IN SEARCH FOR SHARED CHARACTERISTICS OF PHYSICAL AND VIRTUAL PROTOTYPES

Zorn, Stefan;
Hemmer, Michael;
Gericke, Kilian

University of Rostock

ABSTRACT

Prototyping is essential for knowledge acquisition and, thus, for informed decision-making in product development. The gold standard is still the use of physical prototypes. However, with the increase in computing capacity, it is becoming easier also to use virtual prototypes.

The selection of prototyping approaches often starts with the distinction between physical and virtual prototypes and therefore excluding a broad range of possibilities early on.

This paper explains why a selection of prototypes based on the distinction between physical and virtual is not necessarily the best solution and suggests a selection approach based on characteristics which offer the possibility to avoid this limitation. Therefore the characteristics of physical prototypes commonly used in literature are analysed and reduced to a generally valid selection. Examples of virtual prototypes are selected and analysed regarding their characteristics. All elaborated characteristics are then tested for their applicability to the examples of virtual prototypes.

Keywords: Virtual Prototype, Evaluation, Physical Prototype, Product modelling / models, New product development

Contact:
Zorn, Stefan
University of Rostock
Germany
stefan.zorn@uni-rostock.de

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1 INTRODUCTION

Making decisions early in the product development process is critical because the concept and shape of a design determine costs early on (Gebhardt, 2016). A prototype can reduce the risk of costly product changes, and problems can potentially be anticipated in advance (Ulrich and Eppinger, 2012). The gold standard in the industry is still the use of physical prototypes.

However, shorter product development times inevitably lead to shorter model construction times. Shifting the effort of result-critical sub-processes to the earliest possible phases of the overall process, so-called frontloading, enables results to be optimised at an early stage. This leads to the minimisation of later, usually costly product changes as well as to the stabilisation and shortening of project processes (Bracht, Geckler and Wenzel, 2018). According to Liker and Pereira (2018), virtual prototypes have been shown to enable such frontloading, which increases efficiency, improves problem-solving, and facilitates creativity. As a result, ever-shorter cycles in product development require the use of virtual prototypes. In addition, increasing computing capacities make it easier to use new methods such as AR and VR.

As a result, the designer faces complex interdependencies affecting the decision of which prototype to use. The literature provides a few approaches for prototype selection (Petrakis, Hird and Wodehouse, 2019) which differentiate between virtual and physical prototypes.

The selection of prototyping approaches starting based on a distinction between physical and virtual excludes a broad range of possibilities early on. This paper will collect, based on a literature study, generic characteristics of prototypes to enable a better selection that prevents an early exclusion of suitable prototyping approaches. This paper focuses on the identification of characteristics that apply to virtual and physical prototypes.

2 PROTOTYPES IN ENGINEERING DESIGN

The terms prototype and prototyping are often used in the same context. However, everyone typically understands a prototype as a product or idea representation, whereas prototyping describes an activity in which prototypes are generated or utilised (Lim, Stolterman and Tenenberg, 2008).

There are several definitions for prototypes. Jensen et al. (2016) summarise 19 definitions for the term prototype. This paper uses the definition of Lauff, Kotys-Schwartz and Rentschler (2018). They define a prototype as a "physical or digital embodiment of critical elements of the intended design, and an iterative tool to enhance communication, enable learning, and inform decision-making at any point in the design process" (Lauff et al., 2018).

Choosing between a virtual or physical prototype is seen as a critical decision in the product design process. Petrakis et al. in (2019) analysed eight existing taxonomies of prototypes. Only two of them (Stowe, 2008; Ulrich and Eppinger, 2012) included virtual prototypes. Ulrich and Eppinger (2012) highlight the benefits of deciding between virtual and physical prototypes. They provide a 2-dimensional graphical decision-making tool based on the relative accuracy and expense of virtual versus physical prototypes.

Based on this distinction, further tools are developed, for example, Hamon et al.(2014). By answering three questions, which are rated on a Likert scale, a virtual or physical prototype is recommended to the designer.

As already mentioned above, an early distinction between physical and virtual prototypes leads to the exclusion of possibilities. A selection approach based on characteristics offers the possibility to avoid this limitation. Therefore, we require a generic formulation of characteristics suitable for describing both physical and virtual prototypes. This approach is expected to allow a selection based on a comparison between the requirements of a prototype and the characteristics of a finished prototype.

This paper is guided by the overarching research question: Are the characteristics commonly used to describe physical prototypes suitable for describing virtual prototypes?

Based on a literature study, a list of commonly used characteristics of physical prototypes is derived. Subsequently, a list of virtual prototypes is compiled. Additional characteristics are derived from the application areas of these virtual prototypes. Following an evaluation of the suitability to describe selected prototypes, the results are compiled in a matrix.

3 CHARACTERISTICS USED TO DESCRIBE PHYSICAL PROTOTYPES

3.1 Research methodology

A deductive approach is used to answer the research question. For this purpose, general research literature, such as handbooks and textbooks, was searched first, followed by specific monographs. With these boundary conditions and a search string consisting of "product development" and "virtual" and "virtual reality", and "augmented reality", and "prototype", After reviewing these sources, it became apparent that an in-depth search was required, particularly in the area of virtual prototypes and classifications. Thus, other publications were searched.

However, it turned out that the topic area of additive manufacturing technology could only be partially filtered out using search strings. Therefore, then the snowball method was used. The articles found were then reviewed and pre-sorted. In this way, it was possible to gradually dig deeper into the subject area while at the same time providing the reader with an overview of which authors build on the findings of others or take divergent directions. In this way, numerous publications were found, and about 40 were summarised in excerpts. You can contact the first author to access the complete list of publications.

The literature analysis focuses on the dimensions, properties, heuristics and classifications used to describe physical prototypes. They are summarised under the term characteristics. All identified characteristics are documented in Figure 1. The list reflects the different notions of the authors' definitions, thus, distinguishes similar terms. For example, Camburn et al. (2013) define time as "[…] total amount of time allocated to prototyping, in person-hours", which is summarised as "working hours", while Filippi and Barattin's (2012) explanation is "Time represents the phase of the design process when prototyping activities happen", summarised as "development phase".

3.2 Commonly used characteristics

The author identified 150 different characteristics (50 also used as dimensions). The characteristics were sorted according to the absolute frequency of their use as dimensions. These Top 25 selection is displayed in the following Figure 1.

		Wall et. al, 1991; Wall et. al, 1992	Dowlatshahi, 1994	Ulrich & Eppinger, 2012	Virzi, Sokolov & Karis 1996	Houde & Hill, 1997	Thomke 1998, Thomke 2001	Otto & Wood, 2001	Mackay & Beaudouin-Lafon, 2009	Bryan-Kinns & Hamilton	Fishkin, 2002	McCurdy et. al, 2006	Lim et. al, 2008	Hannah Michaelraj & Summer, 2008	Polydoras et. al, 2011	Filippi & Barattin, 2012	Hamon et. al, 2014	Kohler & Hochreuther, 2013	Camburn et. al, 2013 ;Camburn et. al, 2013; Camburn et. al, 2014; Camburn	Jensen et. al, 2015	Jensen et. al, 2016	Auflem et. al, 2020	Real, 2021	Total Amount	Dimensions	Characteristics
		2-3	5	6	7	8	9	11	12	13	14	15	16	17	19	21	22	23-24	25-28	31	32	38	40			
1	Functionality												O	X	O	O		O						5	4	1
2	Cost	X					X	X		X				O	O	O					X			8	3	5
3	Material												O	O						O	X			4	3	1
4	Interactivity											X	O						X	O	X			5	2	3
5	Fidelity/Resolution									X			O							O	X	X		5	2	3
6	Aesthetics	X	O										O											3	2	1
7	Evaluation													O						X	O			3	2	1
8	Data											X	O					O						3	2	1
9	Interaction				X				X		X					X		O						5	1	4
10	Availability	X						X		X				X	O						X			6	1	5
11	Form												X	X	O			X		X				5	1	4
12	Size												X	O				X					X	4	1	3
13	Time									X				X	O						X			4	1	3
14	Scope			O									X							X	X			4	1	3
15	Development/ Design Stage									X				O		X								3	1	2
16	Environment														O	X								2	1	1
17	Presentation								X									O						2	1	1
18	Fit													X	O									2	1	1
19	Spatial structure												O					X						2	1	1
20	Medium			O																				1	1	0
21	Reliability														O									1	1	0
22	Mangerial issues														O									1	1	0
23	Engineering parameters														O									1	1	0
24	General aspects														O									1	1	0
25	Sozial Issues														O									1	1	0

X - used as charachteristic O - used as dimension, domain or subdomain

Figure 1. Ranking of the top 25 characteristics used to describe prototypes

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The table shows the analysed sources, the naming of the characteristics, and the frequency of their mention. When using the characteristics as a higher-level classification (from now on referred to as “dimension”), an O is noted in the table. Characteristics on the lowest order level of the specific source are marked with an X.

Polydoras et al. (2011) listed 109 criteria for prototypes on four classification levels in their paper. For space reasons, the lowest level has been omitted here so that only the dimensions of the second and third levels are noted.

Due to apparent correlations, clustering for the top 25 selection was performed based on the definitions of the specific authors. For example, “Resolution”, “Fidelity”, and “Visual detail” were combined into the term “Fidelity”. For the remaining characteristics, no content clustering has been done yet.

The selection with the definitions from the corresponding sources is once again summarised in the following Figure 2. In some cases, it was helpful to distinguish between the definition as a dimension and the definition as a characteristic. These are marked accordingly.

Dimension/ Charachteristic	Definition
Functionality	The functions that can be performed by the design and the number of functions the prototyping activity should allow to evaluate.
Cost	Cost is used mainly materialwise. If used as a dimension it includes the cost of tooling, prototyping and working team etc. (This characteristics are not included jet).
Material	The medium used to form a prototype.
Interactivity	How a prototype interacts with the users. It may include Feedback and input behaviour.
Aesthetics	Physical properties of the design.
Evaluation	Evaluation purpose of the prototype.
Data	Is the information architecture and the data model of a design.
Fidelity/Resolution	Level of detail or sophistication of what is manifested. The obtainable degree of closeness to eventual design.
Interaction	Interaction capabilities between users and product models.
Availability	Recources available to develop the prototype.
Form	Form, Size,mass or other visual parameter (O). The actual form (X).
Size	The size of the prototype is described by a number of characteristics - number of parts or disciplines etc. [O]. The actual size of the prototype (X).
Time	Used in various forms. Mainly, time needed to produce a prototype. Detailed resolutions are not yet included here.
Scope	Range of what is covered to be manifested.
Development/ Design Stage	Represents the phase of the design process when prototyping activities happen.
Environment	The environment where usage of the prototype takes place and also the effect or interactions with the environment.
Presentation	Describes the form of the prototype.
Fit	Ability of an item to be physically connected to all other components (O). Tolerances (X).
Spatial structure	How each component of a system is combined with others.
Medium	Here used for degree of physicality.
Reliability	The probability that the product will perform its intended function without failure.
Mangerial issues	They are the most typical “pressure issues” to both engineering and corporate executives, namely, cost, time, and risks (O).
Engineering parameters	List of Design Attributs which are further grouped regarding the form-fit-function principles of prototyping (O).
General aspects	New parameters which have come into consideration in engineering and in prototyping (social and environmental considerations) (O).
Sozial Issues	Social considerations, such as support of an enterprise or group and support of national and local economies (O).

Figure 2. Selected characteristics and their definition

4 ANALYSING VIRTUAL PROTOTYPES

4.1 Research methodology

A selection of virtual prototypes is generated to test the applicability of the characteristics of physical prototypes from the previous investigation. On top of that, the examples are examined concerning their

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characteristics. Based on the specific properties used as ordering aspects, we tried to derive characteristics for describing virtual prototypes out of these areas. In the derivation of the characteristics, only examples are discussed which are not yet on the derived list. Due to the limited number of pages, time, costs, effort or availability of tools (in this case, software) are not discussed again.

4.2 Selection of examples of virtual prototypes

In this section, examples of virtual prototypes were selected from the field of mechanical engineering, with an expected increase in complexity. This starts with examples from the area of CAD model types, followed by 3D Modelling Techniques and Simulation Techniques, and finally, some selected samples from the field of AR/VR Applications (Figure 3).

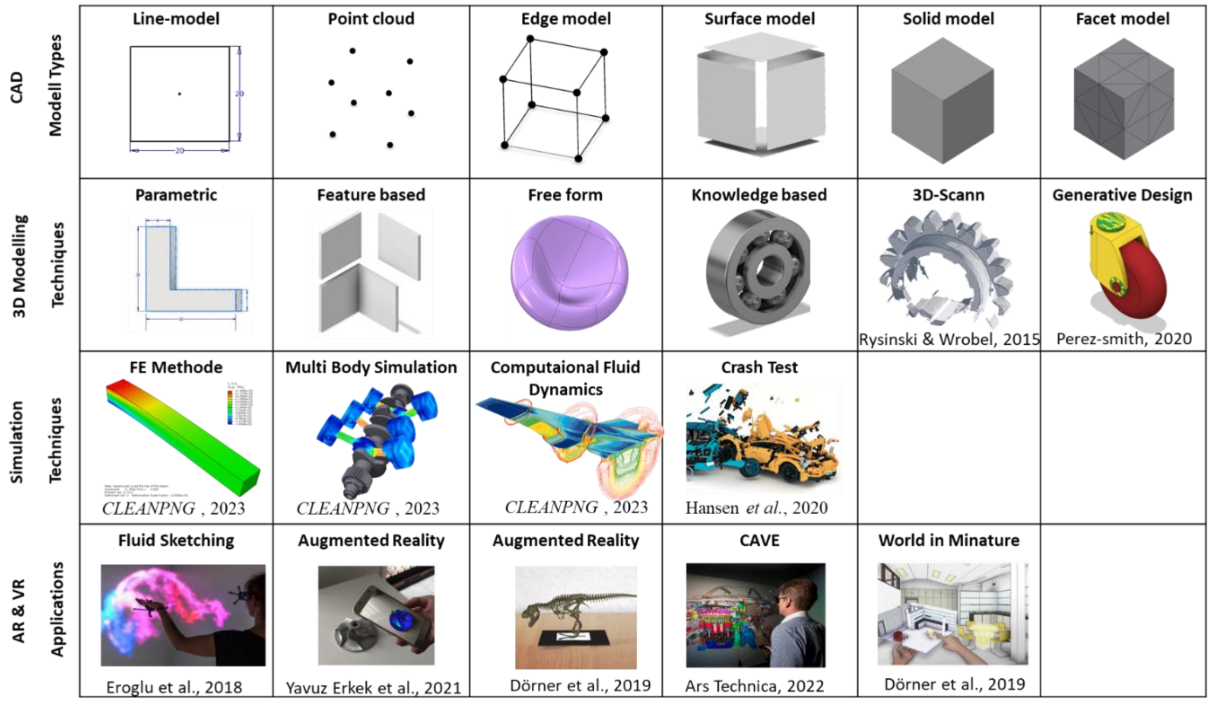

Figure 3. Examples of virtual prototypes from the area of mechanical engineering

CAD model types

The base of virtual prototypes in mechanical engineering is mostly geometrical CAD models. Due to this reason, the methods for geometric modelling were investigated as the first examples with minor complexity. The geometry models are distinguished according to dimensionality (2-, 2½- and 3D), geometry element classes (edge model, surface model, solid model) and their mathematical geometry description (constructive solid geometry method, or boundary representation method) (Vajna et al., 2018). Furthermore, the following characteristics are added for further consideration "Dimensionality", "Geometry Element classes," and Mathematical geometry description.

3D Modelling Techniques

3D modelling techniques are to be understood here as the totality of technologies and techniques or methods for the preparation and execution of product modelling. The VDI guideline 2209 (VDI-2209, 2009) names freeform-, parametric-, feature-based- and knowledge-based modelling techniques as examples. The author added generative design and 3d scanning in this context for this study.

The new characteristic, "model flexibility," supplements the descriptive characteristics with the critical aspect of being able to make changes to the model. "Expertise" try to supplement the knowledge for applying methods, tools, etc.

Simulation techniques

In the next step, the complex 3D CAD models serve as the basis for simulation-based development. This aims to prepare and secure the development steps based on calculation or simulation (IAV GmbH, 2012) to minimise changes to the product and development costs.

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High mathematical-physical competence is required when creating such more complex systems. Virtual prototypes are limited to modelling parameters directly programmed in the respective model (Otto and Wood, 2001). The quality and informative value of the simulation depends mainly on the quality of the input variable and the previously adopted models and calculation methods (Kirchner, 2020). Therefore, using numerical methods requires a critical questioning of the accuracy of the results ("representativeness of the results").
While reading into this topic area, another possible feature emerged. Namely, Bracht et al. (2018) explain the difference between static and dynamic visualisation methods ("dynamics") in connection with the presentation of results. The classical static visualisation methods (two- or three-dimensional) are characterised by no change occurring in space and over time. On the other hand, dynamic visualisation assumes a changeable representation, which can be justified, for example, by the modification of the parameter values for space and time.
The characteristic of "endangerment" was added by considering crash simulation. In the virtual world, danger to persons or the environment is excluded, whereas safety precautions are part of the test preparation in the real world.
Due to the review on this topic, the "representativeness of the results", "dynamics", and "endangerment" were newly added characteristics.

Augmented- and Virtual Reality Applications

The following examples from the Reality- Virtuality Continuum were chosen: Fluid Sketching, Augmented Reality, VR- CAVE and Interactive Worlds in Miniature.
In contrast to the static and dynamic visualisation methods considered so far, where there is no direct possibility of human interaction with the model, virtual reality is defined by immersion and interaction between the viewer and the model. Therefore the degree of "immersion" (Dörner et al., 2019) has been added as a distinguishing feature. Furthermore, "abstraction" in the sense of detachment from the restrictions of the natural world has also been included. An essential component for characterising these prototypes is also the "haptic perception" (i.e., the perception of touch, warmth, and pain, according to Dörner et al., 2019). On top of that, "visual realism" (detailed geometric representation as well as correct reproduction of materials, colours, reflections and others.) and "functional realism" (simulation of processes and object behaviour), according to Schenk and Schumann (2016), was added.

4.3 Characteristics of virtual prototypes

Figure 4 shows the derived characteristics of virtual prototypes, which will be investigated.

Characteristic	Definition
Dimensionality	Dimensionality of the basic elements used.
Geometry Element classes	Class of the used geometry elements.
Mathematical geometry description	Description of the gemetrical data
Model flexibility	Aspect of being able to make changes to the model.
Expertise	Expertise in the application of methods, tools, etc.
Representativeness of the results	Accuracy of the results based of models, calculation methods and assumptions used
Dynamics	Is it possible to modify the parameter values for space and time for the visualization?
Endangerment	Danger to persons or the environment
Immersion	Degree of immersion conditioned by objective, quantifiable stimuli, i.e., multimodal stimulations of human perception.
Design abstraction	Detachment from the restrictions of the real world.
Haptic perception	The perception of touch, warmth, and pain.
Visual realism	Detailed geometric representation as well as correct reproduction of materials, colours, reflections and others.
Functional realism	Correct simulation of processes and object behaviour, as well as the simulation of humans in a virtual (working) environment.

Figure 4. Selection of possible characteristics for virtual prototypes

5 SUITABILITY OF THE CHARACTERISTICS FOR THE DESCRIPTION OF VIRTUAL PROTOTYPES

In the initial section of this paper, we generated two lists of characteristics. First, the 25 most commonly used characteristics and domains for the description of physical prototypes (see Figure 2)

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are based on a literature review. Second, a generic list of possible characteristics of virtual prototypes based on examples from the mechanical engineering area (see Figure 4).

		CAD Modell Types						Modelling Techniques						Simulation				AR/VR Applications				
		Line-model	Point cloud	Edge model	Surface model	Solid model	Facet model	Parametric	Feature based	Free Form	Knowledge based	3D-Scan	Generative-Design	Finite-Element-Methode	Multi-body simulation	CFD	Chrashtest	Fluid Sketching	Augmented Reality	Augmented Reality	CAVE	Interactive World-In-Miniature
Characteristics of physical prototypes	Functionality	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Cost	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Material	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Interactivity	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Aesthetics	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Evaluation	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Data	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Fidelity/Resolution	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Interaction	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Availability	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Form	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Size	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Time	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Scope	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Development/ Design Stage	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Environment	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Presentation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Fit	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Spatial structure	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Medium	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Reliability	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Mangerial issues	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Engineering parameters	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	General aspects	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Sozial Issues	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
Characteristics of virtual prototypes	Dimensionality	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Geometry element classes	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Mathematical geometry description	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Model flexibility	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Expertise	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Representativeness of the results	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Dynamics	○	○	○	○	○	○	◑	◑	◑	◑	◑	◑	●	●	●	●	◑	◑	◑	◑	◑
	System complexity	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Endangerment	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Immersion	○	○	○	○	○	○	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	●	●	●	●	●
	Design abstraction	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Haptic perception	○	○	○	○	○	○	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Visual realism	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Functional realism	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	●	●	●	●	●	●	●	●	●

● suitable ◑ undecided ○ unsuitable

Figure 5. Evaluation matrix for the characteristics regarding their suitability to describe the example prototypes

The accumulated list serves as a starting point to investigate the applicability of the characteristics to the selected samples of virtual prototypes. Therefore, the developed characteristics (see Figure 43) are assessed concerning their suitability for describing the chosen examples of the virtual prototypes. The author evaluated the suitability of the characteristics for every example with a systematic approach based on an ordinal scale in terms of the following criteria; "suitable", "undecided", and "unsuitable". Suitable means that this characteristic is capable of describing the appearance of the example prototype. "Undecided" was chosen if it was not relatively so straightforward. This means that the characteristic is, in principle, suitable to describe an expression; however, the definition of the characteristic would have to be focused here if necessary. This can either mean that it is broadly formulated and contains several characteristics that cannot be evaluated together or that the definition is too firmly focused on one type of prototype. In the case that the characteristic is unable to describe

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the appearance of the prototype, the rating “unsuitable” was assigned. Figure 5 displays the evaluation matrix.

When examining the matrix, it becomes apparent that few selected characteristics are unsuitable for a generally valid description of virtual prototypes. Only “aesthetics” and “fit” were excluded from the physical characteristics list. “Aesthetics is defined as “Physical properties of the prototype”, and “fit” is referred to as the “Ability of an item to be physically connected to all other components (O) or the actual Tolerances (X).”

From the virtual characteristics, we excluded “mathematical geometry description” and “geometry element class.”. This is because they are ordering aspects out of one area but are not suitable for the general characterisation of a prototype.

6 DISCUSSION

This paper aimed to investigate whether physical and virtual prototypes share the same characteristics.

It was found that almost all characteristics for describing physical prototypes can also be used to describe virtual prototypes (see Figure 5). However, the comparison showed particular aspects of virtual prototypes require additional characteristics.

The significant overlap of characteristics shows that it is not necessary to exclude physical or virtual prototypes early on. An early decision on a physical or virtual prototype unnecessarily excludes many possible prototypes, which may result in a non-optimal selection. It seems to be more sensible to select prototypes based on the required characteristics.

Furthermore, a distinction between physical and virtual prototypes is not sufficient nowadays. The spectrum of prototypes expanded by AR/VR technologies, which became more accessible over the recent years. Hence, a sharp distinction between physical and virtual prototypes is no longer trivial. Moreover, with the introduction of mixed reality approaches, the boundary became blurred. These developments resulted in various hybrid prototyping approaches that overlay physical and virtual elements. Hybrid prototypes allow actual tactile prototypes to be overlaid with virtual information or entire overlays. The same is valid for interaction and abstraction; abstract virtual components can form a single entity with physical components; likewise, special MR techniques allow direct interaction with models. A selection based on a distinction between physical and virtual does not incorporate these new approaches.

The evaluation matrix is based on the first author’s subjective assessment. Many of the evaluations can be understood as a basis for discussion and may turn out differently from other points of view.

For the selection of “virtual” characteristics used in this work, no retrospective analysis has yet been performed to determine whether they are suitable for physical prototypes. Furthermore, a clustering of the physical characteristics would be helpful to identify similarities with the virtual characteristics, such as “model flexibility” (virtual) and “configuration freedom” (physical), which are currently not included in the top-25 selection.

The presented work outlines the first ideas for a selection approach based on prototype characteristics. Further research is required before this can be used. For example, this approach requires a taxonomy of characteristics that considers the full range of prototypes and their prioritisation.

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