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A LENS ON FUTURE PRODUCTS: AN EXPANDED NOTION OF PROTOTYPING PRACTICE

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1. Introduction

Prototyping is a core activity of the design process: designers like to describe their practice as a *learning by doing* attitude. It is common to see designers engaging with simple, quick-and-dirty, paper-and-pins prototypes from the very beginning of the conceptual process. This way of *thing-ing* is a learning behaviour through which designers construct knowledge, generated more by the activity itself than by the outcome [Baumer et al. 1996], [Coughlan et al. 2007]. The act of making the prototype is not just an act of reproduction, but it is an art in itself, which involves both creativity and cognitive processes [Sanders and Stappers 2014]. "Prototyping" is commonly associated with the creation of a physical representation of a design concept, to challenge and evaluate its performance. For this reason, criticisms over the benefits of prototyping were advanced by some classic engineering books.
Today, along with a redefinition of the scopes and methods of design practice [Sanders and Stappers 2008], this outlook on prototyping seems too narrow. During the last two decades, the target of the design activity shifted from product functionality, to product usability and then to product experience. Consequently, the body of knowledge describing the design activity was adapted and new methods, processes and tools had been introduced to support a different approach to design. Similarly, the role of prototyping in the product development process is currently debated, to understand how it supports new design practices. Prototypes are now described not only as the first verification of the product-to-be, but also as a valuable instrument for the fuzzy-front end of design. Many frameworks share the encouragement to start exploration-through-prototypes at the very early phases of the design process, suggesting many benefits: to miss no aspects of ideas in the sketches [Stappers et al. 2008], to actively build the product with users in a co-creative approach [Sanders 2002], to confront other stakeholders [Coughlan et al. 2007], to represent a future situation [Buchenau and Fulton-Suri 2000], [Sterling 2013] and to understand the facets of user experience [Buxton 2007]. To our extent, the discussion around the theoretical concepts of prototyping has been fruitful, giving structure to propose a broader definition and a model of prototyping. Achieving a fine-tuned knowledge of prototyping dynamics can contribute to design practice by increasing practitioners' awareness, ultimately facilitating their attitude towards this specific activity [Buchenau and Fulton-Suri 2000]. With this paper, we contribute to the discussion by maturing a refined definition and a novel model of prototyping, building on the current perspectives from the state of the art. Our aim is to provide a clear and synthetic, yet comprehensive answer to the question "what is prototyping?" and clarify its scopes with current design practices.

2. An expanded notion of prototyping

From the Greek etymon (***prŌtotupos***: *prŌtos, 'first'; typos, 'type')* the word 'prototype' means literally

'the first of a kind'. Prototypes are forms of representation used in design as cornerstones, to move from divergent to convergent moments in the traditional alternation of the thinking process [Ulrich and Eppinger 1995]. During the product development process, prototypes may take several roles. They can be useful to explore a design approach, as *proofs-of-concept*, to clarify design's physical embodiment and production feasibility (*proofs-of-product*), to test the production methods for their ability of successfully resulting in the desired product, as *proofs-of-process*, and finally, to demonstrate the complete manufacturing process is effective, giving *proofs-of-production* [Ullman 2003]. In this paper, we are concerned with the role of prototypes in the conceptual stages of the design process, thus we will deal with prototypes in terms of *proofs-of-concept.* Definitions of prototypes can vary according to the design domain, be it architecture, fashion or technology [Beaudouin-Lafon and Mackay 2007]. Generally, prototypes are described as representations or simulations of a design concept. Yet, they are more than just an outcome to evaluate, as they allow and trigger cognitive process. In some documented cases (see, for example, [Houde and Hill 1997], [Buchenau and Fulton-Suri 2000]), storyboards, sketches, concept videos, 3D models were used as prototypes, to engage with the design situation and to explore, evaluate or communicate it. In other words, the scope of the prototyping activity is to answer design questions and generate new ones [Yang 2005]. Many other scholars [McCurdy et al. 2006], [Lim et al. 2008] found insufficient and problematic to classify prototypes according to their properties, such as the level of their 'quality', i.e. the faithfulness of simulation of the product-to-be. The focus of the narration should rather be on the activity of prototyping itself than on the outcome. Consequently, we define prototyping as *the activity of engaging with the product-to-be, instantiating the design process.* Here, compared to other definitions available in literature, larger emphasis is given on what one prototypes for, rather than on what one uses as technique. Prototyping is then described as an activity in which designers generate *instantiations of the design concept as it is in the moment of the design process*. It is a moment of reflection in which designers increase their awareness on both design problems and possible solutions.

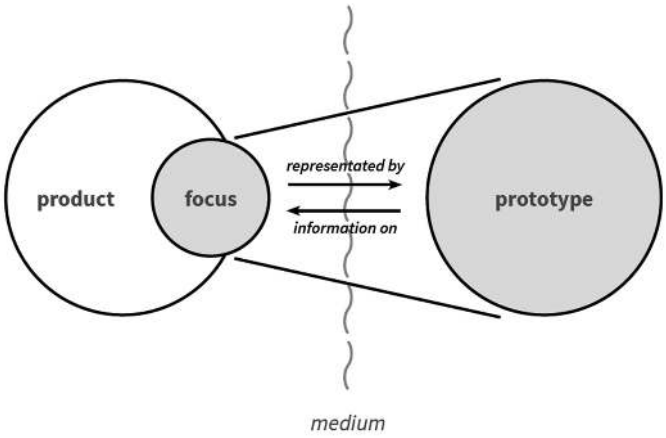

Figure 1. A model of prototyping activity

Lim et al. [2008] describe prototypes with the metaphor of 'filters to a design idea', generating a manifestation that externalizes design ideas. These manifestations should be created focusing on selected aspects of the design idea, instead of aiming at recreating the whole integrated design. Hence, in the model, only parts of the whole idea are filtered. In our view, it is rather the approach and the technique chosen that work as filters to the design idea, than the prototype itself. To expand this concept, we developed a model of prototyping that depicts prototypes as a lens framing a specific aspect of the product-to-be (Figure 1). The *focus* on the product is represented by a specific technique (the *medium* of communication), chosen by the designer in respect to the goals of the prototyping activity. For example, storyboards can work well as a *medium* to prototype the interaction (*focus*) with a new interface (*product*). In other cases, 3D models can be sufficient to evaluate in parallel (*medium*) the look-and-feel (*focus*) of several alternatives of chair concepts (*product*). The model also shows the ability of prototypes to generate information on the product-to-be.

3. Characteristics of prototypes

The model itself is not exhaustive to describe the complexity and the several decisions that designers face when undertaking prototyping. Understanding the characteristics and dimensions of prototypes can be useful for designers, to increase their awareness of prototyping activity and make appropriate design decisions [Blomkvist and Holmlind 2011]. For example, the purpose of involving users in a co-creative session at the early stages of conceptual design may suggest the use of low cost prototyping techniques, as paper and cardboard. Among the properties that can be used to describe prototypes, the *technique* chosen is probably the most common. With this term, we refer to the tools and method adopted [Blomkvist and Holmlind 2011], or the material-fabrication technology used to prototype. Other scholars refer to *technique* as the representation [Beaudouin-Lafon and Mackay 2007], the material [Lim et al. 2008], the technology [Jensen et al. 2015], the physicality [Hare et al. 2013], or the materiality [Wiberg 2014] of prototypes. The technique chosen affects and is affected by several other aspects of the prototyping activity. Ultimately, we define technique not only in terms of the *materials chosen to prototype*, but also as *the specific approach used to conceive how the prototype will be as an artefact*.
In our definition of prototyping, any means can become the medium in which a prototype is created, as the focus is rather on the activity than on the outcome. So, can a sketch be a prototype? We argue that yes, even sketches, in their classic form of pencil on paper, can be *used* as a prototype. Both sketches and prototypes can serve the purpose of answering design questions and generating new ones. They can instantiate the design process and allow the alternation between divergent and convergent thinking [Ulrich and Eppinger 1995]. Just as during sketching, prototyping is more than only the expression (i.e. the representation) of a design idea. Sketching can help developing creative thoughts and stimulate concept generation [Suwa and Tversky 1997], [Yang 2003]. Recent studies have proved similar effects for prototyping, correlating it to the design outcome [Yang 2005], [Hess 2012], [Isa et al. 2015].
Prototypes can also be described by their *fidelity* [Houde and Hill 1997], [Yang 2005], [Blomkvist and Holmlind 2011]. Fidelity is the level of correspondence with the product-to-be, i.e. the quality of the representation that the prototype offers. It is sometimes correlated to the precision of a prototype [Beaudouin-Lafon and Mackay 2007]. Although most sources do not distinguish between *fidelity* and *resolution* of prototypes, we argue that it is important to operate this distinction and differentiate between the correspondence to the future artefact (*fidelity*) and the amount of details included in the prototype (*resolution*). For example, the paper prototype of a stereo interface is low-fidelity, but it might depict all the knobs and buttons, thus providing a high resolution. Going back to the metaphor described in our model, the resolution corresponds to the lens' width.
Other important characteristics to describe prototypes are their interactivity, modularity and evolution. Interactivity is the level of interaction that the prototype provides the user with [Jensen et al. 2015] and its ability to generate data on this interaction [Lim et al. 2008]. Modularity is a specific feature of prototypes that have interchangeable parts, which can be useful to compare and assess many design alternatives. Lastly, prototypes may undergo iterative modifications as the design process continues, fostering a sense of progress [Gerber and Carroll 2011]. Thus, the ability to evolve, i.e. to support modifications in a flexible way, is important to prevent loss of time and resources in the creation of new prototypes.
In the model, the lens framing the product-to-be corresponds to the focus of the prototyping activity. It refers to '*what prototypes prototype*' [Houde and Hill 1997], which can be the representation of the product's aesthetics, its functional behaviour, the interface, and so on. Houde and Hill [1997] defined three possible focuses of prototypes, as shown in Figure 2. These are: the *role* of the product-to-be in our lives, the *look and feel* of the product, and all the components and technical aspects of the artefact that are necessary to fulfil its function (the *implementation*). In other words, the focus corresponds to the aspects of the design idea to manifest through the prototype [Lim et al. 2008]. An integrated prototype, i.e. a prototype that tries to simulate any feature of the product-to-be, is normally very expensive to achieve. Therefore, it normally occurs at later stages of the product development process. On the contrary, at the fuzzy-front end, an integrated prototype can cause idea fixation and demand excessive efforts in time and costs. Hence, the focus of the prototyping activity should be determined consistently and appropriately to the moment in which the activity is approached.

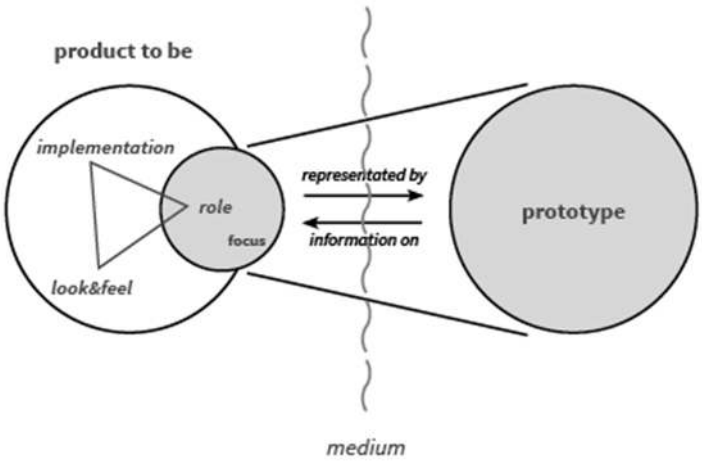

Figure 2. The three possible focuses of the prototyping: role, look&feel and implementation as described by Houde and Hill [1997]

The focus should not be confused with the purpose of the prototyping activity. From a textual analysis of the literature review [Jensen et al. 2015], three major themes of possible purposes were identified: prototyping for *exploring* design situations and design possibilities; prototyping for *evaluating* and comparing design alternatives, to progress in the thinking process; prototyping for *communicating* the design ideas to other stakeholders and to involve users [Schneider 1996], [Buchenau and Fulton-Suri 2000]. Prototypes ultimately solve the need of learning about a design, asking questions and answering them. Sometimes, the purpose is to imagine a future-to-be. After all, designers are *"expected to imagine new things, not to study what exists today"* [Koskinen et al. 2011, p.126]. In this case, the aim is to evoke visions of a far-future technology, context, or product [Sterling 2013]. The use of these *diegetic prototypes* [Kirby 2011] actually "changes the world", in the sense that they can influence the way companies invest in product development [Sanders and Stappers 2014].

When addressing the prototyping activity, designers should consider also the *audience* they will engage with their prototypes. The audience can include users, fellow designers or other stakeholders of the design process. Some sources suggest that the fidelity of prototypes should be tuned in respect to the targeted audience [Houde and Hill 1997]. They bring the example of a concept video, realised by Apple to communicate the idea of a far-future technology. The video was showing many details, to appear as realistic as possible. In that case, the high resolution was necessary to make it viral and target a wide audience. Nevertheless, end-users can answer well also to rough, low-resolution prototypes, as it is often the case with participatory design. If instructed correctly, users will start *imagining* how the product could be, instead of simply *evaluating* the artefact. In other cases, the audience of the prototyping activity can be composed by stakeholders of the product development process. Prototypes will then foster a discussion among professionals of different backgrounds (e.g. technical and design experts), as they can create a shared language.

The model presented here describes prototyping as an activity in which designers engage with the product-to-be, reflecting over specific characteristics. In the next section, we will use the model and the characteristics described in the previous section, to analyse three design cases and the prototypes that have been developed during these.

4. Prototyping cases

The model was developed on the basis of our educational experience over several years of teaching Virtual Prototyping at Politecnico di Milano, both at the School of Mechanical Engineering and at the School of Design. The cases reported here were selected from the students' project of the elective course Virtual Prototyping at the MSc in Design&Engineering, School of Design. All cases were developed by students (age 22-28) attending the course in the academic year 2014-2015. In the course, students are taught a variety of prototyping approaches. For the final project, students are asked to develop a new

concept and choose a medium consistent to the scopes of the prototyping activity. The ultimate purpose of this project is to show their confidence in managing decision making in prototyping.

4.1 AR packaging

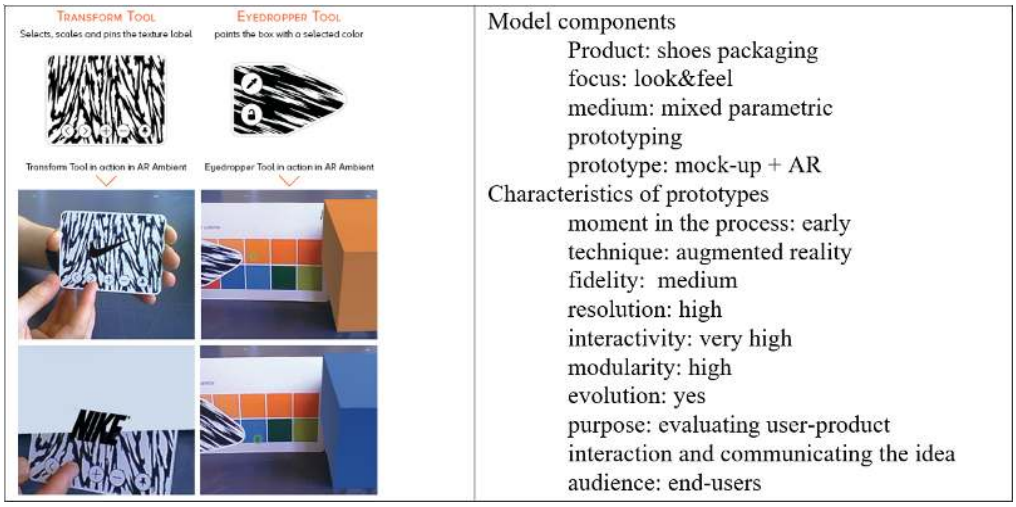

Figure 3. Prototyping case 1: the use of an AR toolkit for design reviews (©F.Bianco, I.Carli, A.Narduzzo)

In this project, designers used an Augmented Reality (AR) toolkit to confront company stakeholders in a collaborative and iterative way on a packaging prototype. The toolkit consisted of a shoebox and small tokens that allowed live modifications in a virtual environment (Figure 3). The AR software application was developed and operated through Unity© (https://unity3d.com). By interacting with the small tokens, designers and marketers could easily negotiate some important features of the packaging design. For example, they could scale and position the company logo, change the colour, enlarge the texture and so on. In this case, the prototyping activity focused on the look and feel of the packaging design. To do so, designers adopted a mixed, parametric prototyping approach to evaluate and compare design alternatives. By means of the prototype, designers could gather a deeper understanding of company stakeholders' preferences and motivations already at the beginning of design process, to inform the subsequent steps. AR highly facilitates these early stages of design thanks to its striking interactivity and modularity. The system also allowed capturing snapshots of different alternatives, thus supplying good evolution abilities. The prototype presented an average correspondence to the final product, but it included many details, thus providing a high resolution. All these characteristics solved the need of exploring and comparing design alternative with an audience constituted of company stakeholders with diverse backgrounds.

4.2 Interactive Mirror Kit

Designers of this project aimed at eliciting a positive daily mood for users by acquiring the right self-perception through facial exercise. They designed a small mirror kit to promote a healthy and balanced relationship with the act of looking at themselves in the mirror. The product encouraged users to spend the right time (not too long, not too short) in front of the mirror and trigger a positive feeling while looking at the mirrored self. To communicate their idea and investigate the user interaction with the system, they set up a prototyping activity soon after they came up with the idea. The focus of the prototyping activity was therefore on the role that this product would take in users' lives, and how it would impact users' everyday routines. The main motivation of the activity was to challenge users' interaction with the product, to explore its advantages and shortcomings, and to understand users' appreciation of the product. To do so, they selected a mixed prototyping approach as a medium, coupling a physical mock-up with augmented reality. As the focus was on the role, they did not invest time and resources in representing the aesthetics of the final product. Rather, they wanted to achieve a satisfying

result in simulating the product interactive behaviour. The prototype developed for this project is then characterised by a low fidelity, although it had been fine-tuned in many details, thus providing a medium/high resolution. Targeting end-users as audience of the prototyping activity, the system was highly interactive. Through the prototyping activity, designers could test the user-product interaction nurturing the design with information on how to improve the final product.

Model components
- Product: interactive mirror kit
- focus: role
- medium: mixed prototyping
- prototype: mock-up + AR

Characteristics of prototypes
- moment in the process: medium
- technique: augmented reality
- fidelity: low
- resolution: medium/high
- interactivity: high
- modularity: none
- evolution: none
- purpose: evaluating user-product interaction and communicating the idea
- audience: end-users

Figure 4. Prototyping case 2: prototyping the interaction with a product to trigger positive feelings in front of the mirror (©L.Cammarano, F.Esposito, M.Violetta)

4.3 Solar tracker

lThe third case focused on the development of a simple servo-actuated sunlight tracker (Figure 5). Designers aimed at creating a system that would orientate a small surface, such as a solar panel, following the direction of sunlight. The ultimate goal was to increase energy efficiency of photovoltaic cells through a light and easy system. The solution designed implied an Arduino board and two servomotors, which, coupled with other components, helped to develop a prototype. The focus of the prototyping activity was therefore on the implementation, to assess the functional behaviour of the product. In terms of audience, the prototype targeted fellow designers and other stakeholders of the development process. Coming in later stages of the concept design process, it was not supporting the parallel testing of any alternative. Yet, the system has been prototyped with a high fidelity to the final artefact, and it was developed in all the technical details. The main purpose of this prototyping activity was to learn from the product behaviour and challenge the technical system as it was imagined by designers.

Model components
- Product: servo-actuated sunlight tracker
- focus: implementation
- medium: realistic physical prototyping
- prototype: functional system

Characteristics of prototypes
- moment in the process: late
- technique: physical prototyping with Arduino
- fidelity: medium
- resolution: high
- interactivity: ?
- modularity: none
- evolution: none
- purpose: testing the functionality
- audience: stakeholders

Figure 5. Prototyping case 3: prototyping the functional behaviour of a servo-actuated sunlight tracker (©G.Menchini, D.Raffelli, G.Rancan)

4.4 Shower Time Manager

Model components
- Product: shower reminder
- focus: integrated
- medium: realistic physical prototyping
- prototype: functional system

Characteristics of prototypes
- moment in the process: late
- technique: physical prototyping with Arduino
- fidelity: very high
- resolution: very high
- interactivity: very high
- modularity: none
- evolution: none
- purpose: evaluating the final design
- audience: end-users

Figure 6. Prototyping case 4: an integrated prototype to evaluate the final design of a product (©M. De Carolis, U.S. Malik, S.Zuo)

In this case, designers developed an advanced prototype to evaluate their final design (Figure 6). They designed a product to encourage a sustainable use of water while showering. Users can connect their smart phone to the device via Bluetooth and select a maximum time for the shower. While showering, the product plays user's music and detects the water flow. As the time passes, the product starts to emit light feedbacks to alert users of their water and time consumption under the shower. After the time is finished, the music will eventually turn off. The prototyping stage described here was carried out in the late stages of conceptual design process, with the intent of evaluating the product final design with end-users. Thus, the prototype is characterised by a very high fidelity to the product-to-be. Moreover, the resolution was very high as the prototype was curated in every detail, from its look-and-feel to the implementation aspects. As the purpose at the end of the ideation process was to test the product in its overall appreciation, the focus of the prototyping activity was an integration of the three components described by Houde and Hill [1997] and earlier in this paper. The approach and materials were chosen to make the prototype a fully interactive, as realistic as possible physical prototype, activated by an Arduino board.

5. Discussion

The selection of design cases is exemplary to show the variety of practices, forms and scopes that prototyping may take. Each of the first three examples (the shoes packaging, the mirror kit and the solar tracker) describe a specific focus of the prototyping activity. This influenced designers' subsequent decisions, for instance in choosing the technique, or the level of fidelity they wanted to achieve in the prototype. When the purpose of the prototyping was to explore users' interactions with the product, understand its role in users' lives, and communicate their idea, designers chose to invest less effort in producing the artefact itself, as it was the case of the Interactive Mirror Kit (4.2, Figure 4). At the same time, a specific focus on one of the product's components, such as the implementation, does not stand immediately for a low fidelity to the product-to-be. In the case of Solar Tracker (4.3, Figure 5), although the focus was deliberately put on the product functionality, the prototype was still representing it in a transparent way. Lastly, it is evident from case 4.1 (AR packaging, Figure 3) that the prototyping activity can be the chance to explore design opportunities and improve the definition of the final design, sometimes activating a collaborative modality with fellow stakeholders or end-users. Through this prototype, designers could engage with the look and feel of the product-to-be and understand soon in the design process their best options. Nevertheless, the last case, Shower Time Manager (4.4, Figure 6), addressed an evaluation of the overall final design of the product. To cope with this purpose, designers needed to develop an integrated prototype to simulate as much as possible the holistic user experience.

Obviously, this type of prototypes required higher costs of time and resources to manufacture the final outcome compared to cases 4.1-4.3. Moveover, this approach to prototyping acquires value only in the later stages of the design process, when the idea has grown mature and solid. It would be totally out of scope to create a definite, realistic prototype at the early stages, with high costs, when changes in the design are still very probable and less expensive than at later stages [Folkestad et al. 2001]. At the same time, early prototyping is extremely important also for commercial purposes as it allows companies to better match end-users desires and needs [Coughlan et al. 2007]. Many companies have made it part of their flagship methodology (i.e. Apple, IDEO, Microsoft, etc.).

The description of the cases presented in this paper shows the soundness of the model introduced in this paper (Figure 1). Compared to other definitions and other models in literature, this model is more inclusive of the diversity of practices that prototyping yields for. It explicits the role of the focus of the prototyping activity in steering all the subsequent decisions. It builds on a classic definition of prototyping to detail the possible focuses. It discusses Lim et al.'s [2008] definition of prototypes as filters to a design idea, proposing instead the medium, i.e. the set of technique, approach and material used to shape the prototype, as the real filter to the prototyping activity. Lastly, the model defines prototyping as an activity that helps designers instantiating the design process, to frame the design problem and generate refined solutions to it. The three cases bring further evidence of the benefits of prototyping [Gerber and Carroll 2011]. It fosters a sense of progress and productivity, by producing instantiations of the evolution of a project. It strengthens beliefs about creativity, as it increases confidence in the design decisions. When engaging in early prototyping, designers are able to construct knowledge and manage uncertainty with less frustration, as they break larger tasks into smaller ones. They are able to produce visible results, and this enhances their sense of progress. Prototyping is also useful to bring up design issues that other forms of representation cannot, during the cognitive process involved to carry it out [Yang 2005].

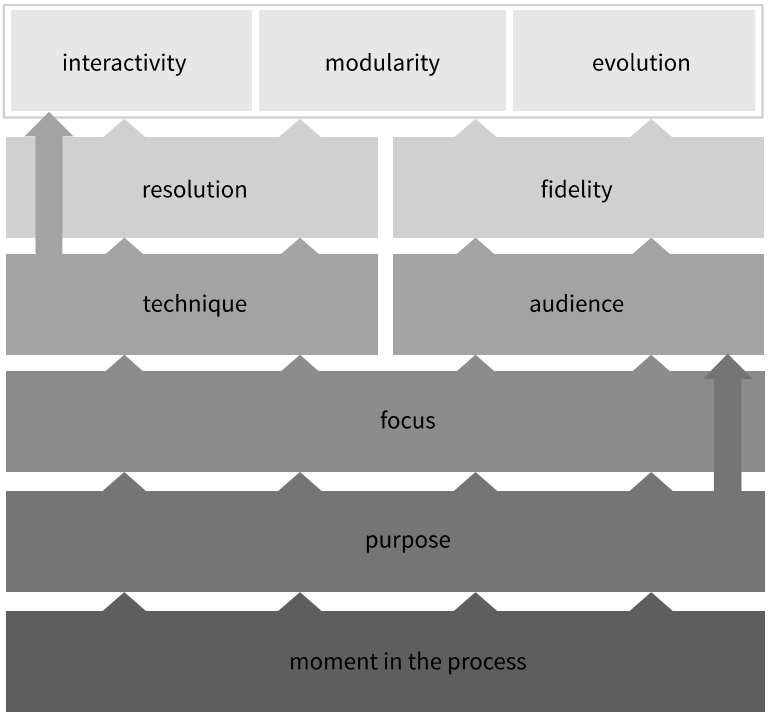

Figure 7. A framework to address prototyping decisions

The model described in the paper can contribute to design professionals by fostering a greater awareness of prototyping practice. By providing a careful description of the characteristics and dimensions of prototypes, it can also support decision making before and during the prepatory steps of prototyping. As

in the four cases presented, it is evident that a framework to tackle prototyping decisions can be sketched as in Figure 7. Fundamental is the moment in the process in which the prototyping activity is undertaken by designers. However, the first steering decision is undoubtedly the purpose of prototyping, which influences all the subsequent decisions, and the focus on the product-to be that the final prototype will represent. Yet, the purpose of the prototyping activity has a direct effect also on the type of audience to involve in the loop, whether they are stakeholders or end-users. Fidelity and resolution of prototypes are two consequent characteristics in respect to the technique chosen and audience addressed. Lastly, the level of interactivity, the prototype modularity and its ability to support iterative changes are a direct output of the technique, and they are the last decision to tackle in the prototyping process.

6. Conclusions

This paper discusses the current perspectives in literature dealing with the theoretical concepts of prototyping. By analysing the state of the art, it explicits the need of redefining this activity, to be more inclusive of the current multifaceted practices and scopes of prototyping. Drawing on these foundations, we proposed a new model and a definition of prototypes. These enforce the role of prototyping in constructing knowledge not only by means of its outcomes, but during the process itself. Specifically, the model, using the metaphor of a lens framing the product-to-be, explains how the medium chosen, i.e. the set of technique-approach-material used, works as filter for the product-to-be to be represented in the prototype. Furthermore, we describe a list of characteristics and dimensions of prototype that yielded for the development of a framework for decision making in the prototyping activity. The ultimate goal is to support design professionals by increasing their confidence and awareness when dealing with prototyping. The new model and definition were used to describe four prototyping cases, selected from our group's vast experience in teaching prototyping at the School of Mechanical Engineering and School of Design at Politecnico di Milano. In the next future, this model will serve as ground to investigate more closely the notion of Experience Prototyping, not only as described by Buchenau and Fulton-Suri [2000], but to answer the questions "can we prototype an Experience? And if so, how?".

References

Bäumer, D., Bischofberger, W. R., Lichter, H., Züllighoven, H., "User Interface Prototyping - Concepts, Tools, and Experience", Proceedings of the 18th International Conference on Software Engineering, IEEE Computer Society, Berlin, 1996, pp. 532-541.

Beaudouin-Lafon, M., Mackay, W. E., "Prototyping tools and techniques", Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies, and Emerging Applications, 2nd edition, Sears, A. Jacko, J. A. (Eds.), CRC Press Boca Raton, FL, USA, 2007, pp. 1017-1039.

Blomkvist, J., Holmlid, S., "Existing Prototyping perspectives: Considerations for Service Design", Proceedings of the 4th Nordic Design Research Conference, Helsinki, 2011, pp. 31-40.

Buchenau, M., Fulton-Suri, J., "Experience Prototyping", Proceedings of the 3rd conference on Designing interactive systems: processes, practices, methods, and techniques, ACM, New York, 2000, pp. 424-433.

Buxton, B., "Sketching user experience: getting the design right and the right design", Morgan Kaufmann San Francisco, CA, 2007.

Coughlan, P., Fulton Suri, J., Canales, K., "Prototypes as (Design) Tools for Behavioral and Organizational Change", The Journal of Applied Behavioral Science, Vol.43, No.1, 2007, pp. 122-134.

Folkestad, J. E., Johnson, R., "Resolving the conflict between design and manufacturing: integrated rapid prototyping and rapid tooling (IRPRT)", Journal of Industrial Technology, Vol.17, No.4, 2001, pp. 1-7.

Gerber, E., Carroll, M., "The psychological experience of prototyping", Design Studies, Vol.33, No.1, 2012, pp. 64-84.

Hare, J., Gill, S., Loudon, G., Lewis, A., "The Effect of Physicality on Low Fidelity Interactive Prototyping for Design Practice", Human-computer interaction - Interact 2013, Kotzé, P., Marsden, G., Lindgaard, G., Wensson, J., Winckler, M. (Eds.), Springer Berlin, Germany, 2013, pp. 495–510.

Hess, T., "Investigation of Prototype Roles in Conceptual Design Using Case Study and Protocol Study Methods", PhD dissertation, Clemson University, 2012.

Houde, S., Hill, C., "What do prototypes prototype", Handbook of human-computer interaction, Vol.2, 1997, pp. 367-381.

Isa, S. S., Liem, A., Steinert, M., "The Value of Prototypes in the Early Design and Development Process", Proceedings of the 20th International Conference on Engineering Design, Design Society, Glasgow, 2015.

Jensen, M. B., Balters, S., Steinert, M., "Measuring prototypes – a standardized quantitative description of prototypes and their outcome for data collection and analysis", Proceedings of the 20th International Conference on Engineering Design, Design Society, Glasgow, 2015.

Kirby, D. A., "Lab Coats in Hollywood: Science, Scientists and Cinema", The MIT Press Cambridge, MA, 2011, pp. 170-193.

Koskinen, I., Zimmerman, J., Binder, T., Redstrom, J., Wensveen, S., "Design research through practice. From the lab, field, and showroom", Morgan Kaufmann Waltham, MA, 2011.

Lim, Y. K., Stolterman, E., Tenenberg, J., "The anatomy of prototypes: prototypes as filters, prototypes as manifestations of the design idea", ACM Transactions on Computer-Human Interaction, Vol.15, No.2, 2008, pp. 1-27.

McCurdy, M., Connors, C., Pyrzak, G., Kanefsky, B., Vera, A., "Breaking the fidelity barrier: an examination of our current characterization of prototypes and an example of a mixed-fidelity success", Proceedings of the SIGCHI conference on Human Factors in computing systems, ACM, New York, 2006, pp. 1233-1242.

Sanders, E. B. N., "From user-centred to participatory design approaches", Design and the social sciences: Making connections, Fracara, J. (Ed.), Taylor Francis New York, NY, 2002.

Sanders, E. B. N., Stappers, P. J., "Probes, toolkits and prototypes: three approaches to making in codesigning", CoDesign, Vol.10, No.1, 2014, pp. 5-14.

Schneider, K., "Prototypes as Assets, not Toys: Why and How to Extract Knowledge from Prototypes", Proceedings of the 18th international conference on Software engineering, IEEE Computer Society, Berlin, 1996, pp. 522-531.

Stappers, P. J., van Rijn, H., Kistemaker, S. C., Hennink, A. E., Sleeswijk Visser, F., "Designing for other people's strength and motivations: Three cases using context, visions, and experiential prototypes", Advanced Engineering Informatics, Vol.23, No.2, 2008, pp. 174-183.

Sterling, B., "Patently Untrue: Fleshy Defribrillators and Synchronized Baseball Are Changing the Future", Wired Magazine, UK, Available at http://wired.co.uk/magazine/archive/2013/10/play/patently-untrue, 2013, [Accessed 11.08.2015].

Ullman, D. G., "The mechanical design process", McGraw-Hill New York, NY, 2003.

Ulrich, K. T., Eppinger, S. D., "Product Design and Development", McGraw-Hill International, Baskerville, 1995.

Wiberg, M., "Methodology for materiality: interaction design research through a material lens", Personal Ubiquitous Computing, Vol.18, No.3, 2014, pp. 625–636.

Yang, M. C., "A study of prototypes, design activity and design outcome", Design Studies, Vol.26, No.6, 2005, pp. 649-669.

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