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MEASURING PROTOTYPES - A STANDARDIZED QUANTITATIVE DESCRIPTION OF PROTOTYPES AND THEIR OUTCOME FOR DATA COLLECTION AND ANALYSIS

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Abstract

This paper addresses the need to learn about the characteristics, functionalities, and intended purposes of prototypes by proposing a standardized framework to describe (1) the characteristics of prototypes and (2) their generated (intended) outcome in a quantified and generally applicable way. Text-analysis software enabled us to merge the diverse concepts from literature regarding definitions and descriptions on the characteristics of prototypes and their generated outcome into one single reference, and to further cluster the entire content into newly defined themes. We further defined 51 closed, quantifying questions, which consistently inquire the entire scope of content-definition of each theme and therefore (indirectly) quantifies prototypes and their generated output in a standardized way. Lastly, we provide a case scenario applying these 51 questions as input values in a prototype library to uniformly capture standard parameters of prototypes and their outcome at any stage within a product development process. The analysis of the library data will allow identifying first principles of prototypes and their intended purposes for the engineering design community.

Keywords: Design engineering, early design phases, prototypes, data analysis, materials

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1 THE NEED FOR DESCRIBING PHYSICAL PROTOTYPES AND THEIR OUTCOME

The sequential alternating pattern of divergent and convergent phases is a major characteristic of the engineering design process (Cross, 2000; Ulrich and Eppinger, 2012; Leifer and Steinert, 2012). During the divergent phases, the aim is to explore, develop, and define new design requirements that solve design challenges in novel and elegant ways. Rapid prototyping and creativity-based human-centered design are cornerstones of these activities (Leifer and Steinert, 2012). Equally important, is the time spent in convergent phases as the analytical and structured counterpart of the design process.

Prototypes are one of the major design tools in this pivoting process of engineering design. They are used to explore and further test specific ideas and product/system concepts. Framed by this context, we understand '*prototypes as a tool to learn'* Leifer et al. (2012). This definition allows us to expand the virtue of prototypes throughout the whole design process from early stage ideation to final product launch.

Prototyping is widely used, accepted and established in engineering design. In order to understand the role of prototypes in the design process, there has been growing interest in creating frameworks for describing the nature of prototypes (Lim et al., 2008; Houde and Hill, 1997; Beaudouin-Lafon and Mackay, 2003; Avrahami and Hudson, 2002). However, literature remains mainly within single case-based examples, which do not allow deducing universally applicable parameters in order to describe prototypes and their intended outcome. Lim et al. (2008) claim that most of conducted studies are based on anecdotal experiences rather than empirical experiments and that there is a strong need for a fundamental knowledge about what prototypes are in order to be able to further advance knowledge and research about prototyping.

One problem in the quest to conduct more empirical analysis on the correlation between the design of a prototype and its generated outcome, is the lack of a conform and valid data set that takes in defined standard parameters for describing prototypes and their corresponding generated (intended) outcome. This paper addresses the need to learn about the actual characteristics, functionalities, and intended purposes of prototypes by proposing a standardized framework to describe (1) the characteristics of prototypes as well as (2) their generated (intended) outcome in a quantified and generally applicable way.

As a first step, we conducted a literature review and identified six academic frameworks that describe collectively the *(1) characteristics of prototypes* in a most diverse and exhaustive way (based on what literature currently proposes). For each framework, we further marked those text sections containing definitions and descriptions of *the characteristics of prototypes* and inserted these sections into a text-analysis software. The text-based content analysis (re-)clustered the entire merged content into six theme areas, which we entitled with superscriptions, namely, material, interactivity, visual detail, purpose, surrounding, and technology. In other words, each theme topic contains of a list of sub sorted prototype characteristics. The latter determine, thus, the content-definition of each theme. Based on the bundle of characteristics associated to each content-definition, we specified quantifying questions for each theme – 20 in total. The answers to those quantifying questions describe the *characteristics of a prototype* in a standardized, repeatable and generally applicable way – covering (in total) the merged definition- and description-content of all six frameworks from literature.

Secondly, we aimed to repeat the text-analysis procedure for literature contents concerning descriptions and definitions of the *(2) generated (intended) output of prototypes.* Since the text-based descriptions were very limited and additionally rather vague in definition, the text-data was not suitable for a content analysis. That is the reason why we included, as intermediate step, the framework of Blomkvist (2014), which divides the purpose of prototypes into three segments: exploring, evaluating, and communicating. Based on these new keywords, it was further possible to collect and content-analyze supplementary literature. In total, we defined 31 standard questions in order to frame the outcome of physical prototypes.

As a result, we propose a total amount of 51 quantifying questions, which inquire *(1) the characteristics of prototypes* and *(2) the generated (intended) output of prototypes.* These questions contain the merged definitions found in literature and allow quantifying prototypes as well as their generated output in a standardized way.

We propose, lastly, a case scenario to apply these 51 quantifying questions in form of an international prototype library to uniformly capture standard parameters of prototypes and their outcome – used at

any stage within a product development process. The analysis of generated library data will further allow identifying first principles and to learn about actual characteristics, functionalities, and intended purposes of 'prototyping' as tool in engineering design processes.
As a final comment, we underline that this paper focuses on physical, non-digital prototypes. Prototypes that are digital, consisting of graphical interfaces such as apps and webpages, are therefore not included. Further, it is beyond our intention to evaluate and rank the identified distinct characteristics of prototypes as well as their generated output.

2 DESCRIBING PHYSICAL PROTOTYPES

This section will present six academic frameworks for describing and clustering prototypes. Our selection of these six frameworks is based on a bibliometric analysis, including the most cited articles for describing physical, non-digital prototypes. Here the following studies were chosen: (1) Lim et al. 2008, (2) Beaudouin-Lafon and Mackay 2003 and (3) Hare et al. 2013. In order to secure diversity, we further selected (4) Wiberg 2014, (5) Blomkvist and Holmlid 2011, and (6) Balters et al. 2015 since they propose complementary alternatives to characterize prototypes from a material-centered, service-centered and human-centered perspective respectively. These six frameworks will serve as starting point for identifying standard input-variables for a quantified online prototype library. In section 2.1 each framework will be briefly described.

2.1 From in-depth descriptions to human sensory measurements

Lim et al. (2008)'s article 'The Anatomy of Prototypes' serves as a description of the characteristics of prototypes in general. They sort prototypes in two overall functionality categories: manifestation and filters. Each category has three and five sub-dimensions respectively. The *manifestation* category covers the actual appearance of the prototype on the spot and is described through: material, resolution and scope. *Filter* should be interpreted as the various aspects of a design idea that a designer tries to represent in a prototype. They refer to it as the aspects of a design idea that the designer must consider in the exploration and refinement of the design. The sub-dimensions for filter are: appearance, data, functionality, interactivity and spatial structure.
When focusing on an interactive prototype, Beaudouin-Lafon and Mackay (2003) define the following dimensions as relevant: representation, precision, interactivity and evolution. These dimensions mainly concern the actual prototype rather than reflections on the prototype in action. In the terminology of Lim et al. (2008) the dimensions mainly concern the *manifestation* of the prototype.
In their study from 2013, Hare et al. explore the level of resolution of a prototype and the effect of the feedback of the participants in a user feedback session. The prototypes represented the same mp3-player, but were made out of different materials – ranging from a simple foam model to an advanced functioning Arduino prototype. The authors define their prototype based on their level of physicality. When doing this they distinguish between passive and active physicality and provide the reader with a graphical representation of their prototypes and how they perform in the level of physicality on a scale from *low* to *high*. Moreover, they compare the cost of prototype manufacturing, differentiating between cost of material and cost of man-hours.
Wiberg (2014) takes the approach of physicality from a *material lens*. He wishes *'to create a methodology, operating as a guideline system to material-centered interaction design research'*. His categorization is hence addressed for future researchers rather than reflections on how to construct a prototype. As main categories he suggests: materials, details, texture, and wholeness and proposes further to work back and forth between these categories. As sub-dimensions he suggests: properties, character, aesthetics, quality, appearance, authenticity, composition, and meaning.
Blomkvist et al. (2011) utilize existing perspectives on prototypes and the history of the usage of prototypes to define a framework revealing the existing toolbox of prototyping. By means of a literature review, they construct a framework of the following sub-dimensions: purpose, fidelity, audience, position in the process, technique, and representation. Apart from Lim et al. (2008)'s representation of the filtering dimension of a prototype, the framework of Blomkvist et al. (2011) is the only one that deliberately takes external factors such as *audience* and *position in the design process* into consideration.
Balters et al. (2015) describe human-object interactions based on the functionalities of the human physiological sensory systems. They distil 21 quantifiable and measurable sensorial input dimensions,

which may come into play when a person interacts with an object. They further provide their Quantified Object Sensation Input (QOSI) matrix, which allows to describe prototypes as object in a standardized and generally applicable manner, even if the objects have fundamentally different properties. In QOSI, the categories of the prototypes are represented by the major five human sensory systems: visual, auditory, olfactory, gustatory and somatosensory. The authors define sub-dimensions in the different categories serving as scientific quantifiable units that affect the human-object interaction. For example the vision category is divided into: level of light (lx), color (nm), motion measured in change over time in $\Delta x/\Delta t$ depth measured in millimetres (mm) and form measured by volume [m^3]. The framework of Balters et al. (2015) is the only one of the six frameworks that defines a prototype by quantified parameters rather than qualitative descriptions.

2.2 Text-analysis of the six frameworks

Based on the six chosen frameworks, 48 sub-dimensions were identified, which were used to describe physical interactive prototypes in literature. A description of the sub-dimensions can be seen in Appendix 1. By analyzing the 48-sub-dimensions, we found that the perspective of a prototype spans from a very physical and materialistic object to a more holistic artifact taking respective external factors as *audience* and *position in the design process* into account. Moreover, we noticed that some of the sub-dimensions such as *material* shared name, but not meaning and vice versa. The finding supports the aim of this paper of creating a quantified, standardized and generally applicable description method in the field of prototyping research.

As a first step, we conducted a concept text-analysis with Leximancer (text-analysis software) to cluster the concepts described in the six different frameworks (Figure 1). We fed in all six frameworks as text and defined further which of the themes were the most common in the six different studies. The text-analysis revealed following themes as principle: material, interactivity, visual detail, purpose, surroundings, and technology. In the following, each theme will be described. Based on the specific characteristics of each theme, we will formulate 'quantifying' questions for an online prototype library.

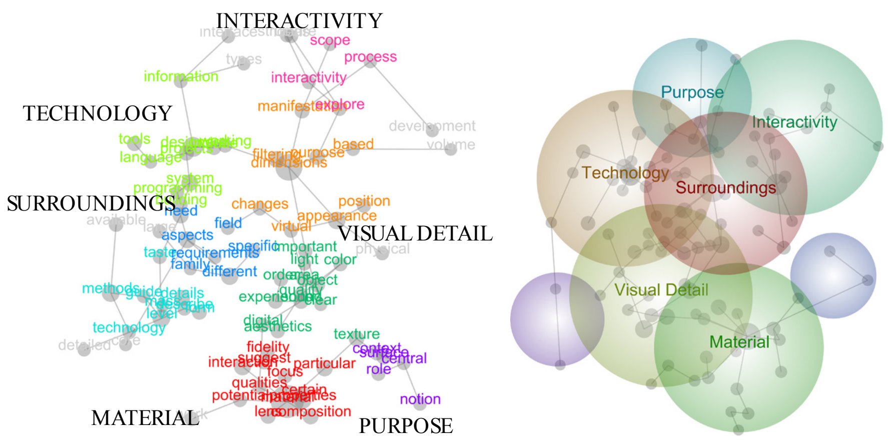

Figure 1. Concept/Theme text-analysis with the six different frameworks as input leads to six overall themes. Above one sees the network of concepts of the six different papers

2.2.1 *Material*

The theme *Material* covers the physical properties of the material used for building prototypes. According to the text-analysis, this theme includes following key-concepts: material, properties, details, and texture.

Material databases for the actual material of the prototype would give information on texture, roughness etc. mentioned in QOSI (Balters et al. 2015). Yet, sub-dimensions as form, color and authenticity, would not be covered by asking solely about the physical material. To include as many sub-dimensions in the theme of material, we suggest the following 'quantifying' questions:

1. What/which material(s) is/are you prototype made of?
2. Which different colors does the prototype have?

3. What are the physical dimensions of your prototype (mm)?
4. What is the volume of your prototype?
5. Is your prototype actively trying to look like another material than the one it is made of?

2.2.2 *Interactivity*

The theme *Interactivity* covers 'how a prototype interacts with the users'. Key-concepts for the theme in the text-analysis include: interface, scope, explore, and manifestation.

Interactivity works in two directions: (1) to what extent the user can interact with the prototype and (2) what the ability for the prototype is, to give feedback to this interaction. Wibergs´ (2014) terms *depth* and *breadth* of interactivity is useful in this connection since they distinguish actually functioning prototypes from eg. Wizard of Oz prototypes (Gray et al., 2010). This also provides us with suggestion for quantifying dimensions such as level of detail, fidelity, and resolution. These are dimensions that traditionally only have been described qualitatively through scales from low to high (Liane et al. 2009, Mørch 2006, Hare et al. 2013).

To include as many sub-dimensions in the theme of interactivity we suggest the following 'quantifying' questions:

6. How many moveable parts does your prototype have?
7. How many functions is the prototype insinuating to have (e.g., fake buttons, handles or similar)?
8. How many functions of your prototype do actually work?

2.2.3 *Visual Detail*

The theme *Visual Detail* covers considerations about level of resolution of a prototype in a visual way. The text-analysis identified level, quality, surface, and form as key-concepts for the theme.

How far is the prototype from looking like a "real" and final product? This theme deals with the level of visual refinement or degree of detail displayed through a prototype. Even though the theme is not similar to *Material* or *Interactivity,* we have decided that *Visual Detail* is covered when asking about the number of material, functions, color, and authenticity. As a result, there are no defined questions in this theme. Still we choose to keep the theme since it serves an example on how important dimensions of prototypes can be defined in other ways than addressing the dimension directly.

2.2.4 *Purpose*

The theme *Purpose* touches upon considerations the designer has to take into account before building the prototype. Key-concepts for the theme in the text-analysis are: context, role and notion.

The theme *purpose* goes closely together with the evaluation of the output of the prototype. It states the goal of the prototype and thereby sets the point of reference when evaluating. Hence, the purpose will be mentioned both in the quantified method for describing a prototype as well as in the quantified method of describing the output of the prototype in section 3. Leifer et al. (2012) define 'prototyping as a way to learn'. The purpose of a learning process would be to achieve knowledge one did not possess before the learning process. However, by only asking 'what do you want to learn through your prototype?', the answers will get too broad for finding common principles. Blomkvist et al. (2011) suggest three main purposes of prototypes: exploring, evaluating and communicating each with their respective purposes. In this context, one prototype may perform in all three domains. We believe this framework to be neither too detailed nor too shallow, when trying to quantify the overall purpose of a prototype. Therefor we suggest to prioritize between the three categories while quantifying the prototype:

9. Prioritize the purpose of the prototype from 1-3 between exploring, evaluating and communicating? (Where 1 is the highest priority and 3 the lowest)

2.2.5 *Surroundings*

The theme *Surroundings* deals with external parameters the designers cannot change, such as the professional background of users of the prototypes or the position in the design process.

Key-concepts for the theme in the text-analysis are: field, requirements, needs, and context.

When describing the audience, three important factors should be identified: (1) the number of participants, (2) the professional background of the participants and their familiarity with the project and (3) engineering design process in general. When quantifying the position in the design process, we suggest focusing on both the time to deadline as well as the number of iterations that has been conducted in the process until a specific point in time. To cover as many sub-dimensions in the theme of surroundings we suggest the following questions:

10. How many participants interacted with the prototype?
11. What is the professional background of the participants?
12. Are your participants familiar with the design engineering process?
13. Have any of the participants been involved earlier on in this project?
14. How many days are you from the final deadline?
15. How many days does the project last overall?
16. How many physical prototypes have been made in the process so far including the one you are describing?

2.2.6 ***Technology***

The theme *Technology* deals with technical detail used for creating the prototype and the corresponding costs. Key-concepts for the theme in the text analysis are: technology, programming, tools, and building. Since certain manufacturing processes, such as 3D printing, might need time and however no actual man-hours, we distinguish between production time and man-hours. To cover as many sub-dimensions in the theme of technology, we suggest the following questions:

17. How was the prototype made?
18. How much did the materials of the prototype cost ($)?
19. How long time did it take to make the prototype (production time in hours)?
20. How many man-hours did it take to make the prototype (in hours)?

3 DESCRIBING THE OUTPUT AND PURPOSE OF THE PROTOTYPE

We aimed to repeat the text-analysis procedure for literature contents concerning descriptions and definitions of the *(2) generated (intended) output of prototypes.* Since the text-based descriptions were very limited and additionally rather vague in definition, the text-data was not suitable for a content analysis. That is the reason why we included, as intermediate step, the framework of Blomkvist (2014), which divides the purpose of prototypes into three segments: exploring, evaluating, and communicating. Based on these new keywords, it was further possible to collect and analyze supplementary literature. However, in comparison to the underlying descriptive and detailed literature of the prior chapter, the identified literature of this chapter is rather broad and imprecise. It is important to note that the following sections (3.1.1. - 3.1.3) contain therefore in addition to the concepts from literature, our interpretations and suggestions.
Each of sections 3.1.1. - 3.1.3 will hence start with an elaboration on how present literature evaluates an exploring, evaluating and communicating process, involving prototypes. Hereafter, we suggest the *purposes* and *results* of such processes. *Purpose* answers the question: ‘What is one looking for?’ when using the prototypes, whereas *results* seeks to answer the question: ‘What do one get from using the prototype?’. This is with the aim to identify standard quantified parameters for evaluating the performance of a prototype used for each purpose. The strategy has been to cover as many as the mentioned themes as possible rather than judging the size of specific importance. In this way, the final parameters serve as a suggestion for the engineering design community with prototype evaluating parameters, which need to be tested in further studies.

3.1.1 ***Purpose and results of exploring activities***

In the exploring process the overall purpose is to get feedback, be inspired or be revealed to new information (Blomkvist and Holmlid, 2011). In order to examine *exploring* in depth, we went through 50 different types of exploring activities (Gray et al. 2010; Tassi 2009). Similarly to section 2, we conducted a concept analysis by using the Leximancer-software (Figure 2). This has been the basis for specifying purposes and results for exploring activities.

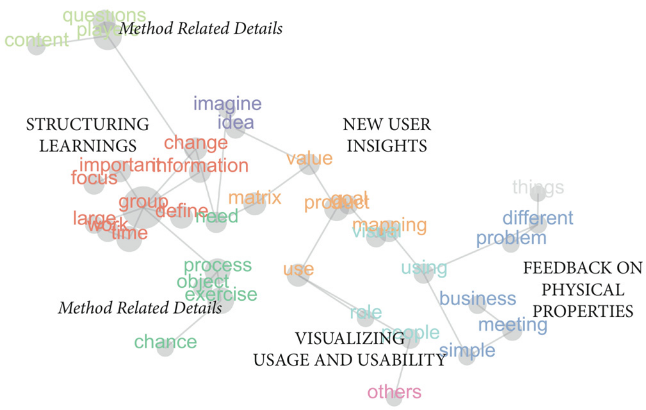

Figure 2. Network of concepts in the concept text analysis of 50 different exploring activities

By means of the text-analysis, we identified the following purposes and results related to the prototype:

Table 1. Purpose and corresponding results in Exploring

PURPOSE What is one looking for?	**Usability feedback**	**Use-case understanding**	**User-insights**	**Feedback on physical properties**
RESULTS What do one get from using the prototype?	• Identified problems with users understanding the product • Suggestions for improvements • Heuristics evaluation of a product • Ideas addressing abovementioned topics	• New identified use-cases/user touch points • New identified understanding of existing use-cases • New identified stakeholders relevant to the product • Ideas addressing abovementioned topics	• New identified users need • New identified pain point in the users life • New identified values and desires in the user´s life • Ideas addressing abovementioned topics	• New identified possible use of materials • New identified technologies to be used • New identified other ways (in the market) of solving the problem in question • Ideas addressing abovementioned topics

3.1.2 *Purpose and results of evaluating activities*

During evaluating activities, the main aim is to create a basis for decision-making (Leifer and Steinert, 2012). Eling et al. (2013) categorize decisions in the early fuzzy front-end as commitment to actions regarding answering the questions: *What to focus on? When to continue to a new stage in a process? or How to continue?* In this way, the evaluation process not only deals with the future direction of the project, but also whether the team are ready to move at all eg. if they lack knowledge about a certain topic or if they failed to explore the problem/solution space sufficiently (Cross, 2000).

Having Eling´s (2013) three questions in mind we see the goal of evaluating processes as creating a basis for decision-making to discard possible directions and find out when and how to follow this path on her way to design a new innovative solution. Tools such as the Pugh Chart (Pugh, 1996) or a Quality Function Deployment (Hauser & Clausing, 1988) serve as good example of how such a basis of decision-making is developed. Critical functional prototypes can also be helpful when testing a hypothesis regarding an actual technical function. In reverse, there are situations when one cannot utilize tests to decide which path to choose. Then, one relies on democratic choices, prioritizing sessions or simply on gut-felling (Eling et al., 2013; Gray et al., 2010).

On the basis of the abovementioned literature we suggest the output of an *evaluating* prototype to be divided in following purposes and results:

Table 2. Purpose and corresponding results in Evaluating

PURPOSE What is one looking for?	**Testing physical functions**	**Discarding possibilities**	**Defining the further process**
RESULTS What do one get from using the prototype?	• Falsification of the hypothesis put up for test	• Prioritized, voted or intuition based decision on the way to the most promising ideas	• Evaluation of the sufficiency of previous work eg. does the product meet the product specifications • Defined action points for the further development of the product • Defined areas to be explored in order for the process to continue eg. possibilities for production and assembling.

3.1.3 *Purpose and results of communicating activities*

When prototypes mainly function as tools for communication, the purpose is tilted towards presentation and persuasion (Blomkvist and Holmlid, 2011). In this way, the prototype becomes a boundary object between participants with different backgrounds and roles in the product development process (Brandt, 2007). Often many different professional fields are involved in engineering design projects, including mechanics, electronics, software, designers, user-researchers, management, and marketing. The differences complicate the collaboration due to specialized education and resulting difficulties of understanding each other's problems and approaches. The purpose of a boundary object is to let the participants create a common language that not necessarily align their priorities, but instead aligns the understanding of the many aspects of the products – that is *what is it?* and *what is it not?* (Holford et al., 2008).

When the prototype mainly serves as such a communication tool, the goals can be agreement in new directions, alignment of understanding the product and persuasion to get buy-in from important stakeholders in order to make the project progressing. A buy-in does not necessarily include financial support, but could be approval from management to continue the work, man-hours or opening up to a relevant network of contacts such as investors or specialists.

On the basis of the abovementioned literature we suggest the output of *communicating* prototypes to be divided in following purposes and results:

Table 3. Purpose and corresponding results in Communication

PURPOSE What is one looking for?	**Alignment in understanding the product**	**Persuading important stakeholders**
RESULTS What do one get from using the prototype?	• Clarification crucial misunderstandings • Insights of many professional dimensions of the product • Insights on the details and core function of the product	• Increased no. of persuaded relevant stakeholders about the value of the product in order to take the project to the next level in the direction wished for

3.1 Standard questions for describing the output of a prototype in terms of exploring, evaluating and communicating

The definition of the purposes and results of the three overall main purposes of prototyping (exploring, evaluating and communicating) served as a starting point for defining standard-inputs for describing the output of a prototype. We transformed the results of each purpose into questions. In addition, we were inspired by evaluation methods in the field of creativity research especially the work of Yoruk and Runco (2014). They define two parameters for evaluating divergent activities: the ideational *fluency* (the amount of ideas) and *ideational flexibility* (to what extend are the ideas in similar fields). The terminologies of *fluency* and *flexibility* were used concerning new ideas, but also other contexts, such as user needs and suggestions for product changes. Hence, each of the four purposes concerning *exploring,* ends with 2 questions touching first on fluency (*how many*) and flexibility (*how broad*).

Overall, the questions are formed as quantifying questions allowing the answers only to be in numbers. We did this in order to create data-sets and learn from greater patterns rather than from individual prototypes. Below, the resulting questions, 31 in total, are presented:

Table 4. The 31 quantifying question for describing the outcome of a prototype

Usability feedback	How many problems did you discover with users misunderstanding the product? How many ideas addressing the usability of your product did you get? How many different themes can you divide your usability-ideas into?
Use-case understanding	How many new use-cases/user touch points did you identify? How many new insights of existing use-cases did you identify? How many new stakeholders relevant to the product did you identify? How many ideas addressing use-cases of your product did you get? How many different themes can you divide your use-case-ideas into?
User-insights	How many user needs did you identify? How many pain point in the users life did you identify? How many values and desires in the user´s life did you identify? How many ideas addressing user-insights of your product did you get? How many different themes can you divide your user-insights-ideas into?
Feedback on physical properties	How many suggestions for new material changes/usage did you identify? How many suggestions for new technologies did you identify? How many example in solving the problem or similar problems in other ways (on the market) did you get? How many ideas addressing physical properties did you get? How many different themes can you divide your physical-properties-ideas into?
Testing functions	How many hypotheses did you aim to test? How many of you hypotheses were able to be tested?
Discarding possibilities	How many possibilities of directions did the project have BEFORE using the prototype? How many possibilities of directions did the project have AFTER using the prototype?
Defining the further process	How many criteria did the prototype satisfy when comparing to earlier stated requirements? How many tasks for future work did you identify? How many topics for further exploring did you identify?
Alignment in understanding the product	How many misunderstandings was identified and cleared out during the session? How many profession-related dimensions/problems of the product were revealed? How many core functions were explained during the session?
Persuading important stakeholders	How many of the participants left the session with a positive perception of the product? Did you manage to convince the relevant stakeholders on your most wanted further process? How many different sort of buy-ins did you receive (could be in terms: money, man-hours, convinced stakeholders)

4 PRESENTATION OF THE ONLINE PROTOTYPING LIBRARY

In section 2.2 and 3.2 the description of a prototype and its corresponding output was defined in 20 and 31 questions respectively. These standardized questions serve as a starting point for an international online prototype library. A presentation and elaboration on such library and its potentials will now follow. A digital prototype of the library can be seen at http://mbisballe.wix.com/prototype-library.

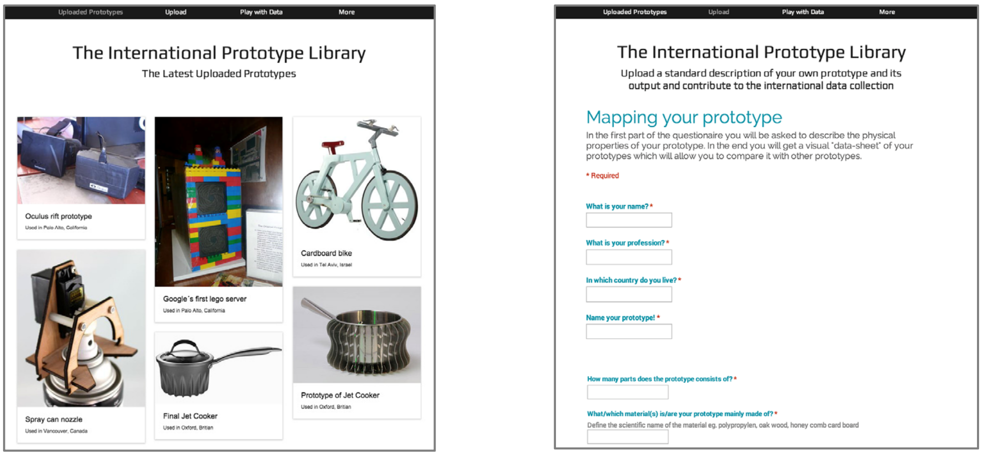

Figure 3. Screenshots of the online International Prototype Library available through: http://mbisballe.wix.com/prototype-library

The online prototype library is an online database where researchers upload a picture of a prototype they have used in an engineering design development process and answer the 51 questions to describe their prototype and its output. It will be open for engineering designers, designers, educators etc. The potentials of the library are divided in three. The first and obvious one is the possibility to hold

different aspects of prototypes together and to learn from the findings. These aspects could be material vs. number of user insights, price vs. ideation level or interactivity vs. number of misunderstandings clarified. In addition, it will allow researchers to include the time and iteration aspect in product-development. By creating a 'project' in the library assigning the used prototypes to the project, one could get a visual timeline of the prototypes used throughout the project. Secondly, as the library grows, a feature could be getting feedback on a prototype idea. A user could type in an idea for a prototype including information on certain external parameters such as *purpose, audience* or *position in the process* and then get feedback based on the output of previous prototypes.
Thirdly, the library could be a helpful trend-spotter in the field of prototyping and identify when certain technologies become more popular to use than others. Furthermore, the geographical trends and technology domestication could be identify with the help of the database.

4.1.1 *What´s in it for the researcher*

So why would researchers around the world be interested in answering the 51 questions about a prototype? The answers are documentation and reflection. Even though prototypes are often physical and documenting in themselves, it is hard to include them in written deliverables or presentations. It can also be very challenging to describe and argue for different conclusion of the output and learning from a prototype. When answering the 51 questions about their prototype the researchers/engineer will, first of all, be 'forced' to consider and 'count' how the prototype performed, but also she will get a graphical presentation of her prototype as a datasheet of any other technical product. This will be automatically generated inpdf-format, produced by a program-function in the online prototype library. Finally, researchers could 'pay' for the access to the data from the online prototyping library simply by contributing to the library.

5 OUTLOOK AND CONCLUSION

This paper addresses the need to gain knowledge about the characteristics, functionalities, and intended purposes of prototypes. Literature remains so far mainly within single case-based examples or broad descriptions, which do not allow deducing universally applicable parameters in order to describe prototypes and their intended outcome. We therefore propose a standardized framework to describe: *(1) the characteristics of prototypes and (2) as well as their generated (intended) outcome* in a quantified and generally applicable way.
As first step, we identified six academic frameworks that define and describe the (1) characteristics of prototypes. The text-based content analysis of these academic frameworks (re-)clustered the entire merged content into six theme areas, which we entitled with superscriptions, namely, material, interactivity, visual detail, purpose, surrounding, and technology. The six themes were further transformed into 20 closed, quantifying questions. Similarly, nine overall themes were defined concerning the second dimension – *(2) the generated (intended) outcome of prototypes*, including usability, use-cases, user-insights, physical feedback, hypothesis testing, discarding possibilities, further process, alignment, and persuasion. The nine themes were transformed into 31 closed, quantifying questions. A total sum of 51 questions, consistently inquire the entire scope of content-definition of each theme and therefore (indirectly) quantify prototypes and their generated output in a standardized way. We suggest using these 51 questions as a standard tool for describing physical prototypes and their corresponding output in a universal quantified and comparable way.
For illustration, we propose a case scenario applying the 51 quantifying questions in form of a questionnaire in an international prototype library to uniformly capture standard parameters of prototypes and their outcome – used at any stage within a product development process. The analysis of generated library data will further allow identifying first principles and to learn about actual characteristics, functionalities, and intended purposes of 'prototyping' as tool in engineering design processes.
As a next step, we will test and evaluate these 51 questions in practice in order to conclude whether all variations of prototypes and their corresponding outcome are covered. This evaluation process will include prototype experts – both from academia and industry. This will allow us to further improve and finalize the questionnaire of our online prototype library. The enabling of a standardized data-collection regarding characteristics of prototypes and generated (intended) output of prototypes, will

contribute to the development of deeper understanding of prototypes, their function and different roles in engineering design processes.

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APPENDIX 1 – SUB DIMENSIONS OF PROTOTYPES FOUND IN LITERATURE

Sub-Dimension	Description	Literature
21. material	Medium to form a prototype	Lim et al. 2008
22. resolution	Level of detail or sophistication of what is manifested	Lim et al. 2008
23. scope	Range of what is covered to be manifested	Lim et al. 2008
24. appearance	Size, color, margin, form, weight, texture, proportion, hardness, transparency, gradiation, haptic, sound	Lim et al. 2008
25. data	Data size, data type, data use, privacy type, hirachy, organization	Lim et al. 2008
26. functionality	System functions, user´s functionality	Lim et al. 2008
27. interactivity	Input behaviour, out put behaviour, feedback behaviour, information behaviour	Lim et al. 2008
28. spatial structure	How each component of a system is combined with others. Can be either 2D or 3D or tangible/intangible	Lim et al. 2008
29. representation	Describing what kind of prototype and form	Beaudouin-Lafon et al. 2003
30. precision	Refering to the level of detail in the prototype´s representation	Beaudouin-Lafon et al. 2003
31. interactivity	Describing the level of interactivity available to users	Beaudouin-Lafon et al. 2003
32. evolution	Looks at the whole expected life cycle of the prototype	Beaudouin-Lafon et al. 2003
33. position in process	When was the prototype used in the design process. Refering to chronological time schedule.	Blomkvist et al. 2011
34. purpose	What is the actual purpose of the prototype?	Blomkvist et al. 2011
35. audience	Who is the audience of the prototype and how do you make them interpret the prototype in the way you want them to?	Blomkvist et al. 2011
36. technique	Which technique did you use to a make the prototype.	Blomkvist et al. 2011
37. fidelity	The level of refinement or degree of detail displayed through a prototype. Level of visual refinement, depth of functionality, breadth of functionality, level of interactivity, depth of datamodel	Blomkvist et al. 2011
38. representation	How the prototype look and its material form	Blomkvist et al. 2011
39. active physicality	How does the prototype look and feel when turned off	Liane 2009
40. passive physicality	How does the prototype react to the user, typically reaction of the interface, the feel of the buttons when operated	Liane 2009
41. cost	What did it cost to make the prototype	Liane 2009
42. color	How many collors and which color does the prototype have	Balters et al. 2015
43. light	How much light does the prototype reflects	Balters et al. 2015

44. motion	Does the prototype move	Balters et al. 2015
45. depth	How long is the the prototype in the (x,y,z)-dimension	Balters et al. 2015
46. form	What is the volume of your prototype	Balters et al. 2015
47. tone	What is the “ground-sound” of your prototype.	Balters et al. 2015
48. volume	How loud is you prototype	Balters et al. 2015
49. touch	How does your prototype feel when…	Balters et al. 2015
50. pressure	How does you prototype feel when…	Balters et al. 2015
51. vibration	Does your prototype vibrate in its groundposition	Balters et al. 2015
52. temperature	How warm is you prototype?	Balters et al. 2015
53. heat conductivity	How warm does it feel?	Balters et al. 2015
54. Motion (somatic)	Movable parts on the prototype	Balters et al. 2015
55. Surface	The surface of your prototype	Balters et al. 2015
56. Salty	Concentration of [Na+]	Balters et al. 2015
57. Sour	Concentration of [H+]	Balters et al. 2015
58. Sweet	Concentration of Sugar molecules	Balters et al. 2015
59. Bitter	Concentration of Quinin	Balters et al. 2015
60. Olf	Unit for measuring smell intensity	Balters et al. 2015
61. Material properties	To understand the physical properties and limitations of a material	Wiberg 2014
62. Material character	The potential of the material. Considering which purposes a specific material could be used for	Wiberg 2014
63. aesthetics	How the details of an object is perceived as a whole	Wiberg 2014
64. quality	A relational concept operating as a measurement between material properties and the ultimate purpose they serve in a composition.	Wiberg 2014
65. appearances	How the prototype communicate material, properties enabling not only visual appearance but also for example haptics	Wiberg 2014
66. authenticity	Whether the prototype looks like the material it is made of or it is ment to look like something else.	Wiberg 2014
67. composition	The co-play between the material and it sorroundings. How does it interact with it´s sorroundings and perform as a whole	Wiberg 2014
68. meaning	How is the prototype/design understood. Does it makes sense to the observer.	Wiberg 2014