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PROTOTYPES IN ENGINEERING DESIGN: DEFINITIONS AND STRATEGIES

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1. Introduction

Prototypes are essential in product development. They can help to create, explore, describe, test and analyse the item being designed. The role and the importance of prototyping has been rapidly changing and progressing as emerging business models - such as crowdfunding and new digital fabrication technologies - directly influence engineering design and product development practices.

Although they are an essential part of product development, the terms 'prototype' and 'prototyping' do not have commonly accepted definitions and refer to a range of artefacts and processes that have different meanings, purposes, and characteristics. This fragmentation stems from different industries and research fields, and we believe that there is a need for identifying and understanding the variations in definitions and strategic roles of prototypes in product development. This paper answers the following questions:

- How are 'prototypes' defined in engineering design literature?
- What are the strategic elements of prototyping?

The basis of this study is a systematic literature review of prototypes in engineering design and product development. The Scopus database was used to perform the review. We found that "prototype" is a very commonly used term in the literature (455,357 publications); whereas its combinations with search terms of 'engineering design' and 'product development' yield only 3,013 publications. The search results were manually screened for their relevance to the aims of this paper, and 81 publications that discuss prototypes and prototyping were identified. The references in these publications were also screened and added to the collection, resulting in 271 publications. This corpus included books, proceedings and journal publications, and constituted the basis of the work presented in this paper.

In the following section, we discuss types and purposes of prototypes and present 19 different definitions of the term that were found in the literature. There seems to be no overarching definition of a prototype, but we have identified five categories of prototype, based on their use and the research context in which they were defined. The third section focuses on the strategic role of prototypes in product development processes and discusses their relevance in terms of scale, integration, logistics, embodiment and evaluation. This leads to a discussion (Section 4), that deals with the increasing complexity and fragmentation of the terminology related to prototypes. We believe that recent advances in prototyping technologies and the use of prototypes in a wider range of activities within product development processes are not well-described in engineering design research. We therefore conclude that a more holistic overview of prototypes and new support tools for selecting prototyping technologies can help practitioners to apply the appropriate prototyping strategies at different stages of their product development.

2. Prototypes and prototyping in engineering design

Prototype and prototyping are two terms often used in the same context. Despite the lack of a general definition it is often accepted that the term *Prototype* designates a representative form of an idea whereas p*rototyping* is referred to as the activity of making and utilizing prototypes in design. [Lim et al. 2008]. When reviewing product development literature, it is clear that the term "prototype" is being used in a broad range of different ways. According to [Ravn et al. 2015] there are two main uses of the term prototype. Both of these serve the overall purpose of creating insights on the future product or object. The difference between the two usages is in terms of the 'width' of the reference and more specifically in what phases of the product development process prototypes are utilized.

The first usage includes a prototyping terminology that covers the whole product development process. Here every model representing a product or idea can be referred to as a prototype. Examples of this approach are found in e.g. [Houde and Hill 1997], [Ulrich and Eppinger 2007] and [Ullman 2010].

The second usage is more specific as it specifically applies the term prototype to a mature model of the product 'late' in the product development process. This model - or prototype – has evaluation as its primary objective [Buur and Andreasen 1989]. Other representations of product properties within this understanding are referred to as design models, design mock-ups or functional models and not prototypes. In this review we focus on these two uses of the term prototype.

2.1 Types and purposes of prototypes

Prototypes in different industries and research traditions serve different purposes: Industrial designers produce prototypes of conceptual ideas to explore form and geometry, engineers prototype designs to validate a functional principle or to benchmark performance and software developers write prototype programs to test user experience or requirement specifications.

A concrete representation and distinction of different types of prototypes is proposed by [Ulrich and Eppinger 2007]. They suggest that prototypes can be classified along two dimensions that relates to the nature of the prototype. The first is to what extend the prototype is physical as opposed to analytical. The second dimension is the degree to which a prototype is comprehensive as opposed to focused. This approach to illustrating different types of prototypes seems a strong tool for e.g. teaching or management related activities. One limitation is its lack of articulation about the actual purpose of the prototype. These authors did present four possible purposes of prototypes in product development:

- "Learning": is used to answer the type of questions "Will it work?" or "How well does it meet customers' needs?"
- "Communication": Prototyping enriches communication with various stakeholders such as management, vendors, partners, extended team members, customers and investors.
- "Integration": Prototypes can be used to ensure that components and subsystems of the product work together as expected.
- "Milestones": Particularly in the later stages of product development, prototypes are used to demonstrate that the product has achieved a desired level of functionality.

Authors such as [Polydoras et al. 2011], [Beaudouin-Lafon and Mackay 2003] and [Ullman 2010] present a relatively similar and compact classification of prototypes. The basis of these classifications are the prototype purposes, and [Ullman 2010], for example, also links the purpose to a specific state of the design process by defining prototype types such as a 'proof of concept prototype.' A dimension which is not addressed in these classifications is the fundamental purpose of a prototype. A prototype can be either a creative 'idea-generating tool' or a 'concluding tool'. This differentiation leads [Lindow and Sternitzke 2016] to two overall categories of prototype: 'The design prototype' and 'The technological prototype'. Similarly, [Lim et al. 2008] underline the differences between 'Prototypes as manifestations' and 'Prototypes as filters'. Based on the distinction between the terms and classifications, we argue that prototypes can serve respectively divergent (ideation, synthesis) and convergent (evaluation, selection) purposes in a product development process.

Another aspect is how well a prototype is capable of articulating something about its specific purpose. Every prototype is intended to have some characteristics in common with the future product or object being designed. These 'common characteristics' are the properties which can communicate something about the future product [Andreasen et al. 2015]. [Houde and Hill 1997] use the same argument and state that "Choosing the right kind of more focused prototype to build is an art in itself, and communicating its limited purposes to its various audiences is a critical aspect of its use." One reason for this difficulty is that there is not necessarily a coherence between the label of the optimal prototype and the maturity level of the design – which is in conflict with the specific purpose classification by [Ullman 2010] of successive design stages. The challenge of creating the optimal prototype can only increase in complexity with 'Concurrent Engineering' for low cost, early market entry and an ever-increasing number of available tools for prototyping. [Houde and Hill 1997] propose a triangular model to describe what design questions to answer with the prototype, claiming that such an approach makes it easier to decide what kind of prototype to build. The triangular model describes the following four dimensions: 1: "Role" refers to the way in which it is useful to the user. 2: "Look and feel": denotes questions about the sensory experience. 3: "Implementation": refers to questions about the "nuts and bolts" of how it actually works. 4: "Integration": Prototypes built to represent the complete user experience of an artefact. Such prototypes bring together the artefact's intended design in terms of role, look and feel, and implementation. This is a valuable approach to the creation of prototypes but the concept does not follow 'the train of thought' to its logical conclusion, as it offers no elaborated and concrete support as a strategy or method for the actual prototyping approach.

2.2 Definitions of a prototype in the literature

From our literature review we present an overview of 19 definitions of the term 'prototype'. The definitions have been collected from the publications where the term is expressed in relation to engineering design and product development. The results are shown in Table 1.

Table 1. 'Prototype' definitions in engineering research

Author(s) and Publication	Definitions of prototype in Engineering
[Goldfarb and Kondratova 2004] - Proceedings of 7th CATE	"A prototype can be defined as a concrete representation of part or all of an interactive system."
[Preece et al. 2015] - Book, John Wiley and Sons	"A prototype is one manifestation of a design that allows stakeholders to interact with it and to explore its suitability: It is limited in that a prototype will usually emphasize one set of product characteristics and de-emphasize others."
[Jangir et al. 2012] - International Journal of Software Engineering and Applications	"A rudimentary sample, model, exemplar or archetype built to test so that the design can be changed if necessary before the product is manufactured commercially or can be said to be a concept or process or to act as a thing to be replicated or learned from."
[de Beer et al. 2004] - Rapid prototyping journal + [Polydoras et al. 2011] - ISRN Mechanical Engineering	"A prototype can be defined as an artefact incorporating characteristics of the new product under development that enables designers to test various aspects of their ideas before committing themselves to the expense and risks of producing commercial quantities."
[Hannah et al. 2008] - ASME 2008 IDETC	"A prototype is a physical instantiation of a product meant to be used to help resolve one or more issues during product development."
[Ulrich and Eppinger 2007] - Book, McGraw-Hill Higher Education	"An approximation of the product along one or more dimensions of interest."
[Wall 1991] - Research in Engineering Design	"Prototypes are considered to be test beds that enable designers to test their design hypotheses."
[Otto and Wood 2003] - Book, Pearson, Prentice Hall	"An artefact or model of design which acts as a catalyst for further development and evolution."
[Jensen et al. 2015] - Proceedings of 20th ICED	"We understand 'prototypes as a tool to learn."
[Christie et al. 2012] - American Society for Engineering Education	"An initial instantiation of a concept as part of the product development process."

[Lindow and Sternitzke 2016] - Book, Springer	”A material or virtual object, or an experimental arrangement, simple or more complex functionality in which an idea to be realised is manifested in different stages of development—in part only in its selected properties and components.”
[Drezner 1992] - National Defence Research Institute	”A prototype is a distinct product (hardware or software) that allows hands-on testing in a realistic environment. In scope and scale, it represents a concept, subsystem, or production article with potential utility. It is built to improve the quality of decisions, not merely to demonstrate satisfaction of contract specifications. It is fabricated in the expectation of change, and is oriented towards providing information affecting risk management decisions.
[Wall 1991] - Research in Engineering Design	“Technically, a prototype is the first thing of its kind … In our definition of a prototype we include both electronic and physical representations of the part or product.”
[Yang 2005] - Design Studies	“A prototype is an early embodiment of a design concept. Prototypes can range from simple 2-D sketches that represent design thinking … to foam core mock-ups to sophisticated 3-D rapid prototyping designs that are nearly indistinguishable from a manufactured item. By definition, prototypes are not production stage design.”
[van Harmelen 1989] - proceedings of 5th BCSHCI	”A prototype can be defined as a trial version of a software or hardware system.”
[Kirjavainen et al. 2005] - CHI2006 Conference	“A preliminary version or model of all or a part of a system before full commitment is made to develop it.”
[Krogstie 2012] - Book, Springer	"An executable model of (or parts of) an information system, which emphasises specific aspects of that system."
[Beaudouin-Lafon and Mackay 2003] - Human Computer Interaction	“We define a prototype as a concrete representation of part or all of an interactive system. A prototype is a tangible artefact, not an abstract description that requires interpretation.”
[Houde and Hill 1997] -Book, Elsevier	“We define a prototype as any representation of a design idea—regardless of medium.”

Based on the definitions, we identified five prepositions that could categorize these definitions. In order to clarify their relation to specific stages of product development and illustrate overlapping elements in the definitions we have arranged them in an illustration, shown in Figure 1.

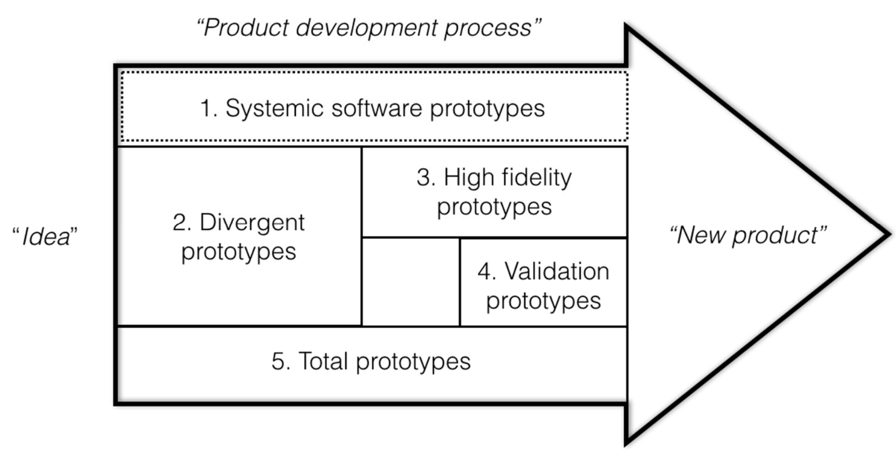

Figure 1. Graphical illustration of five prepositions to categorise prototype definitions

- Group 1: “Systemic Software Prototypes”: These definitions originate from software engineering related publications. They represent systemic thinking and emphasize that prototyping activities with both partial and whole systems can take place. Such openness in scope and design stage relation is illustrated by the dotted enclosure in Figure 1. We see [Beaudouin-Lafon and Mackay 2003], [Goldfarb and Kondratova 2004] and [Krogstie 2012] as representatives of this group.
- Group 2: “Divergent Prototypes”: Only [Jensen et al. 2015] and [Otto and Wood 2003], present definitions that includes a clearly divergent interpretation of prototypes. These two conclude this group and is opposed to the majority of definitions, which are oriented towards prototypes as convergent tools with a concluding nature. As the exploratory elements of product development are often concerned with the early design stages we link this group to the initial stages of the development process.
- Group 3: “High fidelity prototypes”: These definitions generally imply that a prototype is concerned with some aspect of testing. [Beaudouin-Lafon and Mackay 2003] and [Drezner 1992] have presented definitions that also imply a prototype to include a certain level of complexity and maturity. We categorise these to generally relate to the later stages of product development.
- Group 4: “Validation prototypes”: This group define a prototype as a mature model of a product before commitment to production is made. This is in line with narrow understanding of prototypes presented by [Buur 1989], which was introduced earlier. We recognise this understanding in [Kirjavainen et al. 2005] and [de Beer et al. 2004].
- Group 5: “Total prototypes”: This group concerns an understanding where every model representing a product or idea can be referred to as a prototype. [Yang 2005] represents this "wide usage" of prototyping and specifically states that prototypes can be used at all stages of the design process.

3. Prototyping strategies

Prototyping strategies refer to the use of prototypes within product development, and also the concrete management of the design knowledge so generated. Our review reveals that little research has been concerned with strategies- Examples are [Camburn et al. 2013] and [Christie et al. 2012], where the authors proposed some initial steps towards a structured approach to organising prototyping efforts. On the other hand, a number of authors expressed the need for a better understanding of the role of prototypes and prototyping strategies in product development [Hardgrave et al. 1999], [Thomke 2003]. [Christie et al. 2012] suggested that a prototyping strategy can be defined as “The set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s).” This would answer questions such as: “How many concepts should be prototyped?”, ”How many iterations of a concept should be built?”, ”Should the prototype be virtual or physical?”, ”Should subsystems be isolated?”, ”Should the prototype be scaled?” and ”Should the design requirements be temporarily relaxed?” [Dunlap 2014].

We based our review of prototyping strategies on the model presented by [Camburn et al. 2013], and categorized the findings from the literature on strategic elements of prototyping in five sections: Scale, Integration, Logistics, Embodiment and Evaluation.

3.1 Scale

‘High fidelity prototypes’ vs. ‘Low fidelity prototypes’: What prototype fidelity suits your need? (Liu and Khooshabeh 2003) concluded that paper prototyping is insufficient for unique ‘Ubiquitous computing’ requirements. On the other hand [Youmans 2011] showed that ‘low fidelity prototyping’ can be a valuable tool in reducing design fixation.

‘Full Size model’ vs. ‘Scaled model’: For larger products scale models can be valuable, if it is not possible to produce a full size prototype quickly and easily. Examples could include models of buildings or ships [Christie et al. 2012].

3.2 Integration

'Sub-System' vs. 'Entire System': [Avrahami and Hudson 2002] argued that for interactive physical products it is important to holistically explore form (geometry) and interactivity simultaneously. On the other hand, sub-system prototypes might make more sense in situations where the interactivity of the product is less all-important. [Ulrich and Eppinger 2007] claimed that a combination of comprehensive (Entire system) and analytical prototyping is not feasible. Other researchers have presented examples of how a comprehensive and analytical design is useful in the automotive and maritime industries [Kim et al. 2002], [Wohlke 2005]. [Clark and Fujimoto 1991] exemplified cultural differences in the automotive industry and pointed out that European high-end brands utilize prototypes as "master models" whereas the Japanese car industry uses "prototypes as early problem detectors".

3.3 Logistics

'Informational value of prototype' vs. 'Cost of prototype': What, if and how to prototype is a fundamental question to ask. [Thomke 1998] theoretically analysed what he referred to as 'optimal mode switching strategies' to choose between computer simulations (virtual prototypes) vs. physical prototypes. Computer simulations are typically cheap to execute compared to physical prototypes but the physical prototypes possess values that cannot yet be incorporated into the simulations.

Time constraints' vs. 'No time constraints': Researchers have found that time constraints lower the number of solutions proposed but also increase the speed of iterations. Parallel prototyping has been found to be attractive in time constrained environments as a higher quality of design results [Savage et al. 1998], [Dahan and Srinivasan 2000].

'Cost constraints' vs. 'No cost constraints': Experiments show that with cost constraints fewer design solutions are generated. No cost constraints lead to more creative and unusual designs but they increase allocated time [Savage et al. 1998], [Dahan and Srinivasan 2000].

'Resource (material) constraints' vs. 'No resource constraints': Resource constraints have negative impacts on the number of designs proposed but they seem to create a more tangible design task and environment for the designers [Savage et al. 1998], [Dahan and Srinivasan 2000].

'Parallel concepts' vs. 'Single concept': The attractiveness of parallel prototyping is greater when time-to-market is important, when prototyping costs are lower, and when new prototyping technologies are available [Dahan and Mendelson 1998]. If prototypes are to be presented to users, parallel prototyping resolves some residual uncertainty after the concept phase compared to the 'single concept' approach. [Srinivasan et al. 1997]. A second line of research suggests that parallel prototyping requires suitable processes, resources, and organizational structure to be successful [Smith 1991]. Parallel testing proceeds faster than serial testing but does not take advantage of the potential for learning between tests in a single concept approach [Loch 2001].

'Iterative approach' vs. 'Single model per concept': It is generally accepted in product development that an iterative approach obtains better design outcomes [Ulrich and Eppinger 2007]. How to iterate is probably highly case-specific and there is no prototyping tool that supports all areas of investigation [Houde and Hill 1997].

3.4 Embodiment

'Virtual models' vs. 'Physical models': Various software tools have been widely used in product development. [Zorriassatine et al. 2003] surveyed the potential for virtual prototyping in mechanical product development, and concluded that virtual tools were being rapidly developed and that the potentials and pitfalls were case-specific. [Dahan and Srinivasan 2000] demonstrated a scenario where virtual prototypes had been used for market share predictions that were nearly identical to those based on physical prototypes. Other research however has shown that physical parts create value, e.g. idea generation, that is not obtained from virtual simulations [Viswanathan and Linsey 2010]. "Designers' mental models of a products' behaviour are often inaccurate or incomplete unless they have extensive experience or training in a particular area." [Viswanathan and Linsey 2010].

'Test (easily available) materials' vs. 'Final (manufacturing) material': In recent years additive manufacturing tools have become widely available. These tools offer new possibilities, although a

disadvantage of these technologies is the limited selection of materials that is available. Their product properties also differ from the results of conventional manufacturing methods [Wohlers Associates 2013]. According to [Drezner 1992] "There should be no commitment to production during the prototyping phase."
'Outsource work' vs. 'Internal resources': It can be a dilemma to most companies to decide what aspects of product development to outsource. An investigation of rapid prototyping by [Ruffo et al. 2007] proposed that under most circumstances it is the best strategic decision to produce physical parts in-house, using rapid manufacturing techniques [Ruffo et al. 2007]. [Drezner 1992] stated that "Prototype teams should be composed of highly skilled individuals working [in-house] with little or no disturbance."

3.5 Evaluation

'Relaxed requirements. 'Requirements as in the final design': [Camburn 2015] concluded that prototyping with relaxed requirements can save cost and time. [Drezner 1992] however stated that prototypes should be "built with the goal of meeting minimum design requirements … If it is apparent that objective requirements cannot currently be met it is not wise to proceed with prototyping efforts." [Drezner 1992].
'Generative nature' vs. 'Analytical nature': Prototypes are used both as generative and analytical tools. From the definitions presented earlier the analytical aspect of prototyping was dominant. This however does not negate the value of generative prototyping, which is especially embraced for idea generation and 'front end' activities. The real challenge in prototyping is probably related to matching optimal tool selection and the objectives of generative or analytical prototyping efforts. [Viswanathan and Linsey 2010] stated that "prototypes "assist the designer by supplementing their mental models of how products behave, resulting in higher quality designs."

4. Discussion

4.1 Prototype usage, types, purposes and definitions

In view of our findings on how diverse and broad the term prototype has become, it is fair to state that most of the literature reviewed in this paper – with a few exceptions in the section on prototyping strategies - was focused on providing generic information on prototyping. To describe the purpose of prototypes in four overall paragraphs does not adequately describe the complex purposes of prototyping activities, and can provide only mediocre support in an engineering design perspective.

4.2 The future of prototyping

The process of decision making in prototyping is likely to become ever more complex in the future, the process of prototyping is changing along more than one dimension. New business models, such as Crowd Funding, are changing the traditional understanding of products and thus the product development processes. Versions of physical products that traditionally would be considered preliminary are being sold as products in a context where 'prototypes' become the product. New digital fabrication technologies are becoming available in 'Open Workshops', FabLabs and Makerspaces all over the world and through online platforms. If the competitive and innovative companies of the future hope to use effective prototyping, they will need support in their decision making.

4.3 Prototyping strategies

[Schrage 2010] stated that "effective prototyping may be the most valuable 'core competence' that an innovative organization can hope to have" [Schrage 2010]. Our interpretation of this statement is that innovative organisations are good at creating and executing prototyping strategies. The above section on prototyping strategies makes it clear that such decision-making is multidimensional and complex. There is a current lack of explicit knowledge on how to establish prototyping strategies and also how to effectively carry them out. What is required is a holistic overview of strategic decision-making and support tools for understanding, selecting and applying the specific prototyping technologies. They are needed to support product developers in answering questions such as: 1: “What can we learn [from prototyping]?” 2: “What possibilities do we [in our specific situation] have for obtaining knowledge by using prototyping tools?” 3: “When the tools are selected: How do we best make use of them?” Note that these questions have hierarchical levels of abstraction, and that the strategy section in this paper takes initial steps towards answering the second question. In order to provide concrete support on prototyping and to include the current changes within the field does require further research. It is our aim and hope that this overview of prototyping literature, which is focused on how the term is defined and what is known about strategic elements of prototyping, can help researchers and practitioners in making more enlightened decisions on prototyping activities. Further we hope to increase awareness and support further research within the field.

5. Conclusion

Prototypes are an important part of the product development process. A review of different understandings, types, purposes and definitions of the term prototypes makes it possible to state that there are two current usages and to define five categories, based on the purposes of prototypes that were identified. There is a lack of research on prototyping strategies, but it was possible to identify how the different aspects relate to the decision-making processes in prototyping. The role and importance of prototyping has been rapidly changing in the recent years, and there is a clear need to develop support tools focusing on prototyping strategies that that can provide a holistic overview of strategic decision-making and the selection and application of specific prototyping technologies.

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