioned product rather than partial designs and uncertainly reduction	Prototype only parts of the system and systematically prototype the minimum model needed	(Viswanathan et al., 2014)
Fixation from prototyping	Lacking building/testing skills can lead to design fixation	Proficient building/testing skills reduce fixation from sunk costs	(Viswanathan et al., 2014)

As outlined in Table 1, novice designers are reported to have a limited understanding and awareness of prototyping (Lauff et al., 2017). Comparatively, professionals show a broader perception and utilization of prototypes as an aid in decision-making and a tool to learn about unknowns throughout the design process. Hostettler et al. (2017) also underlined that novice designers in agile hardware projects, despite very frequent prototyping, lacked the ability to concretize the purpose of their prototypes. Simply put, novice designers do not poses the mindset for prototyping that experts do. Prototyping support is hereby of obvious relevance to designers with limited or intermediate experience, and understanding these differences in behaviour helps us identify which aspects of the design activities to support.

1.2. Existing prototyping support

With the offset in the identified need to support novice designers, we investigated existing prototyping support tools in engineering design research. In a recent study by Menold et al. (2019), the authors identified six existing support tools or guidelines to help designers in prototype fabrication. An example is Christie et al.'s (2012) suggested thirteen decision variables to consider in establishment of a prototyping strategy, e.g. that the approach to prototyping can consist of multiple concepts in parallel vs. prototyping

only a single concept. The emergence of such methods hint that others have also identified the need to study, understand, and support prototyping activities.
A shared characteristic for the six identified prototyping support tools are their main focus at i) optimizing resource allocation of the time and cost associated with prototype fabrication, and ii) assessing performance of the final design outcomes. Similarly, Menold et al. (2019) argued that existing prototyping frameworks have mainly assessed a single attribute, e.g. the feasibility of the final designs, or optimization of resource use during the prototyping process.
Based on the identification of this limited focus of existing prototyping support, Menold et al. (2016) proposed the 'Prototype for X' framework, which incorporates human centred design aspects, such as user satisfaction and user-perceived value. Further, Lauff et al. (2019) recently introduced the Prototyping Canvas, which aims at creating purposeful prototypes to answer critical questions.
While there is a place for all of the existing prototyping support, we argue that there is still an unaddressed need for support that encompasses prototyping holistically as a process and not primarily as a fabrication activity. Prototyping is a complex product development activity that is often serving multiple purposes and is interwoven to different processes. Therefore, it requires an overall project understanding to define, plan, execute and evaluate prototyping activities. In this study, we expand on the existing body of knowledge to create a support tool that emphasises, not only purposeful prototyping, but also how to evaluate, document, share and act on prototyping results throughout the design process.

1.3. Research objective

The objective of this study is to introduce prototyping support that fosters prototyping mindsets in novice designers and teaches a formalised approach to prototyping. We aim to achieve this with a prototyping tool – the Prototyping Planner – that forces designers to structure their prototyping activities and holistically consider both the purpose, fabrication, testing, and results from prototyping.
This paper outlines the development and evolution of the Prototyping Planner, which spans two years, as well as its evaluation by 20 design teams. To assess the effects of using the Prototyping Planner and to develop it further in the future, we investigated how novice designers perceived its effects on their prototyping activities, guided by the research question: *How do novice designers perceive the effect of a prototyping support tool that forces them to adopt a formalised approach to prototyping?*

2. Methods

In this research, the Prototyping Planner was developed followed by two rounds of testing and evaluation. The initial development of the Prototyping Planner was guided by the presented comparison of novice and expert behaviour as well as the investigation of existing design support. The first version of the Prototyping Planner was tested and evaluated in a design challenge with 10 teams of novice designers at a technical university in 2018. Feedback from the evaluation was used to develop a second version of the Prototyping Planner, which was tested and evaluated in a similar setup in 2019.

2.1. Developing the Prototyping Planner

The Prototyping Planner is intended to be a support tool for novice designers or design teams to use at multiple points during a development project, each time they wish to prototype a concept. Therefore, a number of considerations are made regarding its format. To keep the simplicity known from similar tools such as the Business Model Canvas (Osterwalder et al., 2010), we aimed to structure the Prototyping Planner in a simple 1-page format that can either be printed or used digitally. Similar to the Business Model Canvas, the Prototyping Planner intends to structure prototyping activities by providing a formal process for prototyping with a number of questions that force deliberate decision-making from the designers. The development of the Prototyping Planner consisted first of determining the overall structure of the tool, before considering its specific questions.

2.1.1. Structuring prototyping

Recent literature presents prototyping as a systematic step-by-step process (Lugnet et al., 2018; Menold et al., 2017). According to Menold et al. (2017), prototyping consists of the three phases: Frame, Build,

and Test. As we wish to increase focus on the evaluation and results from prototyping, the Prototyping Planner follows an overall *four*-step process that combines the Prototype for X framework with the Shewhart iterative testing cycle (Plan, Do, Check, Act) described by Deming (1986). Thus, the Prototyping Planner's layout is structured following the four steps: Think, Build, Expose, and Act, see Figure 1. The Think, Build, and Expose steps ensures a clear purpose and strategy for the fabrication and testing before prototyping, while the Act step identifies conclusions from the prototyping.

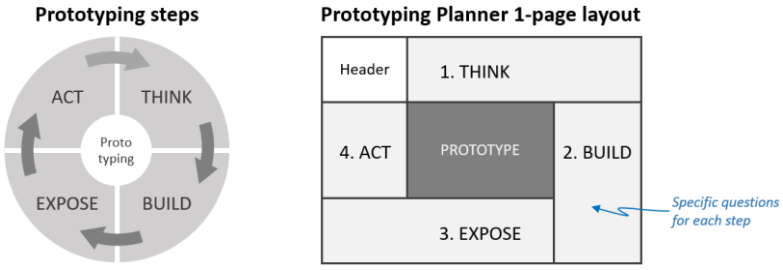

Figure 1. The Prototyping Planner's layout follow the four steps inspired by the Shewhart cycle

2.1.2. Questions for prototyping

Each of the prototyping steps, Think, Build, Expose, and Act, include domain specific questions to cultivate reflections guiding the design team to adapt best practice behaviour. The purpose of the Prototyping Planner is not to dictate the exact behaviour of the novice designers, which depends on the design context, but to ensure deliberate decision-making. Table 2 shows a number of questions that have been selected from literature to include in each step.

Table 2. Purpose and questions in each prototyping step

Step	Questions
THINK. Reflect on the development of the project and clarify current objectives. Answers to the Think step should inform the following Build and Expose steps	What is the timing in the development project? (Ullman, 2010) What is the overall objective and critical question that the prototype should answer? (Houde and Hill, 1997) Does the prototype need to test desirability, feasibility, or viability aspects of the product? (Menold et al., 2017) Does your objective require a divergent or convergent development approach? (Cross, 2008). Who can answer the critical question and how will the prototype communicate with these stakeholders? (Lauff et al., 2018) What are the minimum requirements for the prototype to answer the critical question? (Schuh et al., 2018)
BUILD. Prepare the prototype fabrication by considering the most optimal prototype scope	What type of prototype will you build? (Buchenau and Suri, 2000) Which prototyping strategies to use during fabrication? (Christie et al., 2012) How will you build the prototype? Which media and fabrication techniques to use? What resources are needed and what are the limitations? The generated information feeds into establishing the Build plan
EXPOSE. Define the activity, where the prototype is put into use to answer the critical question	How will you test the prototype? How will the test be conducted? What is the expected outcome and success criteria for the test? What data will you collect from the test? How will you collect data from the test? The generated information feeds into establishing the Test plan
When the design team has considered the Think, Build, and Expose steps, they carry out the prototyping following the prepared Build and Test plans. In the centre of the Prototyping Planner V2, pictures of the prototype are placed to document the prototype activity itself and follow prototype evolution (Nelson et al., 2019)	
ACT. Evaluate the obtained insights and define actions	What learnings and insights did you obtain from the prototyping? What actions and design decisions will you make? Is there a need for further prototyping? How will you document and share the results with stakeholders?

2.1.3. Feedback from industry experts

In order to collect feedback on an initial outline of the Prototyping Planner, five industry practitioners were invited for a four-hour workshop. They represented experiences in product development responsibility in a tech start-up, medical device R&D, and product development consultancy. During the workshop, the industry experts were introduced to and applied the Prototyping Planner. Following this, prototyping best practices and recommendations for the Prototyping Planner were discussed.
Feedback from the workshop was generally positive regarding the overall concept of the Prototyping Planner and supported the authors in refining the tool. For instance, it was supported that a coherent prototyping strategy must balance both the prototype specification and fabrication.

2.2. Testing the Prototyping Planner

The Prototyping Planner was tested by novice designers carrying out a design challenge in design teams of 6-7 people, see Table 3. All participants were enrolled in the design engineering program at a technical university in Scandinavia. In the first design challenge, participants were asked to design and fabricate a speaker, while utilizing digital fabrication technologies. The participants were instructed in the use of fabrication technologies, but not on prototyping strategies. The project lasted seven weeks and the students used Prototyping Planner V1 to structure their prototyping activities. Feedback from this test informed the development of Prototyping Planner V2, which was used in the second test. Here, the design teams developed machines for food processing and production, such as tofu or kombucha makers, over the course of three weeks. The participants were given a detailed introduction to the Prototyping Planner's structure and content. During the design challenges, the participants could ask questions and receive guidance on the use of the support tool.

Table 3. Timeline for testing the Prototyping Planner

Year	Purpose	Teams	Students	Survey respondents
2018	Testing V1	10	65	52 (79%)
2019	Testing V2	10	60	50 (78%)

2.3. Evaluating and evolving the Prototyping Planner

The perceived effect of the Prototyping Planner was evaluated through survey questionnaires. The questionnaires consisted of a number of closed questions covering how much the Prototyping Planner was used in the participant's team, team number, the attractiveness of layout and format, the likelihood of using the tool again, and the perceived effects of using the Prototyping Planner. The survey further asked the participants to provide open-ended feedback on positive aspects of the tool and aspects with room for improvement. The surveys were conducted with the participating designers after the conclusion of each design challenge. 79% and 78% of students completed the questionnaires, respectively.
In order to assess the open-ended feedback, it was coded using qualitative content analysis (Hsieh and Shannon, 2005), where responses from the participants were read carefully and coded with negative tags (e.g. unclear mode of action, lack of examples) and positive tags (e.g. clear communication, structured planning). The responses were reassessed and tagged, using as many tags as necessary to describe the response. These positive and negative tags show the strengths and limitations of the Prototyping Planner. Field notes from observations and informal discussions with the design teams during the design challenges added additional details about the use of the Prototyping Planner.

2.3.1. Further developing the Prototyping Planner

The feedback from the first evaluation survey was used to improve Prototyping Planner V1. Much of the feedback indicated a wish for more clarity in the mode of action. The following major changes were made, leading to the creation of Prototyping Planner V2: i) The overall four-step structure was kept, but the layout changed so the cycle structure became more prominent, ii) All questions in the original Prototyping Planner were open ended and required further explanations to understand. Some of these were changed to closed-ended questions in V2, and iii) Room was added for pictures of the fabricated prototypes to increase the Prototyping Planner's ability to support documentation and communication.

3. Results

We present the Prototyping Planner V2 and its perceived effect as evaluated by novice designers. The Prototyping Planner template can be found online at www.prototypingplanner.com/ppV2. Figure 2 shows the Prototyping Planners made in a group that developed an automatic spice dispenser. According to their Prototyping Planners, they prototyped nine times, mostly in the beginning of the process.

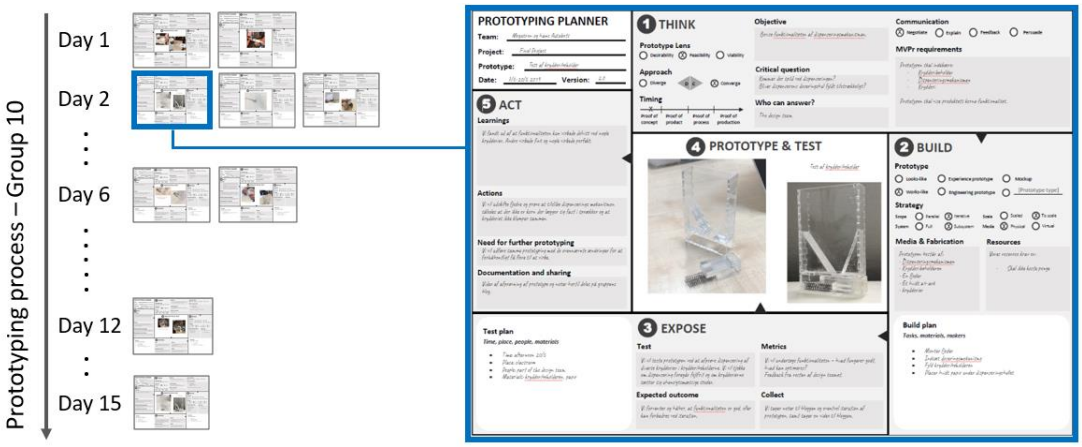

Figure 2. The use of Prototyping Planners in group 10 who developed a spice dispenser

Figure 3 shows the extent to which each of the ten design teams used the Prototyping Planner throughout the three-week design process to develop food production machines. On average, each design team made 13 Prototyping Planners. The average extent of usage estimated by each participant in the survey is 3.8, which means that the teams stated that they used the Prototyping Planner for most prototyping activities.

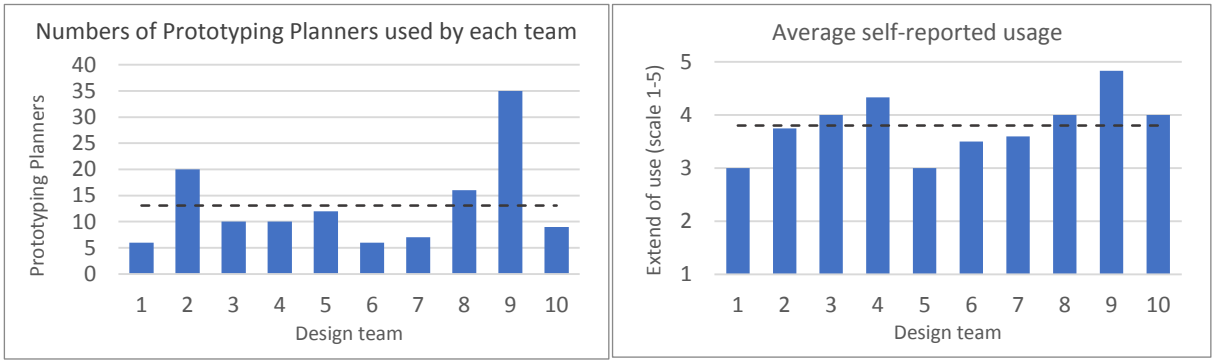

Figure 3. Actual (left) and self-reported (right) Prototyping Planner usage by all design teams

3.1. Perceived effects of the Prototyping Planner

Figure 4 shows the perceived effects of the Prototyping Planner on the overall mindset for prototyping and the perceived effects of the tool on certain prototyping behaviours. 65% of participants agreed that the Prototyping Planner created a mindset for how to prototype in the future. However, some aspects of prototyping were perceived to be affected more than others. Defining a clear purpose and evaluating results were generally rated to be highly supported by the Prototyping Planner, while only 23% agreed that the Prototyping Planner ensured more efficient prototyping.

Table 4 shows the categorised positive feedback from participants and the areas where they saw room for improvement. Overall, the positive aspects relate to acquiring a structured way of working that ensured conscious decision-making and clear results. The students mentioned several of the areas that were targeted during the development of the Prototyping Planner. Most aspects concerning room for improvement relates to understanding how to use the Prototyping Planner and understanding unfamiliar terms, such as ‘prototype lens’ or ‘subsystem prototyping’. Furthermore, some participants found the tool too time consuming and complicated to use.

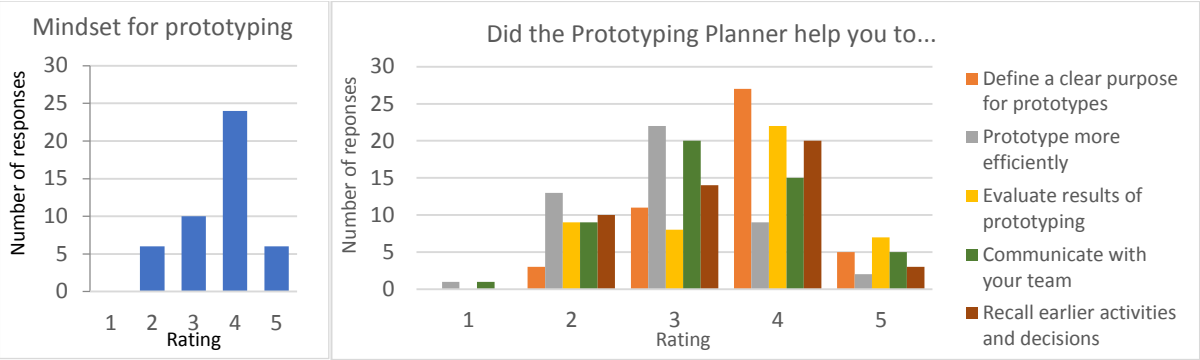

Figure 4. Does the Prototyping Planner create a mindset for prototyping in the future (left) and the perceived effect of the Prototyping Planner (right)

Table 4. Summary of open-ended feedback mentioned by minimum five participants

Positive aspects	Example quotes	Instances
Positive aspects of the Prototyping Planner (answered by 37 participants)		
Ensures purpose & focus	"The idea is good – making you think of why you prototype", "The purpose is much more clear"	12 (32%)
Clear layout & structure	"Good layout – intuitive"	11 (30%)
Supports communication & sharing	"Being on the same page whilst prototyping", "Describes findings to team"	10 (27%)
Evaluation & results oriented	"It clarifies what we learned"	10 (27%)
Triggers reflections	"Potential for developing important insights"	7 (19%)
Planning & working structured	"Makes sure you have a plan"	7 (19%)
Provides overview of prototyping	"It provides an overview"	5 (14%)
Areas with room for improvement (answered by 36 participants)		
Confusing / not descriptive enough	"Terms could be more descriptive"	10 (28%)
Similar / redundant fields	"Too many similar 'questions'"	7 (19%)
Too time consuming	"Takes time from actual prototyping"	6 (16%)
Overly complex / too much content	"Too many features for smaller sessions"	6 (16%)
Project too short	"Didn't make sense to use in such a short project"	5 (14%)

4. Discussion

4.1. Perceived effects of the prototyping planner by novice designers

The objective for the Prototyping Planner was to create a prototyping mindset in novice designers by teaching a formalised approach to prototyping and encourage deliberate decision-making. In this study, 20 design teams with a total of 125 novice designers used the Prototyping Planner to structure multiple prototyping activities during development projects running several weeks. The majority of these participants reported on the Prototyping Planner's ability to gain a mindset for prototyping, to make purposeful prototypes and evaluate results, but fewer people experienced its effect in other desired areas.

The Prototyping Planner attempts to help designers **make purposeful prototypes** by asking them to state a critical question and to consider the minimum effort needed to answer this question. The evaluation showed that 65% of participants agreed that the Prototyping Planner helped them in this area and this was also the most frequently mentioned positive aspect of the tool in the qualitative feedback. These results support the findings from the evaluation of the Prototyping Canvas, which professional designers perceived to support intentional prototyping practices (Lauff et al., 2019).

Compared to similar works, the Prototyping Planner highly emphasises the outcome from prototyping; how to evaluate results and use them in the further design process. In the evaluation, 63% of participants agreed that the Prototyping Planner helped them **evaluate results from prototypes**. This

is of special importance, as benefits from prototyping can only be reached when its learnings are applied in the further design process (Drezner and Huang, 2009).
Related to this, the Prototyping Planner is also intended to support **documentation and communication** of prototyping activities and results. Using the Prototyping Planner ensures automatic documentation of the design process. Such documentation allows for retrospective reflections and communication with stakeholders who did not take part in the prototyping. 40% of participants agreed that the Prototyping Planner helped communicate within the teams and 49% agreed that it helped recall earlier activities and decisions. The results in these areas are not as clear as for the purpose and evaluation aspects. However, working closely in 6-7 people teams during a three-week project, the importance of documentation and communication may not have been as obvious as in more complex projects over a longer time period.
In the open-ended feedback, some participants point out the simple underlying value of the Prototyping Planner to **planning and working structured** (19%) and to **reflect** (19%) over decisions and activities during the development project, which is often the purpose of design support (Daalhuizen et al., 2014).

4.2. Limitations and challenges of the Prototyping Planner

The evaluation survey also identified limitations of the Prototyping Planner and areas for further development. Much of this feedback is related to the format and content of the Prototyping Planner.
A portion of the participants mentioned that the Prototyping Planner was **confusing and not descriptive enough** (28%) and that it contains too **many similar questions** (19%). However, not everyone agreed with this as 30% of participants also indicated that a positive aspect of the Prototyping Planner was its clear layout and structure. There is a trade-off between making a tool that is easy to use and but can also teach novice designers best practices and expert concepts related to prototyping.
Following this, 16% of participants also thought the tool too **time consuming** and only 23% agreed that the tool made prototyping more efficient. Some stated that using the Prototyping Planner takes valuable time away from what they consider 'actual' prototyping (i.e. building a prototype). Similarly, Daalhuizen et al. (2014) showed that students that use systematic methods during a design task experience significantly higher perceived time pressure and lower motivation than student using a set of heuristics did. Efficiency of prototyping was not an initial focus point for the Prototyping Planner, but part of its underlying value is that prototyping will become more efficient and effective when a prototype has a clear purpose and its results are actually being used. If the Prototyping Planner is perceived as too complex and the barrier to understand is too high, students may choose not to use it, or simply use it to document the prototyping activities that they have already carried out. Therefore, it is important that the values of the Prototyping Planner becomes apparent to the novice designers.
A few participants also stated that the Prototyping Planner was **overly complex** (16%) and that the **project was too short** to use it properly (14%). This feedback is related to the flexibility and comprehensiveness of the tool. Some participants expressed that the tool did not fit smaller, quicker prototyping tests and it did not suit a project where prototypes were produced every day for three weeks. This could be a result of the students' unfamiliarity with the tool. When the questions and purpose of the tool are understood, the designers should be able to evaluate where to focus their efforts. Over time, it may become more of a checklist and does not have to be filled out in detail for every prototype. However, it is important that the Prototyping Planer can easily be integrated in the existing development projects and that it feels like a natural support rather than an obstacle.

4.3. Contribution, limitations and future perspectives

This study builds upon the recent works within design research to support designers with their prototyping strategies. Based on a comparison of novice and expert designers' prototyping and product development capabilities, we have introduced a new prototyping support tool that teaches novice designers to structure their prototyping. Similar to other tools, the Prototyping Planner encourages purposeful prototyping, but also extends the focus to the evaluation, communication and sharing of results from prototyping. The Prototyping Planner is intended for use during student development projects at universities to support professors engaged in engineering education who struggle to deliver education that incorporates prototyping activities (Jensen et al., 2016), or even in the increasing number of startups, where young candidates constitute a large part and operate without support from experienced

designers (Wu and Atkinson, 2017). The Prototyping Planners can be used once to learn how to structure a prototyping activity or multiple times for the support of prototyping in an entire development process. Evaluations of the tool show that many novice designers recognised its intended effects on their prototyping activities. However, the evaluation in this study only considered the perceived effect of the Prototyping Planner and future studies should investigate the actual effect of the tool on prototyping processes or results. Furthermore, some participants did not perceive the intended effects of the Prototyping Planner. Their feedback presents a number of challenges for the success of the Prototyping Planner, but also identifies improvement areas for the future, such as refining the descriptiveness of the questions. We believe that the identified challenges must be considered in most prototyping support. We are currently continuing the development of the Prototyping Planner to overcome these challenges.
The Prototyping Planner also needs to be tested further in different contexts. It currently presents one format for prototyping, and further studies should investigate whether different levels of expertise or different types of development projects require different versions of the tool. Furthermore, the current Prototyping Planner is to be used when it has been decided to prototype, and its relationship to the points in the process where designers have not yet decided to prototype should be further explored. The data that is inherently captured when the Prototyping Planners are used could also be further investigated to provide insights on how students prototype and where they need additional support. Future developments should also consider digitalising the tool to provide opportunities for knowledge management, which might be valuable for professionals as well.

4.4. Conclusion

Novice designers do not poses the same prototyping and product development abilities as expert designers. They can benefit from the prototyping support that the design research community is beginning to provide. In this study, we introduced and evaluated the Prototyping Planner – a prototyping support tool intended for novice designers to adopt a prototyping mindset. The Prototyping Planner intends to teach novice designers to create a clear purpose for prototyping, but also to emphasise the evaluation of results, the communication and documentation of results, and the structured use of several prototyping activities over the design process. The Prototyping Planner has been tested, evaluated and iterated twice, showing that many novice designers perceive its ability to create a prototyping mindset for the future and that it helps them create a clear purpose and evaluate results from prototyping.

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