**Abstract**

Prototyping is a crucial element of the design activity. Prototypes serve as temporary and incomplete embodiments of design ideas with which designers explore the design problem as well as propose and refine possible solutions to the problem. Given its deep connection to solutions, prototyping has been typically associated with the later stages of design. A stage in which the problem has been sufficiently mapped that a solution can be proposed and refined based on the discovery of requirements. Yet the question of what it means to prototype for problem exploration remains. To provide an answer to this question, first we take a quick look at what the role of prototypes is in design and more specifically what their role might be in the early stages of design. And later we discuss from the perspective of the reflective conversation that the designer has with the artifact it has created and what we reflect on when dealing with problem exploration. Subsequently some illustrative examples are presented of unintentional problem exploration prototyping from student design projects. To conclude, a reflection of the importance of design education in preparing practitioners to better deal with different types of prototyping beyond solution refinement.

Problem-space; early design; problem-oriented prototyping; design education; prototype
have been studied. Aspects such as the process of prototype creation and their relation to materials and techniques used, levels of refinement and definition, so-called fidelity (Rudd et al., 1996; Virzi, 1989; Virzi et al., 1996), the roles of prototypes (Menold et al., 2017; Ulrich et al., 2008), prototyping strategies (Camburn et al., 2017; Domingo et al., 2020; Houde & Hill, 1997; Menold et al., 2017), etc. Among them we can also find the aspect of timing (Camburn et al., 2017) which refers to when in the process of design prototypes are created and used. Given the nature of prototypes as representation of possible solutions, even if only temporary, they are deeply connected with the later stages of the design and engineering process. This means that a lot of the attention given to prototyping is more closely related to prototypes as embodiments of explorations of solutions, and in a stage in which the design problem should be “less” ill-defined and more aspects of the problem should have been uncovered. However, studies have shown the importance of prototyping in the early stages of design (Camburn et al., 2017; Rothenberg, 1991; Virzi, 1989) and several authors refer to prototypes as objects of active learning or exploration, yet not much has been shown in the literature of how this might happen. This then leads us to the question of what does it mean to prototype with the (sole) purpose of problem exploration in the early stages of design?

What do Prototypes do & Role of prototyping

The creation and use of prototypes is an activity that is not exclusive to design. Prototypes are used in many engineering disciplines as well as in informatic disciplines. It is not uncommon to see the term being used to describe artifacts or processes that spam from software development all the way to showcasing conceptual futuristic products, which highlights how field dependent our understanding of prototypes is. This wide range of usages of the term prototype means that the concept has many possible descriptions and definitions, based on where and for what the term is being used. For these reasons, we will not attempt to present a definition of what prototypes are, but rather discuss what prototypes do and what their role is in understanding design problems in the early stage of design.

If we review prototype/prototyping literature and the many definitions provided, we can discern what prototypes do, and what is the role they play in the design process. One of the primary functions of a prototype is that of serving as an embodiment, regardless of shape or medium either physical or virtual, of a design idea with the intention of providing the designer a means to expand their understanding of the design space (BenMahmoud-Jouini & Midler, 2020; Camburn et al., 2017; Houde & Hill, 1997; Lande & Leifer, 2009; Menold et al., 2017; Ulrich et al., 2008). From this we can already start to see certain key elements about the prototyping act and the artifacts created through it that can help us then examine the question of prototyping for problem exploration.

Embodiments of ideas

The first part, and perhaps the one that has been explored the most in the literature, is that of prototypes as embodiments of design ideas. The extensive exploration of idea embodiment can provide us some clarity on the different ways or methods of representing ideas (BenMahmoud-Jouini & Midler, 2020; Camburn et al., 2017; Pei et al., 2011) the technologies that could be utilized to create them, as well as their level of detail or fidelity among other important aspects of the artifacts we create as prototypes.
Yet the question posed by Houde and Hill (1997, p. 368) "is a brick a prototype?" and its subsequent answer "depend on how it is used" reminds us of two crucial aspects of prototyping. Firstly, that an over-emphasis on the prototype itself can create a fixation to think more about the artifact rather than on the objective for which we have created it. Which in turn could lead to over-design and over-trust on the prototype artifact (BenMahmoud-Jouini & Midler, 2020). And secondly, that however important the embodiment of design ideas is, what questions we ask of our prototypes and the answers or learnings we extract from them are of the outmost importance (ibid).

Means of exploration

The second part that we can then examine is that of prototypes providing the means of expanding the understanding of the design space, which is deeply related to the roles or objectives that prototypes have in design problem-solving process. An important part of design work is to be able to use design tools, such as prototypes, to better understand what are the different important elements that make a situation problematic. This could mean an exploration of what are pain points, challenges, needs, or desires that must be addressed and what possible solution, or combination of solutions, can be better suited to solve this problematic situation. This is often done in an environment of collaborative work, with other design practitioners, people from different professional backgrounds, potential users, and clients.

Given how wide the range of explorative actions is that designers need to address, prototypes become fluid objects that could serve multiple purposes. If we look at multiple examples from prototyping in the literature, we can find multiple characterizations or divisions of prototype roles.

Ulrich, Eppinger & Yang (2008) propose a two-sided approach. Firstly, by proposing a two-by-two matrix of type of prototypes which in its first axis has a dimension of physical vs analytical prototypes and on the second axis a dimension of comprehensive vs focused. And secondly a division of prototypes by their purpose which is divided in four: learning, communication, integration, and milestones.

In Camburn, et al.'s (2017) review of prototyping literature, they identify four distinctive objectives: Gradual Refinement of design solutions, Exploration of new design concepts, Tools of Communication between different stakeholders, and for the process of Active Learning and gaining new knowledge.

Menold et al. (2017) propose a framework of prototypes that draws from human-centered design methodologies to subdivide prototyping into three different categories: Prototypes for desirability or the appeal of certain solution to the users, prototypes for feasibility or technical possibility of the solution to work, and prototypes for viability or the likelihood of a solution to be profitable and a sound business option.

Benmahmoud-Jouini and Midler (2020) go even further to present three archetypes of prototypes, stimulators, demonstrators, and validators, with the intention of presenting an overarching set of characteristics that go beyond a simple individual role.

Yet, from the previous examples, we can observe that very little separation is being made in terms of different objectives of prototypes based on which stage of the design process are
the prototypes being used. As shown in Camburn et al.’s (2017) review, a great majority of literature mainly focuses on solution refinement which is connected to final stages of design process that extends to the other studies here presented. Along with some of the other categories of prototype roles and objectives that are of vital importance to the entire design process and not to one specific stage. Leaving only very few that mainly focus on early stages of design and none with the specific objective of prototyping for problem exploration which is rather treated as a possible consequence of prototyping.

One thing can be discerned from these different categorizations of prototyping and how they are used that lead into the reason for exploring problem-oriented prototypes of this paper. From the previous authors we can separate prototyping from different perspectives into two distinctive areas, prototyping for solving a problem and prototyping for testing of a solution. From this we can propose a third area, to be further explored in prototyping research, of prototyping for discovery and learning of the different possible variables of the problem to be solved (Figure 1).

![Figure 1. Prototyping for discovery](image)

Some prototyping techniques, like Lego prototypes of services, can be and are being used to also explore current situations. In such a case, the Lego representation could be seen as a discovery process, but it is likely to result in a hybrid activity both identifying potential problems and proposing solutions. Hence, the prototyping technique and activity are not exclusively focused on exploring the problem. In other fields of design, such as critical design, the whole purpose may be to expose a problem (as one example, Anna Odell’s project Undersökningen, in which she invited influential men to experience the denigrating experience of sitting in a gynecology chair undergoing an examination, comes to mind). But here the object that questions or exposes said problem is a final design, and not a prototype. Hence, we are not claiming that what we propose is entirely new. Yet what we aim to explore in this paper is what it would mean to develop prototypes in the early stages of a process, that in the end is aimed at yielding some kind of solution later on, but where the initial prototyping efforts have the sole purpose of exploring (some aspects of) the problem.
Prototyping in early stages of design

Early-stages of design

Design projects can have a wide range of starting points based on the level of advancement of the design brief and the designated starting point of the project. There are many degrees in variability in terms of known and unknown information that designers would deal with at the starting point (Ruiz, 2020).

Several seminal authors within design offer a distinction in between two types of design activity. Firstly, design activity in which a lot of the variables and constraints of the design space are known to the designer and their job is to find the best combination of elements that address these variables to produce a solution. And secondly, design activity in which a lot of information is conflicting or unavailable to the designer at the starting point, and before a solution can be produced, the designer’s job is to provide the space with more clarity and understanding of what the problems, goals, limitations, and criteria to possible solutions are. Simon (1973) refers to this as well-define and ill-define problems, Gero (1990) refers to them as routine and non-routine design, while Buchanan (1992) refers to them as determinate and wicked problems.

For the focus of this paper, we mainly refer to the second set of problems. The kind of design problems in which the designer spends a great deal of time in the early stages of the design process to provide structure to the problem (Simon, 1973; Voss, 2005). Through establishing a problem space area by determining what are possible users and stakeholders, what needs, and problems do these users face, what are acceptable criteria for a sensible solution and what are possible limitations and constrains that need to be considered (Goel & Pirolli, 1992; Simon, 1973; Smy et al., 2016).

One of the main reasons for this paper is the behavior observed in classroom of our design projects course. The course is based on design thinking methodology and grounded in challenge-based learning, experiential learning, and iterative models of design for problem solving. In it, groups of students are selected and assigned to real industry projects provided by an industrial partner. Over the course of nine months, students follow a methodological process of simultaneous problem and solution exploration through the use of ethnographic studies and prototype development that follow design thinking iterative process (Domingo et al., 2020; J. Ruiz, 2020; J. F. Ruiz & Wever, 2022). One of the difficulties that students face during the first missions of the project is to produce prototypes that are not intended as fully fleshed solutions but rather as problem probing and exploration.

Prototype-based reflection in action

In 1983, Donald Schön proposed that, in the practice of design, this behavior of searching for creative solutions is one of reflection-in-action in which the designer engages in a ‘reflective conversation’ with the design problem. He explains that in design activity, designers follow a process of path creation in which new understandings about the situation are created by making “moves” and evaluation or reflecting on said move and their significance on the path taken (Schön & Bennett, 1996). This means that designers engage on a process of discovering the design space and desirable path by building prototypes, testing them, and
reflecting on what it means for the particular design problem (Cross, 2004; Schön, 1983; Schrage, 1996).

The process of Reflection-in-action process is based on the use of a framing process. The process as explained by Schön is cycle of four steps (Figure 2). First the designer names or establishes the elements of the problem that will be addressed. Then a context or frame in which they will be addressed is created. Next the designer proposes experimental/temporary prototypes or moves. Finally, the designer tests and reflects on the results of said moves to either accept them as desirable moves or to propose new ones (Cross, 2004; Schön, 1983; Valkenburg & Dorst, 1998).

![Figure 2. Reflection in action process cycle](image)

When can see a clear connection of this process for prototype creation in the later stages of design (Figure 3). Here the problem has already been explored and the elements of the problem that will be addressed can be named, which allow the designer to propose a frame in which a series of possible moves can be proposed, evaluated, and reflect on their significance for a solution within this frame.

![Figure 3. Solution focused reflection-in-action](image)

**Problem focused reflection-in-action**

If we on the other hand look at the state of the different element on the earlier stages of design, we can observe that neither the problem has been sufficiently explored that will allow for the elements to be named nor a “permanent” frame can be created in which the designer can propose and evaluate moves. Yet, from our previous understanding of the design activity we can infer that instead of being in a state of paralysis over lack of problem definition, designer instead use prototypes to engage in active learning to provide definition to the problem (Figure 4). What changes is the element in which the designer reflects, and the question they ask of their prototypes, effectible using the temporary frame and temporary
moves to reflect on the elements named. This task then places a lot of importance on the question the designer asks of its prototypes and the ability to not fixate on the artifact created but rather to focus the reflecting on problem definition.

Figure 4. Problem focused reflection-in-action

**Unintended Examples of Problem Exploration Prototypes**

In this section we will use three examples taken from project of our Design Thinking course, and we will discuss them from the perspective of the problem focused reflection-in-action model previously discussed. The course itself has a structure of missions/milestones designed to guide the students through a design process that start with divergence and exploration of the problem are and later into a converging face to develop solution.

During the project the students are provided with a unique real-life project from a real industrial partner, design methodological content and a set of deliverables based on the state of the project. The missions in which the three examples where situated, belong to the early stages of the project.

In this stage students are asked to develop a deep understanding of the problem area and users within it, while at the same time create prototypes that answer non-evident design questions. The missions are very much intended for students to develop the ability ask non-evident design question based on their research and to create prototypes that prove those questions. While some students are able to use prototypes others struggle to use prototypes solely for problem exploration and become fixated on the artifact and the solution it offers to the problem. The three examples here presented, among others no in this paper, are of the groups of students who successfully used prototypes for problem exploration and allowed for a dissection and reflection of the actions performed that led to the model here presented.

**Improving great looking eyes**

**Problem space:** In this project the group of students was provided with a design brief from a multinational make-up company in which the company provided a very open challenge for exploration. The main prompt of the brief was how might we improved great looking eyes and what are problems that user experience when applying make-up.

**Element of the problem:** after a period of space exploration research, user interviews conducted, and testing of current solutions, the design team had discovered that there is a steep learning curve, high expertise level and time investment to obtain good results. This
deterred many users from applying make-up on a daily basis as they might have limited time in
the morning before their daily routine began. Another finding that the team discovered was
the perception of users that make-up application is a personal identity activity that is closely
related to self-care and “me time”.

**Question:** These findings led the team to find a paradox of fast speed for results vs slow
speed for enjoyment. From this the question that the team had about the problem and the
user was: *Would user be willing to give up control of their daily make up routine to obtain
better results?*

**Artifact created:** Based on this the team decided to construct an automated make-up
machine (Figure 5a) with the premise of superfast application but no control over the results.
You just put on the mask, pushed a button, and wait for the results. The machine was based
on a wizard of oz prototype. The mask itself didn’t work at all and was just a modified mask
(Figure 5b) to look like it could possibly be a real machine, and a real make-up artist
equipped with an airbrush and hidden behind a door secretly performed the make-up
application (Figure 6).

**Figure 5a & 5b Automated make-up machine**

**Figure 6. Prototype testing**

*Problem reflection-in-action:* In this case the machine was not technical feasibility. However,
the team was not interested on the possibility of actually building the machine but rather to
see the willingness of users to submit themselves to an automated process that offered great
results but in which they had no control. In this case the design artifact was the make-up
mask, but the prototype was the experience of automated make-up application that they use
to better understand their users.
Contribution to problem-solving: In the end the design team didn’t create a make-up application machine. The learning they extracted from that prototype gave them and insight in understanding that user would be willing to utilize simplified tools that limited their ability to customize results but that provided quick and effortless results with no learning curve and predictability in results.

Rescue in hard-to-reach terrain

Problem space: In this project the group of students was provided with a design brief that dealt with rescue operations from and industrial partner that collaborated with a research center for disasters. The main prompt of the brief was how might we extend the survival time of victims in emergency situation.

Element of the problem: Among the scenarios of research that the teams used was the Trängslet Dammen plane crash in the north of Sweden. This scenario exemplified a situation in which victims had to wait for a very long period of time before any help was provided due to the difficulties of the terrain in which it occurred. For the victim this meant that they had to endure very cold temperatures and lack of supplies while they waited for help to slowly arrive.

Question: The scenario presented, coupled with the teams’ research on similar situations, led the student group to consider multiple physical prototypes of systems that contained all possible tools and equipment that victims could use while waiting for rescue services. The team explored the creation of a survival system and how to and where to place it that would be easily accessible and not interfere with cabin design or weight distribution on planes. However, the team discover that many similar kits or systems either already existed or could be easily assemble. This reflection led the team to a second question of accessibility to the tools and more specifically to would passengers even think or remember to bring them in case the emergency was happening?

Artifact created: Based on this question the team decided not to build the system of survival tools anymore but rather decide to test the issue of would it be useful in a case of emergency. For this the team decided to use a simulation of the tools represented by a pillow and constructed a simulation of a plane crash and to make it as stressful as possible (Figure 7). in the simulation, the aircraft crew, performed an A/B test in which they either gave detailed instructions to remember to bring the kit or just loosely mentioned it.

![Figure 7. Simulation as prototype rather than the artifact](image-url)
Problem reflection-in-action: In this case, once again the team was not after a technically feasible solution but rather, they wanted to better understand the behavior of people in stressful situations and how they would behave around feasible solutions. In this case the artifact was a representation of the kit in the form of a pillow, but the prototype was the testing platform of the simulation that allowed for testing of user behavior.

![User in stress situation forgot the instructions given](image)

Contribution to problem-solving: From the test conducted the team quickly discovered that in very stressful situation the users won’t easily remember instructions no matter how elaborate (Figure 8). In the end the team reflected on the path taken once a new piece of information was found in a subsequent prototype that pointed to a very low incidence of plane related crashes combined with a very low survival rate after impact. Based on this discovery decided the team decided to change path to post disaster rescue in hard-to-reach areas but the learning that solution needs to be easy to use with minimal instruction and accessibility to user in very stressful situation was carried to final solution.

Medical imagery

Problem space: In this project the group of students was provided with a design brief that dealt medical images and the patient-doctor relation surrounding the use of said images.

Element of the problem: After the initial exploration period, where students conducted research and interviews, the group started to see a pattern of disconnection in between health professionals and the patients. They discover a twofold problem, first of prolonged waiting times in between the image been captured, and diagnosis been produced. second the problem of poor communication in the diagnosis segment of medical imaging as they are hard to read and require high expertise to do so. The problems are, of course, exacerbated on one hand by limited availability and time of medical professionals that can read, and interpret the images. And on the other hand, by impatience from patients that experience anxiety regarding their health issues.

Question: Based on these finding, the group of students started questioning several assumptions from the current state of the problem, like could it be possible to create medical images that are self-explanatory and don’t immediately require a medical professional to evaluate them but can provide initial understanding to the patient. This path led the team to examine current medical images and how much can patients currently understand?
Artifact created: Based on this question the team decided to create several prototypes that aimed at helping patients to understand current images by either giving them a point of comparison or by providing an easier to read image. First, they presented a baseline to understand what healthy image looked like versus what the image of their condition looks like to establish if they could understand their situation better (Figure 9a). And secondly the team provided patients with different sets of images in both 2D images (sliced view) and 3D images to establish if seeing the bones or organs in their actual shape would facilitate understanding (Figure 9b).

![Figure 9a Comparison of healthy vs unhealthy image](image1)

**Figure 9a Comparison of healthy vs unhealthy image**

![Figure 9b Comparison of 2D vs 3D representation](image2)

**Figure 9b Comparison of 2D vs 3D representation**

Problem reflection-in-action: In this case, once again the team was not after a technically feasible solution or digital system that could actually display the information to the patients. Rather, they explored what is their current level of understanding of images and how can it be enhanced by providing certain visual aids. The artifacts use were simple modified images either printed or in a PowerPoint deck which they used to test with the users (Figure 10).

![Figure 10. Prototype testing](image3)
Contribution to problem-solving: In the case of this team, the reflection and learning from this early prototype was rather a big “failure” from the perspective of the artifact, but a great success in terms of defining their problem area. The students discovered that patients had a bigger tendency to overreact, misinterpret and misidentify basic elements from the images. From the medical community they also discovered that not providing a full load of information on the patient is part of the diagnosis as to not overwhelm and further produce anxiety. For the long-term project this prototype served to dissuade them from the path of self-diagnosis but pointed at and interesting revelation of visualization of same object in multiple modes in a common platform to simplify communication between image technicians who communicate 2D and doctors who communicate in 3D.

Summary/Conclusions

In design education, a range of models and prototypes get generated by students. A degree show, with appearance models (Pei et al., 2011) on pedestals, is experienced by many students as the celebratory culmination of their many years of study. But as Pei (ibid) made clear so nicely in his taxonomy of design representations, different types of models and prototypes each have their function, to either explore, validate, or communicate aspects of our design.

Academically trained designers may be expected –even though current practice might be different– to explicitly articulate and argue for the type of design representation they will use, as well as at which fidelity they will create it.

Design education should train students both at the skills to create different types of design representations, as well as in strategically employing them. Current educational practice may well fall short on this.

Here however, we raise yet another question: if we were to have programs properly training students on the use of different models and prototypes, how would such training further evolve once we challenge students to employ prototypes purely for the exploration of their problem? Basically, all the sketches, drawings, models, and prototypes included in Pei’s taxonomy are solution-oriented.

The easy first step to take is to challenge students to start creating prototypes even earlier and use them in interactions with participants from their problem area. Asking at each coaching session, as we do in our weekly feedback sessions on the design thinking projects, what they have built and what they have learnt from their prototypes helps.

It also requires a mindset from teachers to except that they have no clue where a project will end up. Experienced design teachers will be able to see potential (and will have to bite their tongue to not point it out to students).

Proper briefing is of paramount importance, for projects where you want students to explore their problem space through prototyping. Briefs should be sufficiently open, or students need to be actively steered towards challenging the brief if it is more closed.
References


Juan Ruiz

Juan Ruiz is a researcher and teacher in design engineering and product development at the Division of Product Realisation at Linköping University, Sweden. He has both practical and teaching experience in user-centered design, design methods, and Design Thinking methodology as tools for complex problem solving, design innovation, and product development, focusing on areas of problem formulation, problem exploration and research, prototyping, and technology-driven market creation, among others. His research focuses on design problem-solving, in which he has conducted research on the topics of problem formulation and prototyping in the early stage of the design process and the consequences that both of these aspects present to problem solving. He has also conducted research on design engineering education that focuses on team formation and student collaboration within design challenge-based education.

Dr Renee Wever

Dr Renee Wever is a Professor at the Linköping University, Department of Management and Engineering, Division of Product Realisation. He holds a MSc and PhD in Industrial Design Engineering from Delft University of Technology in the Netherlands. His research interests are design research, circular economy, packaging design, sustainable behaviour, and sustainability in the front end of innovation. He has (co)authored some 20 journal articles on these topics as well as numerous conference papers. He has supervised multiple doctoral students who were working on design processes, tools, and methods, including prototyping. Since 2013, he has also served as editor for the Journal of Design Research.