International Journal of Engineering Education Vol. 38, No. 6, pp. 1747–1760, 2022
Printed in Great Britain

0949-149X/91 $3.00+0.00

CAD as a Virtual Prototyping Method: Uses and Timing of Computer-Aided Design Artifacts in Hardware Design*

HANNAH BUDINOFF
Department of Systems and Industrial Engineering, University of Arizona, USA. E-mail: hdb@arizona.edu

JULIA KRAMER
Department of Mechanical Engineering, University of Michigan, USA. E-mail: kramerju@umich.edu

Prototypes are critical learning tools in the design and development of innovative products. Computer-aided design (CAD) models are most closely associated with detailed design, but emerging research suggests a role for CAD to create virtual prototypes earlier in the design process. In this study, we explore the use of CAD as a prototyping method throughout the design process. We conducted a literature review of scholarly works that described designers using a 3D CAD model to learn about their design. A total of 24 studies were included in our review and were coded to identify common uses of CAD as a prototyping method. CAD was used as a virtual prototyping method from early conceptual design through detailed design but was most frequently used to create operational prototypes when a design was substantially developed, rather than as a simple mock-up. The most common use of CAD prototypes was to assess feasibility of technical aspects of the design. We also observed several examples of CAD models that were used to explore the design solution space and as means of communication with stakeholders. The benefits and limitations of using 3D CAD models as virtual prototypes are also summarized.

Keywords: CAD; virtual prototyping; engineering design process

1. Introduction

Prototypes are critical learning tools in the design and development of innovative products. While varying definitions of prototypes exist, we define them as physical or digital representations of a design of varying fidelity [1] that provide a "means by which designers organically and evolutionarily learn, discover, generate, and refine designs" [2]. Prototypes are useful for exploring both the problem space and the solution space [3,4]. Many methods for creating prototyping exist, from sketching to 3D printing [5,6]. In this study, we specifically focus on exploring purposes and timing of creating 3D models as a prototyping method throughout the design process. Using computer-aided design (CAD) software to create a 3D model can be a convenient and potentially low-cost prototyping method, but the role of CAD as a prototyping method has not been thoroughly explored.

Nourimand and Olechowski [7] suggest that modern CAD packages which facilitate efficient collaboration may contribute towards an emerging practice of "conceptual CAD" (i.e., using CAD during conceptual design before detailed design). Additional research supports the role for CAD as a prototyping method early in the design process [8,9]. While virtual prototypes – digital mock-ups of a physical product that can be presented, analyzed, and tested as if a real physical model [10] – have been a popular topic in academic research for 20 years, it is unclear to what extent designers currently use 3D CAD models as virtual prototypes. Deininger et al. note that the presentation of a prototype matters for how a stakeholder may perceive an idea, and therefore it is critical for designers to select a prototyping format that is both appropriate for the intended stakeholders and is well-suited to represent the features of the design that require feedback from stakeholders [11]. A better understanding of the strengths, limitations, and utility of virtual prototypes compared to physical prototypes could help incorporate virtual prototypes into the design process in more optimal ways.

CAD models have several notable advantages compared to physical prototypes. One commonly cited advantage of all virtual prototypes is that they can be more economical, with a lower cost of production especially for large or extremely complex systems [5, 12–15]. Virtual prototypes may also be created in less time than physical prototypes [16]. Creating a CAD representation of a design can enable analysis with computer-aided engineering and computer-aided manufacturing software tools, providing valuable information about functional performance and manufacturability. Virtual prototypes can have a high degree of fidelity, which has been found to be correlated with higher ratings from external stakeholders [17]. Moreover, CAD is more accessible than ever: CAD courses are ubiqui-

* Accepted 20 June 2022.

tous in engineering education curricula, many university students are "digital natives", and CAD software has experienced rapid improvements in usability and accessibility [18]. As remote learning and remote work are becoming more common [19], virtual prototypes could be increasingly useful to allow collaboration in the prototyping process. In industry, there is a trend towards less physical testing [20], so virtual prototypes may play an increasingly important role in the design process.

Potential downsides of using CAD as a prototyping method early in the design process include concerns of design fixation [21, 22] and doubts about its effectiveness compared with physical prototyping, in part because of perceptions that stakeholder feedback is more difficult and time consuming to elicit when using a virtual prototype [17, 23]. Many researchers agree that physical prototypes produce richer feedback from stakeholders [24–28], which may be a limitation of CAD models relative to physical prototypes. Still, this does not appear to be a universal difference between the two approaches since there is evidence that, under certain circumstances, virtual prototypes can be equally useful as physical prototypes [12, 29, 30]. While benefits and limitations of virtual prototypes have been the subject of prior research, there is little research that specifically focuses on 3D CAD models. Another gap in the literature is industry-relevant strategies for how to prototype efficiently and effectively across a variety of dimensions.

Understanding how, why, and when CAD models are used by designers during the design process can help define the circumstances in which the use of CAD models may be most helpful as a prototyping strategy. In this study, we specifically examine the following question: *How do designers use CAD models as virtual prototypes?* We address this question by performing a scoping review of research papers that describe usage of virtual prototypes by designers and students and then coding the prototyping usage in each paper. Our results provide insight into how CAD is commonly used as a virtual prototyping method, which may help to expand its use in circumstances where it can be most helpful.

2. Methodology

To explore the role of CAD as a prototyping method, we conducted a literature review of scholarly papers that described designers using a 3D CAD model to learn about their design. We followed Arksey and O'Malley's five-stage methodology for conducting scoping reviews [31]. The steps conducted were: identifying the research question; identifying relevant studies; selecting studies; charting the data; and collating, summarizing and reporting the results. Our scoping literature review specifically sought to identify what is known from the existing literature about the type of questions designers seek to answer using CAD models and in what phases in the design process designers use CAD as a prototyping method.

2.1 Search Process

The search was conducted using Scopus, which included IEEE and ScienceDirect databases. We conducted a search for papers that included a mention of prototypes, of the population creating prototypes (e.g., engineers or designers, students or practitioners), of the data that was collected (e.g., qualitative or quantitative data relating to the use of the prototype), and were classified within the subject area of "engineering". The following search criteria were used to search articles' titles and abstracts:

> *TITLE-ABS ((prototyping OR {prototypes}) AND ({engineers} OR {designers} OR {students} OR {practitioners}) AND (interview* OR survey* OR questionnaire OR qualitative OR {focus group} OR {focus groups} OR recorded OR reported OR observational))*

This search resulted in 545 records. We then developed criteria post hoc to determine studies suitable for inclusion. We applied the following criteria in phases as we first reviewed duplicate entries, followed by paper titles, paper abstracts, and finally the full paper text: (1) The paper must be available in English; (2) The paper must describe students or practitioners using virtual 3D models as a prototype (i.e., using CAD to create a prototype and using this virtual prototype to learn something about their design); and (3) The paper must include qualitative or quantitative data from students or practitioners (e.g., interviews, surveys, observational studies, or experimental studies with students or practitioners).

Additionally, we chose to include following specific types of papers that appeared in our search: papers that describe finite element analysis (FEA) or other technical simulations that use virtual 3D models, as long as the authors discussed what design insight was gained from using these technical simulations; and case studies of a single project where the authors were the designers who describe how they used CAD as a virtual prototyping method. We chose to exclude the following types of papers: papers that discuss a design process where K-12 students are the designers; papers that describe 3D CAD only as a means for fabrication (e.g., generating a file for 3D printing) and do not

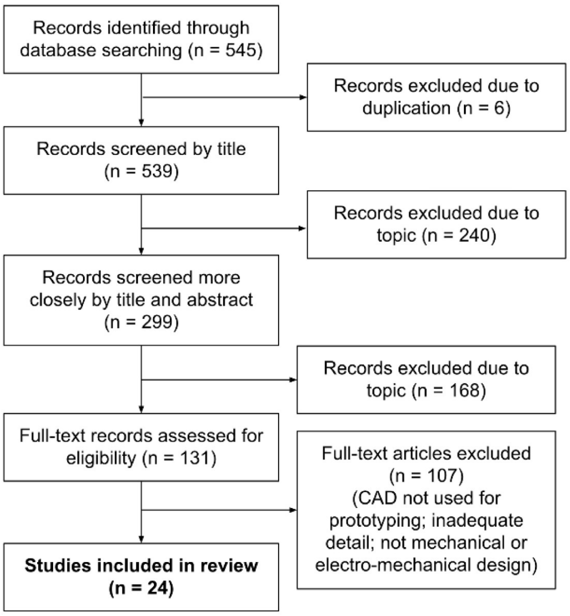

Fig. 1. Flow chart of paper identification and selection process, adapted from [32].

describe what design insight was learned from making the 3D CAD model; and papers that describe designs that do not include some mechanical engineering (i.e., "hardware") component. Out of the 545 records that were identified in our search, we evaluated 131 articles in full, and 24 articles were selected for inclusion in our study (Fig. 1).

2.2 *Coding for Details of Virtual Prototyping*

The literature we identified in our search was categorized using an ontology developed by Roschuni et al. [33], which builds on prior work reviewing the various roles of prototypes [34], and is currently utilized in theDesignExchange – an online platform and method repository to support the design community of practice [35, 36]. We chose to use Roschuni et al.'s ontology because it was developed through a triangulation of complementary research efforts: (1) a rigorous evaluation of 82 different design processes [37], (2) a literature review of design cases and design methods [33], and (3) a series of workshops with design experts. Additionally, Roschuni et al.'s ontology builds on existing ontologies related to design, including Hartmann [38] and Michaelraj [39]. Because Roschuni et al. ontology was based on several sources of both existing work and novel research, we felt the ontology was holistic and therefore the best basis for our coding.

The factors of this ontology include: purpose of the prototype (i.e., why the prototype was created); aspect (i.e., the features or characteristics of a product that the prototype approximates); stage of process (i.e., when in the design process the prototype is used); and scope (i.e., the extent to which the prototype represents the full design). Each factor in the ontology is divided into specific sub-factors (Table 1), which were used for coding. The stage-of-process codes in this ontology (mock-up, operational, production) do not correspond exactly with design process model stages such as conceptual design and detail design, but instead represent a measure prototype fidelity that is connected to design process stages. For example, it is unlikely that a production prototype would be used during concept development. All papers were coded separately by two researchers. Inconsistencies in coding were discussed and resolved.

One example prototype from the scoping review comes from Dimitrokali et al. [42]. In this paper, the study authors describe a case study of their own design work to create photovoltaic tree structures, or "artificial solar structures that look like sculptural trees." First, the study team gathered insights from stakeholders at the university about initial concepts for photovoltaic trees. Stakeholders were asked to consider "the built and natural environment on the University campus" and to develop ideas "for a solar tree to fit in with the surrounding urban context." Then, the study team refined these initial concepts into four CAD model and 3D printed concepts. The study team tested these prototypes in a series of focus groups and exhibitions. In these sessions, participants were asked to consider "urban and non-urban locations and the potential effect this may have on public perception and subsequent design". The study team presented CAD images of the four solar tree concepts placed "in a contextual scenario" (Fig. 2, right image). The prototypes were presented on an interactive white board.

Based on the authors' account of the prototype development and testing, we applied the following codes from our codebook. We coded the Purpose as "experiment" because multiple prototypes were tested in a focus group setting. We coded the Aspect as both "appearance" and "role/context" because participants offered feedback both on the aesthetics of the solar tree ("appearance") and on the way the solar tree prototypes fit into the environment surrounding the university ("role/context"). We coded the Stage of Process as "mock-up" because the prototypes shared were only built to replicate the form of the eventual design but not the function (i.e., the technical performance of the photovoltaics). We coded the Scope as "horizontal slice" because the prototypes explored multiple aspects of the design (e.g., both "appearance" and "role/context") without going into depth on either aspect.

Table 1. Coding scheme used to categorize identified studies

Factor	Sub-factors	Definition	Virtual prototyping example
Purpose	Persuade	Aim to convince stakeholders of the product's attributes	A design team shared CAD models with financial decision makers to convince them of the project potential [Coulentianos et al., 2020b] [40]
	Explore	Explore the solution space of design options	Participants used linkage design software to create a four-bar linkage, and began prototyping with no preconceived ideas of their design. [Camburn et al., 2015] [12]
	Demonstrate	Aid communication between different project stakeholders	Stakeholders (i.e., healthcare workers) were asked to provide feedback on virtual prototypes (a sketch and a CAD model) for "a medical device concept that assists with the insertion of a long-term contraceptive implant" [Deininger et al., 2019a] [17]
	Experiment	Conduct focused experiments comparing two or more options	Participants were asked to provide feedback on virtual prototypes of washing machine components (door, drawer, knob and buttons) and compare the virtual prototypes to the physical prototypes of the same components. [Carulli et al., 2013] [41]
Aspect	Role/context	Investigate the product's role in a larger context, beyond use of the product	CAD images of a "solar tree" prototype were placed in a contextual scenario (e.g., a park) for feedback from participants in a focus group session. [Dimitrokali et al., 2015] [42]
	Implementation	Investigate the technical implementation of the product's function	A CAD model of a handle was developed and a sustainability analysis was carried out to assess the environmental impact of creating the handle with different materials. [Gallimore & Cheung, 2016] [43]
	Behavior	Investigate the product's behavior and response ("acts-like")	In a software program called Statechart, a UI "behavior model" was developed to simulate how a 3D virtual prototype of a digital camera would respond to user inputs. [Kanai et al., 2009] [44]
	Appearance	Investigate the product's visual appearance ("looks-like")	A medical device designer created a rendering of the design and sent the rendering to remote stakeholders to enable feedback and discussion on the product's appearance. [Coulentianos et al., 2020a] [45]
Stage of process	Mock-up	A virtual prototype of the form but not function of a product	Designers use biomimicry to inspire new ideas, and interviews with these designers showed that many start by translating biomimicry analogies immediate into a 3D CAD model mockup [Rovalo & McCardle, 2019] [46]
	Operational	A virtual prototype that simulates an operational physical prototype	A designer used CAD as a "virtual toolbox" to try out different designs of a new wheel that offers suspension in all directions. The designer's CAD workflow led to a simulated operational prototype that was then translated directly to an operational physical prototype. [Crilly et al., 2019] [47]
	Production	Prototype is ready to be produced	No examples from corpus, but may include the final CAD model used to optimize for mass manufacturing
Scope	Horizontal slice	Investigate one level (i.e., multiple aspects) of the product's design with limited depth	At a product strategy firm, designers create simulations and mock-ups to bring ideas "to life", demonstrating to managers and clients what the idea will look like, how the idea will work, and how the idea represents a new strategic direction. [Stevens, 2013] [48]
	Vertical slice	Investigate one aspect of the product's design in depth	University students designed various energy generation mechanical devices (e.g., a wind turbine or water wheel). Students created CAD models of their designs solely for the purposes of conducting a finite element analysis and 3D printing their design. [Paudel, 2015] [49]
	Full scope	Investigate the full design (i.e., all aspects) of the product	University students completed their senior design project to redesign an electronic nail file. The final 3D CAD model students created was used to conduct a finite element analysis, to investigate assembly, and to gain feedback from stakeholders on the design's aesthetics. [Rodriguez et al., 2010] [50]

2.3 Extracting Benefits and Limitations of Virtual Prototyping

After coding the papers identified in this scoping review for details regarding the Purpose, Aspect, Stage of Process, and Scope (as described in Section 2.2), we then extracted the stated benefits and limitations of virtual prototyping as identified by the authors of the papers or by the study participants themselves. To extract all benefits and limitations of virtual prototyping, we read each of the papers identified in the scoping review fully and highlighted both participant quotes and author-written text describing explicit benefits or limitations of virtual prototyping. After highlighting all the stated benefits and limitations of virtual prototyping across all papers, we conducted a thematic analysis to identify themes of benefits and themes

Fig. 2. Solar tree physical prototype (left) and virtual CAD prototype (right). Only the virtual prototype was coded in our study. Reprinted from *Procedia Engineering*, 118, Dimitrokali et al., Moving Away from Flat Solar Panels to PVtrees: Exploring Ideas and People's Perceptions, 1208–1216, Copyright (2015), with permission from Elsevier.

of limitations. These themes are described in Section 3.3.

For example, in Deininger et al., 2017 [51], the authors quote two study participants who remarked:

> "The CAD models really helped us to figure out what kind of problems we might run into. That helped us have more realistic design that was then much easier to turn into a physical model" (Participant 15).
>
> "In contrast, 'The concept in SOLIDWORKS was all right. It looked nice and everything. but obviously, in SOLIDWORKS, your [model] is not going to tip over" (Participant 10).

These two quotes illustrate both a stated benefit and limitation of a virtual prototype. Participant 15 notes a benefit of virtual prototyping being that the team could create a CAD model to sort out design issues before needing to create a physical model. Participant 10 on the other hand notes a limitation of virtual prototyping being that a CAD model created in Solidworks was not sufficient for technical testing.

3. Results

3.1 Summary of Papers Identified

We identified 24 papers, which were published between the years of 2003 and 2020. The majority of identified papers were published after 2012 (n = 20). The papers were published in a variety of venues, including both conference proceedings and journals. The most popular venues for publication were the *American Society for Engineering Education (ASEE) Annual Conference and Exposition* (n = 7), the *American Society of Mechanical Engineers (ASME) International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE)* (n = 3), and the journal *Design Studies* (n = 2).

3.2 Details of Virtual Prototyping Among Papers Identified

In Table 2, we provide details on each paper related to our research question. The most common "designer population" was students (n = 14), including students who were working in design teams (n = 8) and students who were participants in experimental and interview studies (n = 6). Other designer populations studied were industry design practitioners (n = 5), and the paper authors themselves (i.e., authors describing a case study of their own design work) (n = 5). In the papers, there was a wide range of objects that were designed, including toys, cars, and medical devices. In Table 2, papers that reported on the design of "various" objects were papers where the authors either studied teams of students working on a variety of projects, or the authors asked participants to reflect on their prior design experience without necessarily going into detail on the specific object that participants designed.

Several papers presented details of multiple projects where virtual prototypes were used (e.g., [45]). For these papers, we coded each virtual prototype separately. Additionally, several papers describe virtual prototypes being used multiple times or for multiple events (e.g., [46]). For these papers, we coded multiple purposes, aspects, scopes, and/or stages of the process as necessary. Rarely, there was insufficient detail to code one or more of the factors (e.g., [24]) but in the cases where this was true, we coded as much as possible while leaving the factors we could not code blank.

3.2.1 Purpose

The most common purpose of a virtual prototype in the papers identified was to *experiment* (n = 18).

Table 2. Details of identified studies, including prototype purpose, aspect, scope, and stage of process. Alphabetized by the last name of the first author

Ref. #	Authors & Year	Designer population	Object designed	Purpose	Aspect	Stage of process	Scope	Post-hoc category
[52]	Andersson, 2013	Teams of undergraduate students	Urban car concept	Experiment	Implementation	Operational	Vertical slice	Technical
[53]	Bailey, 2015	Undergraduate students	Bracket	Explore, Experiment	Implementation	Operational	Full scope	Technical
[12]	Camburn et al., 2015	Undergraduate students	Four-bar linkage	Explore	Behavior	Mock-up	Vertical slice	Exploratory
[8]	Carfagni et al., 2020	Master's students	Ladder	Explore, Demonstrate	Behavior, Implementation	Mock-up	Horizontal slice	Exploratory
[41]	Carulli et al., 2013	Paper authors (describing design case study)	Washing machine	Experiment	Behavior	Operational	Vertical slice	Technical
[45]	Coulentianos et al., 2020a	Industry design practitioners	Medical device	Experiment	Implementation	Operational	Full scope	Technical
			Medical device	Demonstrate	Appearance, Behavior	Operational	Full scope	Polished communication
[40]	Coulentianos et al., 2020b	Industry design practitioners	Various medical devices	Demonstrate, Persuade	Behavior	Mock-up	Horizontal slice	Exploratory
[47]	Crilly et al., 2019	Industry design practitioners	Wheel	Experiment	Implementation	Operational	Full scope	Technical
[51]	Deininger et al., 2017	Undergraduate and master's students	Various	Demonstrate, experiment	Implementation	Operational, Mock-up	Full scope, Vertical slice	None
[17]	Deininger et al., 2019a	Paper authors (describing design case study)	Medical device	Demonstrate	Appearance, Behavior, Role/context	Operational	Full scope	Polished communication
[24]	Deininger et al., 2019b	Undergraduate students	Various	Experiment, Demonstrate	Implementation, Behavior	*Insufficient detail to code*	*Insufficient detail to code*	None
[42]	Dimitrokali et al., 2015	Paper authors (describing design case study)	Photovoltaic tree structures	Experiment	Appearance, Role/context	Mock-up	Horizontal slice	None
[43]	Gallimore & Cheung, 2016	Paper authors (describing design case study)	Automotive component	Experiment	Implementation	Operational	Full scope	Technical
[54]	Holland et al., 2013	Teams of undergraduate students	Various	Experiment	Implementation	Mock-up	Vertical slice	None
[55]	Howard et al., 2015	Undergraduate students	Bracket	Experiment	Implementation	Operational	Full scope	Technical
[44]	Kanai et al., 2009	Paper authors (describing design case study)	Digital camera	Experiment	Behavior	Operational	Vertical slice	Technical
[49]	Paudel, 2015	Teams of undergraduate students	Energy generation mechanical devices	Experiment	Implementation	Operational	Vertical slice	Technical
[50]	Rodriguez et al., 2010	Teams of undergraduate students	Electric nail file	Demonstrate	Appearance, Implementation	Operational	Full scope	Polished communication
[46]	Rovalo & McCardle, 2019	Industry design practitioners	Various	Explore, Experiment, Demonstrate	Implementation, Behavior	Mock-up	Vertical slice	Exploratory
[56]	Schmueser et al., 2018	Teams of master's students	Car frame	Experiment	Implementation	Operational	Vertical slice	Technical
[57]	Shergadwala et al., 2019	Teams of undergraduate students	Toy car	Experiment	Behavior, Implementation	Operational	Full scope	Technical
[48]	Stevens, 2013	Industry design practitioners	Mobile phones/devices	Demonstrate	Appearance, Implementation	Mock-up	Horizontal slice	Exploratory
			Telecom	Demonstrate	Appearance, Implementation	Mock-up	Horizontal slice	Exploratory
[58]	Will & Tougaw, 2003	Teams of undergraduate students	Various	Experiment	Implementation	Operational	Full scope	Technical
[59]	Vanasupa et al., 2008	Teams of undergraduate students	Hip replacement component	Experiment	Behavior	Operational	Vertical slice	Technical

Experimentation with virtual prototypes included technical tests or simulations where the designers sought to compare multiple design options to one another. For example, in a paper describing a project to create a new washing machine, designers created a virtual prototype to test multiple different configurations of components with users [41]. The next most common purpose was to *demonstrate* ($n = 10$), such as showing the prototype to a stakeholder (e.g., a user) and getting the stakeholder's feedback on the design. For example, in a paper describing a project to create a new electric nail file, student designers created a virtual prototype for the expressed purpose of showing the design to stakeholders to elicit feedback [50].

It was less common for designers to use a virtual prototype to *explore* the solution space using virtual prototyping ($n = 4$). A designer using a virtual prototype to explore would create a virtual prototype without yet having a clear idea of their concept; they leveraged virtual prototyping as a way to formulate their conceptual ideas. An example of exploration is found in [12], where student designers were asked to create a virtual four-bar linkage. In this example, the students used the virtual prototyping software as they were formulating their concepts, and they did not necessarily have a conceptual idea of their design before they began prototyping. Similarly, it was uncommon for designers to use a virtual prototype to *persuade* ($n = 1$). Many papers discussed that designers felt physical prototypes were better suited for persuasion, with one paper describing how designers had "greater power to convince financial decision makers of the project potential" with physical rather than virtual prototypes [40].

3.2.2 Aspect

Implementation was the most common aspect explored ($n = 18$), and most papers we identified used virtual prototypes to explore the technical implementation of the product's functions. Implementation included FEA, which was commonly mentioned as a use of a virtual prototype. For example, in a paper describing a project to create a new urban car concept, student designers created a virtual prototype and conducted FEA on the wheel suspension system [52]. *Behavior* was the next most common aspect explored ($n = 11$) and included instances where the virtual prototype was created to test the basic functions of the design for feedback (e.g., with users). One paper described the design of a digital camera and discussed how virtual prototypes were used to test the user interface of the digital camera with users [44]. This paper did not describe the use of virtual prototypes to test the hardware or software of the camera (which would correspond to *implementation*) but rather focused on the basic functionality of the camera.

The *appearance* of a design was explored only six times, and the *role/context* of a design in a larger ecosystem was only explored twice. One paper provides an illustrative example of testing both the appearance and the role/context of a design: designers created virtual prototypes and tested the prototypes with users to get feedback on the photovoltaic trees' appearance and how the photovoltaic trees might fit into a natural environment, like a park [42].

3.2.3 Stage of Process

The most popular stage at which to create a virtual prototype was the *operational* stage ($n = 17$). It was common for designers to create virtual prototypes after earlier stages of diverging to develop a wide range of ideas and converging to select ideas to carry forward. For example, in a paper describing a student design project to create a toy car, students created virtual prototypes of their designs after going through an earlier "conceptual design" process, and they then used these virtual prototypes to fabricate functional physical prototypes [57].

Mock-up virtual prototypes were described nine times. One paper describes two different virtual prototypes, both of which were created in the mock-up stage [48]. In this paper, the virtual prototypes were created to provide "a visual embodiment of a possible future" and to "bring technology to life". The prototypes at this stage were not created to explore the operational details of the design but rather to provide an early concept of what the design could be. *Production* was not mentioned in any of the papers in this scoping review, and it is possible that our coding definition for a production-ready virtual prototype may not be considered by others to be "prototyping".

3.2.4 Scope

Designers often explore the *full scope* of their design through their virtual prototypes ($n = 11$). An example of a *full scope* virtual prototype is provided in [43], which describes the creation of a virtual prototype to explore the ergonomics, material properties, and sustainability of a handle in a car. The virtual prototype goes into depth on assessing each of these features, thus differentiating it from a *horizontal scope.* Nearly as common as *full scope*, designers often created virtual prototypes to explore a *vertical slice* of their design ($n = 10$). For example, one paper described a project to create a renewable energy technology (e.g., a wind turbine), where student designers were tasked with creating a virtual prototype of their design with the purpose of assessing motion and loading [49]. In this example, the virtual prototypes were created to go deep on the vertical slice of loading conditions and associated stress and deflection. The virtual prototypes were not created to assess other aspects of the design, like appearance.

Horizontal slice was not very common among papers in this scoping review. An example of a horizontal slice virtual prototype is the previously described paper focused on the creation of prototypes for photovoltaic trees [42]. These prototypes were created to represent multiple aspects of the design (i.e., *appearance* and *role/context*) without going into deep detail on one aspect (which would correspond to *vertical slice*).

3.2.5 Connections between Factors

In the coding process, we observed that certain subfactors/codes tended to occur together (refer to Fig. 3, where dot size indicates frequency each code combination). For example, the scope of mock-up prototypes tended to be either horizontal or vertical slice, whereas more complete operational prototypes tended to be full scope.

Three distinct categories emerged after coding was complete where prototypes within each category had the similar combinations of codes across all four factors (Table 2). We refer to these post-hoc categories as technical prototypes, exploratory prototypes, and polished communication prototypes. Technical prototypes ($n = 13$) were at the operation phase and were made for the purpose of experimentation. These prototypes were either full scope or vertical slice and focused on either implementation or behavior. Often, these prototypes involved finite-element analysis that was conducted to explore geometric shape and material choices.

Exploratory prototypes ($n = 6$) were at the mock-up phase, horizontal or vertical slice scope, the purpose was typically to demonstrate or explore. The exact aspect evaluated in exploratory prototypes varied, but most frequently included behavior and implementation. An example of an exploratory prototype is a CAD model created by a designer who sought to "approximate the forms and behaviors" of a biological system used to inspire biomimetic designs early in the abstraction process [46]. Polished communication prototypes ($n = 3$) were full-scope and at the operational stage. Their purpose was to demonstrate, and the aspect evaluated was appearance and either implementation or behavior. One example of a polished communication prototype was a CAD model of an electric nail file, created elicit feedback from stakeholders [50].

Four prototypes did not fit into these categories. It was infeasible to categorize two of the prototypes because of a single prototyping having conflicting multiple codes, or because there was insufficient detail to code. The remaining two uncategorized prototypes were similar to exploratory prototypes, but their purpose was experimentation, suggesting a more parametric design approach rather than exploration of the solution space.

3.3 Benefits and Limitations of Virtual Prototyping

Many of the papers ($n = 17$) listed some benefits and/or limitations of virtual prototyping. In review-

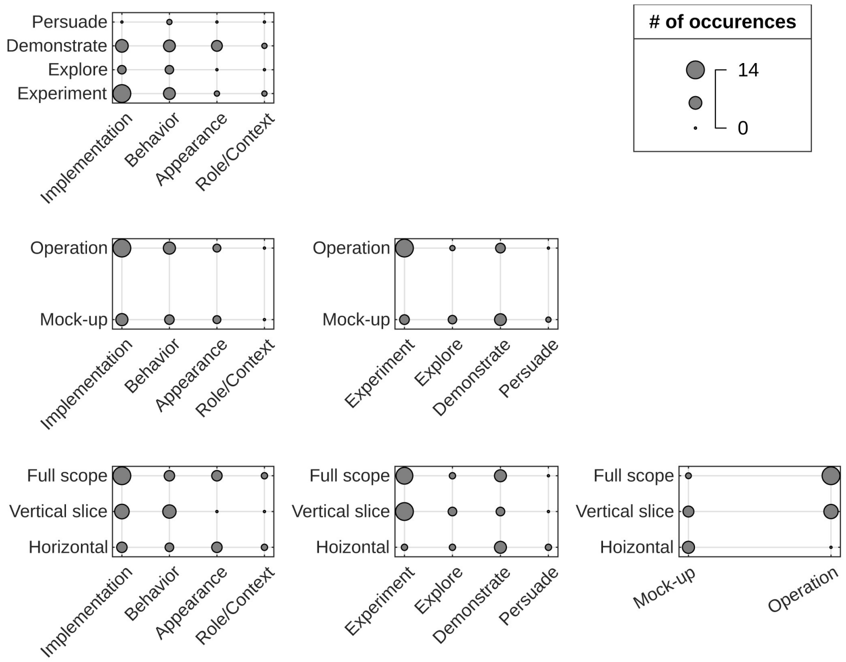

Fig. 3. Bubble plots showing the frequency of combinations of different codes.

ing the papers, we identified the stated benefits and limitations of virtual prototyping relevant to the study itself and we did not, for example, identify more general benefits and limitations of virtual prototyping that may have been noted in the background sections of the papers. Not all papers stated explicit benefits or limitations of virtual prototyping, and the level of detail provided on the benefits and limitations of virtual prototyping varied widely between papers.

3.3.1 Benefits of Virtual Prototyping

One of the most often mentioned benefits of virtual prototyping in the papers was that *virtual prototypes reduced the time and cost of prototyping, particularly when multiple versions or iterations of a design were created to test at once.* In [47], virtual prototyping allowed designers to flexibly develop their design and to test multiple iterations in rapid succession. Virtual prototypes reduced the cost and time needed to manufacture prototypes [57], particularly when designers needed to create multiple versions of prototypes to test with customers [41]. Virtual prototyping was also useful for students because students were able to create virtual prototypes significantly quicker than physical prototypes [12], and the virtual prototypes provided students a low-cost way of carrying out experiments [54].

Virtual prototypes were useful for designers to bring their conceptual ideas to life, and to help designers facilitate early feedback on these conceptual ideas to highlight early design issues. This benefit was true for students [50, 51] and for industry design practitioners [48]. In [48], industry design practitioners used virtual prototypes to capture the future vision of a product, useful for product and organizational strategy discussions. In [17], early conceptual virtual prototypes were found to facilitate more useful feedback than sketches.

Several papers noted that *virtual prototypes were particularly useful for engaging remote stakeholders and technical stakeholders.* In [45], designers facilitated feedback by emailing renderings of designs to remote stakeholders. Additionally, technical stakeholders (e.g., engineering professors or expert advisors) were able to provide early feedback on virtual prototypes [40, 51].

Virtual prototypes offered several options that physical prototypes did not. Virtual prototypes allowed for real-time prototype modification and were therefore useful in testing customizable versions of products [41]. Additionally, virtual prototype and testing setups allowed for testing results to be automatically analyzed [44]. Virtual prototyping software tools allowed designers to simulate the environmental impact of their designs [43], and to quickly mock-up and test the applicability of biodesign principles in their designs [46]. In one paper, virtual prototypes uniquely allowed designers to capture auditory and haptic feedback, which would have otherwise been difficult to prototype and test in physical prototypes [41].

Finally, *virtual prototypes overcame some contextual limitations of physical prototypes*, including limited access to physical prototyping tools and equipment [24].

3.3.2 Limitations of Virtual Prototyping

A frequently mentioned limitation of virtual prototyping is that *virtual prototypes were not sufficient on their own and were limited in their ability to test all aspects of a design.* In one paper, the authors noted that virtual prototypes faced some technical limits in providing a natural experience, particularly in testing haptic features of a design [41]. Additionally, virtual sustainability tools were limited, particularly in their inability to consider the effects of production volume and other factors outside the bounds of the product's design itself [43]. Virtual simulation tools were limited in their ability to represent physical properties of designs [24], and in general virtual prototypes were not sufficient for technical testing [51].

Several papers noted that *virtual prototypes were not as effective as physical prototypes to facilitate feedback, particularly to communicate or persuade stakeholders.* In [45], the authors found that industry design practitioners perceived physical prototypes to be more useful than virtual prototypes to communicate with project decision-makers (e.g., financial stakeholders), and in [8], the authors noted that engineering students did not use virtual prototypes for communication purposes. Designers viewed physical prototypes as more effective than virtual prototypes to engage users, particularly in persuading decision-makers of the design's potential [40, 46]. In an experimental study [17], the authors found that virtual prototypes did not facilitate as much consistently useful feedback as physical prototypes.

There were also limitations with the software required to create and test virtual prototypes. *Designers required technical skills to use virtual prototyping and testing software*, and students were limited in their knowledge, expertise, and confidence in using CAD/FEA software (e.g., they needed guidance on setting appropriate boundary conditions or were unaware of physical simulation tools) [54, 57]. In a study comparing the design experiences of engineering students and industrial design students [8], the authors found that industrial design students did not feel comfortable using virtual prototypes exclusively and preferred to use them in tandem with physical prototypes (engineering students however were comfortable using virtual prototypes exclusively). Finally, the availability of virtual prototyping software was limited, particularly for designers working on low-resource settings [24].

4. Discussion

4.1 Study Scope and Limitations

We focused the literature review on studies that presented qualitative or quantitative data from multiple designers. As a result, our search terms may have excluded studies that present a novel innovation but include few details about the design process. We also found several studies that met our search criteria but did not meet the inclusion criteria because they did not give a specific example of the use of virtual prototyping (e.g., [60–62]). These studies, which mentioned that virtual prototyping was used minimally or not used, were excluded because they could not be coded. Another limitation of our study is that the majority of the identified studies focused on student designers ($n = 14$), rather than design practitioners in industry ($n = 5$). Given this overrepresentation, our findings may be most indicative of student practices, rather than practitioner practices.

An additional limitation of our work is that we only coded virtual prototype usage. Because of this choice, we cannot compare how common uses of virtual prototyping differ from those of physical prototyping. Instead, we are limited to summarizing benefits and limitations of virtual prototyping versus physical prototyping that were explicitly stated in the papers we analyzed. Future work could use our coding scheme for literature describing physical prototyping use and compare with the results described here for virtual prototyping.

4.2 Study Research Question

To answer our research question, *How do designers use CAD models as virtual prototypes?*, we explored four elements related to designers' prototype usage: Purpose, Aspect, Stage of Process, and Scope. We found that virtual prototypes were most often used as what we called technical prototypes to experiment with various design parameters to refine technical aspects of designs. Another common usage was exploratory prototypes, where rough, approximate CAD models are used to explore some aspect of the design. Finally, we saw some use of CAD models as polished communication prototypes. In the following paragraphs, we will explore the details of how virtual prototypes were commonly used.

Designers generally used virtual prototypes to focus more on functionality (i.e., aspect explored was implementation or behavior) rather than appearance or relationships with the world (i.e., role/context). One potential reason for the frequent focus on functionality is that multiple papers described student design projects where students were tasked with exploring product functionality with CAD models. Developing CAD models as an input to FEA software was a particularly common use. Given that CAD models are a required input for FEA, this use of virtual prototypes is not surprising. However, since a common role of physical prototypes is to explore form or relationships between the design and the world at large, more research is needed to understand how virtual prototypes can be used to explore design aspects beyond functionality.

Virtual prototyping was used predominantly in the operation phase ($n = 17$) rather than the mock-up ($n = 9$) or production ($n = 0$) phases. We attribute this finding to the technical nature of questions that designers sought to ask with virtual prototyping. Still, the number of papers in our scoping review that used virtual prototyping in the mock-up phase is not insignificant, perhaps consistent with findings that CAD is beginning to be used more commonly as a prototyping method earlier in the design process [7–9]. Exploratory virtual prototypes were used early in the design process as a broad exploration of different aspects of the design (horizontal slice) or an in-depth exploration of a single aspect (vertical slice). This emerging role of virtual prototypes has not been well documented in prior work, and there is a paucity of research on best practices for early CAD usage for prototyping. Future work should focus on the effectiveness of CAD for early design exploration.

One key element of the effectiveness of CAD in early prototyping is prototype fidelity. There are mixed opinions on the role of prototype fidelity in eliciting feedback from stakeholders. In one experimental study, high fidelity CAD models were found to elicit more useful feedback from stakeholders than sketches [17]. This may be because higher fidelity prototypes offer more concrete features about which stakeholders may offer comments. Another benefit of higher fidelity prototypes is that they can cause stakeholders to perceive the underlying design as higher quality [45]. However, prior work has indicated that stakeholders viewing a higher-fidelity prototype may feel that the design is too developed to benefit from significant alterations [63]. Our results indicate designers are using both mock-up and more polished, operational CAD models to elicit feedback. Further research could study how virtual prototype fidelity impacts the effectiveness of prototyping for demonstrating a design to stakeholders, but also for other purposes such as design exploration, experimentation, and to persuade decision makers.

The designers' skill levels and preferences appeared to have an impact on their use of CAD as a virtual prototyping method. Our sample size for designers in industry is small ($n = 5$), but it appears there may be differences between professional practitioners and students. The majority of the virtual prototypes (4 of 6) used in industry were exploratory, whereas only 13% (2 of 16) of student prototypes were exploratory. Designers who had limited CAD skills were shown in a previous study to struggle with creating virtual prototypes to "identify functional blocks", a prototyping best practice that enables designers to address complex challenges by breaking them down into smaller pieces early in the design process [24]. Students most frequently used technical virtual prototypes (11 of 16), but for practitioners, technical prototypes were less frequently observed (2 of 6) than exploratory prototypes. However, there were commonalities between these groups, as well: both students and practitioners used all three categories of prototypes and had similarly wide-ranging uses of virtual prototypes.

4.3 Comparing Virtual and Physical Prototypes

Prior work has shown that cost-effectiveness and model accuracy are two important considerations when choosing between virtual and physical prototypes [16, 64]. We identified several studies that used virtual prototypes to answer technical questions for complex systems that would be challenging to physically prototype (e.g., car structures). Virtual prototyping may also be particularly useful in resource-limited settings [62] as it may offer a more time- and cost-effective way to explore design options, even if used to limit the number of physical prototypes that ultimately need to be made rather than to replace physical prototypes. These potential advantages in resource-limited settings, however, must be balanced with concerns that modeling tools may not be widely available in resource-limited settings, do not account for the cost and local availability of materials, and may not capture the operating context well [24, 62]. Aside from some of these more extreme cases, it is not clear when virtual prototyping may be cheaper than physical prototyping. Future work to quantify costs of prototyping could help novice designers to assess the benefits and limitations of physical versus virtual prototyping.

We identified conflicting trends in terms of designer preferences for virtual or physical prototyping. Two papers described that some designers prefer virtual prototyping to physical prototyping [12, 65]. However, another paper noted that when student designers were creating virtual prototypes, they expressed a frustration at not being able to physically prototype their designs sooner [58]. Additionally, one of the papers notes that student designers did not recognize virtual objects as prototypes [51], which may affect how these designers use virtual objects to elicit feedback and to advance their designs.

For most designs we identified in this study, designers interacted with CAD prototypes on a computer screen. However, there were several examples of more multisensory interactions (e.g., haptic feedback, virtual reality, projecting CAD models on interactive whiteboards and annotating on the CAD model). These modes of interaction may engage more of the designer's senses, which could ultimately result in more creative and paradigmatic shifts in thinking about a design [22, 66, 67] and could reduce some perceived limitations of virtual prototypes, especially for use early in the design process.

4.4 Implications

Researchers have noted a generational shift in the acceptance of CAD, especially early in the design process [7] and increased use and acceptance of simulations and virtual prototyping [68]. Considering disruptions to common work modalities caused by the COVID-19 pandemic, use of virtual prototypes is especially relevant. CAD software that allows for collaboration and cloud-based storage (e.g., OnShape, Fusion 360) have become increasingly popular and industry practitioners see potential for remote collaboration with virtual prototyping with new cloud-based CAD tools [68]. In our retrospective literature review, we did not identify collaborative or remote usage of CAD, beyond designers sharing CAD models with remote stakeholders. We expect that as simultaneous editing and real-time collaboration capabilities of CAD software improve, the use and effectiveness of virtual prototypes could grow exponentially. Collaborative CAD packages could enable stakeholders to directly edit a 3D model in real-time. Increasing capability of simulation software and virtual reality may also increase usage of virtual prototypes.

We see a growing role for virtual prototyping in tandem with physical prototypes, both within the classroom and in industry. Virtual prototypes could be used to explore more of the design space that would be infeasible to explore with physical prototyping. Techniques such as generative design and design automation could help designers generate a broad range of CAD models to use as design stimuli. As research continues to explore the effectiveness of virtual prototypes for different purposes and as design software continues to advance, guidance for students and design practitioners about when to use virtual or physical prototyping (e.g., Ulrich and Eppinger [64] and others [5, 6, 16]) should be updated.

5. Conclusion

In this study, we summarized common uses of CAD as a prototyping method and highlighted findings regarding the effectiveness of CAD as a prototyping method in various stages of the design process. By coding of prototyping usage using a prototyping ontology, we identified three emergent categories of virtual prototypes: exploratory, technical, and polished communication prototypes. We found that virtual prototyping was most used in the operational phase to explore technical aspects of a design, but also identified emerging use of exploratory CAD models in the mock-up phase. While CAD models were frequently used to explore technical implementation, designers also utilized them to explore other aspects such as appearance and role/context. We found more frequent use of exploratory virtual prototypes by design practitioners compared with students, indicating virtual prototyping practices may vary with skill or experience level. Results indicate that CAD models have broad use, but more work is needed to understand how virtual prototypes can be used effectively, especially early in the design process.

References

1. B. Moggridge, *Designing Interactions*, MIT Press, Cambridge, MA, USA, 18 October 2006.
2. Y.-K. Lim, E. Stolterman and J. Tenenberg, The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas, *ACM Trans. Comput.-Hum. Interact.*, **15**(2), pp. 7:1–7:27, 7 July 2008.
3. M. Buchenau and J. F. Suri, Experience prototyping, *Proc. 3rd Conf. Des. Interact. Syst. Process. Pract. Methods Tech.*, Association for Computing Machinery, New York, NY, USA, 1 August 2000: pp. 424–433.
4. K. Dorst and N. Cross, Creativity in the design process: co-evolution of problem–solution, *Des. Stud.*, **22**(5), pp. 425–437, 1 September 2001.
5. B. Camburn, V. Viswanathan, J. Linsey, D. Anderson, D. Jensen, R. Crawford, K. Otto and K. Wood, Design prototyping methods: state of the art in strategies, techniques, and guidelines, *Des. Sci.*, **3**, pp. e13, 2017.
6. E. Christie, D. Jensen, R. Buckley, D. Menefee, K. Ziegler, K. Wood and R. Crawford, Prototyping Strategies: Literature Review and Identification of Critical Variables, *2012 ASEE Annu. Conf. Expo. Proc.*, ASEE Conferences, San Antonio, Texas, June 2012, pp. 25.1091.1–25.1091.22.
7. A. Nourimand and A. Olechowski, Prominence of Conceptual Design with Computer-Aided Design Tools for Junior and Senior Product Designers, *2020 ASEE Virtual Annu. Conf. Content Access Proc.*, ASEE Conferences, Virtual On line, p. 35101, June 2020
8. M. Carfagni, L. Fiorineschi, R. Furferi, L. Governi and F. Rotini, Usefulness of prototypes in conceptual design: students' view, *Int. J. Interact. Des. Manuf. IJIDeM*, **14**(4), pp. 1305–1319, 1 December 2020.
9. R. Mahtani, K. Umstead and C. Gill, Efficacious Prototyping For Early Stage Industrial Design: Understanding What Matters in Prototyping to Make Prototyping Matter More, *95 Proc. 21st Int. Conf. Eng. Prod. Des. Educ. EPDE 2019 Univ. Strathclyde Glasg. 12th –13th Sept. 2019*, The Design Society, 13 September 2019.
10. G. G. Wang, Definition and Review of Virtual Prototyping, *J. Comput. Inf. Sci. Eng.*, **2**(3), pp. 232–236, 2 January 2003.
11. M. Deininger, S. Daly, K. Sienko, J. Lee, S. Obed and E. Effah Kaufmann, Does prototype format influence stakeholder design input?, *87–4 Proc. 21st Int. Conf. Eng. Des. ICED 17 Vol 4 Des. Methods Tools Vanc. Can. 21-25082017*, pp. 553–562, 2017.
12. B. Camburn, B. Dunlap, T. Gurjar, C. Hamon, M. Green, D. Jensen, R. Crawford, K. Otto and K. Wood, A Systematic Method for Design Prototyping, *J. Mech. Des.*, **137**(8), pp. 081102, 1 August 2015.
13. E. Tiong, O. Seow, K. Teo, A. Silva, K. L. Wood, D. D. Jensen and M. C. Yang, The Economies and Dimensionality of Prototyping: Value, Time, Cost and Fidelity, *Vol. 7 30th Int. Conf. Des. Theory Methodol.*, American Society of Mechanical Engineers, Quebec City, Quebec, Canada, 26 August 2018: p. V007T06A045.
14. C. W. Elverum and T. Welo, The Role of Early Prototypes in Concept Development: Insights from the Automotive Industry, *Procedia CIRP*, **21**, pp. 491–496, 2014.
15. V. Viswanathan and J. Linsey, Build to Learn: Effective Strategies to Train Tomorrow's Designers, *2012 ASEE Annu. Conf. Expo. Proc.*, ASEE Conferences, San Antonio, Texas, June 2012: p. 25.273.1–25.273.14.
16. C. Hamon, M. Green, B. Dunlap, B. Camburn, R. Crawford and D. Jensen, Virtual or Physical Prototypes? Development and Testing of a Prototyping Planning Tool, *2014 ASEE Annu. Conf. Expo. Proc.*, ASEE Conferences, Indianapolis, Indiana, June 2014, pp. 24.1361.1–24.1361.16.
17. M. Deininger, S. R. Daly, J. C. Lee, C. M. Seifert and K. H. Sienko, Prototyping for context: exploring stakeholder feedback based on prototype type, stakeholder group and question type, *Res. Eng. Des.*, **30**(4), pp. 453–471, 1 October 2019.
18. S. Junk and D. Spannbauer, Use of Cloud-Based Computer Aided Design Software in Design Education, *2018 17th Int. Conf. Inf. Technol. Based High. Educ. Train. ITHET*, IEEE, Olhao, pp. 1–6, April 2018
19. S. Lund, A. Madgavkar, J. Manyika and S. Smit, What's next for remote work: An analysis of 2,000 tasks, 800 jobs, and nine countries, *McKinsey Glob. Inst.*, 23 November 2020.
20. P. G. Maropoulos and D. Ceglarek, Design verification and validation in product lifecycle, *CIRP Ann.*, **59**(2), pp. 740–759, 2010.
21. B. F. Robertson and D. F. Radcliffe, Impact of CAD tools on creative problem solving in engineering design, *Comput.-Aided Des.*, **41**(3), pp. 136–146, March 2009.
22. J. Edelman and R. Currano, Re-representation: Affordances of Shared Models in Team-Based Design, C. Meinel, L. Leifer, H. Plattner (Eds.), *Des. Think. Understand – Improve – Apply*, Springer, Berlin, Heidelberg, pp. 61–79, 2011.

23. B. Macomber and M. Yang, The Role of Sketch Finish and Style in User Responses to Early Stage Design Concepts, American Society of Mechanical Engineers Digital Collection, pp. 567–576, 12 June 2012
24. M. Deininger, S. R. Daly, K. H. Sienko, J. C. Lee and E. E. Kaufmann, Investigating prototyping approaches of Ghanaian novice designers, *Des. Sci.*, **5**, p. e6, 2019.
25. M. E. Wiklund, C. Thurrott and J. S. Dumas, Does the Fidelity of Software Prototypes Affect the Perception of Usability?, *Proc. Hum. Factors Soc. Annu. Meet.*, **36**(4), pp. 399–403, October 1992.
26. E. Brandt, How Tangible Mock-Ups Support Design Collaboration, *Knowl. Technol. Policy*, **20**(3), pp. 179–192, 18 October 2007.
27. D. J. De Beer, R. I. Campbell, M. Truscott, L. J. Barnard and G. J. Booysen, Client-centred design evolution via functional prototyping, *Int. J. Prod. Dev.*, **8**(1), p. 22, 2009.
28. J. Sauer and A. Sonderegger, The influence of prototype fidelity and aesthetics of design in usability tests: Effects on user behaviour, subjective evaluation and emotion, *Appl. Ergon.*, **40**(4), pp. 670–677, July 2009.
29. J. Rudd, K. Stern and S. Isensee, Low vs. high-fidelity prototyping debate, *Interactions*, **3**(1), pp. 76–85, 2 January 1996.
30. M. Walker, L. Takayama and J. A. Landay, High-Fidelity or Low-Fidelity, Paper or Computer? Choosing Attributes when Testing Web Prototypes, *Proc. Hum. Factors Ergon. Soc. Annu. Meet.*, **46**(5), pp. 661–665, September 2002.
31. H. Arksey and L. O'Malley, Scoping studies: towards a methodological framework, *Int. J. Soc. Res. Methodol.*, **8**(1), pp. 19–32, 1 February 2005.
32. D. Moher, A. Liberati, J. Tetzlaff and D. G. Altman, and The PRISMA Group, Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement, *PLoS Med.*, **6**(7), pp. e1000097, 21 July 2009.
33. C. Roschuni, J. Kramer, Q. Zhang, L. Zakskorn and A. Agogino, Design Talking: An Ontology of Design Methods to Support a Common Language of Design, Milan, Italy, pp. 285–294, 2015.
34. B. Hartmann, Gaining Design Insight Through Interaction Prototyping Tools, PhD, Stanford University, September 2009.
35. C. Roschuni, A. M. Agogino and S. L. Beckman, The DesignExchange: Supporting the design community of practice, *68–8 Proc. 18th Int. Conf. Eng. Des. ICED 11 Impacting Soc. Eng. Des. Vol 8 Des. Educ. LyngbyCopenhagen Den. 15-19082011*, pp. 255–264, 2011.
36. theDesignExchange, https://www.thedesignexchange.org/, Accessed 27 September 2021.
37. C. N. Roschuni, *Communicating Design Research Effectively*, UC Berkeley, 2012.
38. B. Hartmann, *Gaining design insight through interaction prototyping tools*, Stanford University, 2009.
39. A. Michaelraj, *Taxonomy of physical prototypes: structure and validation*, Master's, Clemson University, 1 May 2009.
40. M. J. Coulentianos, I. Rodriguez-Calero, S. R. Daly and K. H. Sienko, Stakeholder Engagement With Prototypes During Front-End Medical Device Design: Who Is Engaged With What Prototype?, *2020 Des. Med. Devices Conf.*, American Society of Mechanical Engineers, Minneapolis, Minnesota, USA, p. V001T08A001, 6 April 2020
41. M. Carulli, M. Bordegoni and U. Cugini, An approach for capturing the Voice of the Customer based on Virtual Prototyping, *J. Intell. Manuf.*, **24**(5), pp. 887–903, October 2013.
42. E. Dimitrokali, J. Mackrill, G. Jones, Y. Ramachers and R. Cain, Moving Away from flat Solar Panels to PVtrees: Exploring Ideas and People's Perceptions, *Procedia Eng.*, **118**, pp. 1208–1216, 2015.
43. A. Gallimore and W. M. Cheung, Effects of environmental impact based on alternative materials and process selection in automotive component design, *J. Ind. Prod. Eng.*, **33**(5), pp. 321–338, 3 July 2016.
44. S. Kanai, T. Higuchi and Y. Kikuta, Applying User Interface-Operable 3D Digital Prototypes to Human-Centered Design of Information Appliances, *Vol. 3 28th Comput. Inf. Eng. Conf. Parts B*, ASMEDC, Brooklyn, New York, USA, 1 January 2008: pp. 867–876.
45. M. J. Coulentianos, I. Rodriguez-Calero, S. R. Daly, and K. H. Sienko, Global health front-end medical device design: The use of prototypes to engage stakeholders, *Dev. Eng.*, **5**, pp. 100055, 2020.
46. E. Rovalo and J. McCardle, Performance Based Abstraction of Biomimicry Design Principles using Prototyping, *Designs*, **3**(3), p. 38, 16 July 2019.
47. N. Crilly and R. Moroşanu Firth, Creativity and fixation in the real world: Three case studies of invention, design and innovation, *Des. Stud.*, **64**, pp. 169–212, September 2019.
48. J. Stevens, Design as communication in microstrategy: Strategic sensemaking and sensegiving mediated through designed artifacts, *Artif. Intell. Eng. Des. Anal. Manuf.*, **27**(2), pp. 133–142, May 2013.
49. A. Paudel, Realizing Proof of Concept in Machine Design with 3D Printing, *2015 ASEE Annu. Conf. Expo. Proc.*, ASEE Conferences, Seattle, Washington, June 2015, p. 26.1309.1–26.1309.13.
50. J. Rodriguez, A. Choudhury and L. Rodriguez, Applying Design Process To Redesign A Personal Care Product – Integration Of Technical And Marketing Issues, *2010 Annu. Conf. Expo. Proc.*, ASEE Conferences, Louisville, Kentucky, pp. 15.186.1–15.186.9, June 2010
51. M. Deininger, S. R. Daly, K. H. Sienko and J. C. Lee, Novice designers' use of prototypes in engineering design, *Des. Stud.*, **51**, pp. 25–65, July 2017.
52. K. Andersson, Impact of Model-Based Design in Engineering Design Education, *Vol. 1 15th Int. Conf. Adv. Veh. Technol. 10th Int. Conf. Des. Educ. 7th Int. Conf. Micro- Nanosyst.*, American Society of Mechanical Engineers, Portland, Oregon, USA, p. V001T04A022, 4 August 2013
53. R. Bailey, Using 3D Printing and Physical Testing to Make Finite-Element Analysis More Real in a Computer-Aided Simulation and Design Course, *2015 ASEE Annu. Conf. Expo. Proc.*, ASEE Conferences, Seattle, Washington, pp. 26.1646.1–26.1646.15, June 2015.
54. D. Holland, C. Walsh and G. Bennett, An assessment of student needs in project-based mechanical design courses, *2013 ASEE Annu. Conf. Expo. Proc.*, ASEE Conferences, Atlanta, Georgia, pp. 23.153.1–23.153.11, June 2013.
55. W. Howard, R. Williams and S. Gurganus, Using Additive Manufacturing and Finite Element Analysis in a Design-Analyze-Build-Test Project, *2015 ASEE Annu. Conf. Expo. Proc.*, ASEE Conferences, Seattle, Washington, pp. 26.1653.1–26.1653.20, June 2015.
56. D. Schmueser, J. Brooks, R. Prucka and P. Pisu, Innovative Graduate Engineering Education Implemented with Project-focused Learning: A Case Study – The Clemson University Deep Orange 3 Vehicle Prototype Program, *2018 ASEE Annu. Conf. Expo. Proc.*, ASEE Conferences, Salt Lake City, Utah, p. 30668, June 2018.

57. M. N. Shergadwala, J. H. Panchal and K. Ramani, Students' Decision-Making in a Product Design Process: An Observational Study, *Vol. 3 21st Int. Conf. Adv. Veh. Technol. 16th Int. Conf. Des. Educ.*, American Society of Mechanical Engineers, Anaheim, California, USA, p. V003T04A016, 18 August 2019.
58. J. Will and D. Tougaw, An Innovative Multidisciplinary Capstone Design Course Sequence, *2003 Annu. Conf. Proc.*, ASEE Conferences, Nashville, Tennessee, p. 8.201.1-8.201.8, June 2003.
59. L. Vanasupa, K. C. Chen, J. Stolk, R. Savage, T. Harding, B. London and W. Hughes, Converting Traditional Materials Labs to Project-based Learning Experiences: Aiding students' Development of Higher-order Cognitive Skills, *MRS Proc.*, **1046**, pp. 1046-W03-03, 2007.
60. S. Srinivasan, Z. F. Li, Y. L. Han and B. A. Camburn, The Impact of Prototyping Strategies on Crowdfunding Success, *Vol. 8 32nd Int. Conf. Des. Theory Methodol. DTM*, American Society of Mechanical Engineers, Virtual, Online, p. V008T08A045, 17 August 2020
61. T. A. Björklund, *Rough prototyping as an effective and efficient means of conveying intent*, Aalborg, Denmark, 2008.
62. S. Chou and J. Austin-Breneman, Prototyping methods and constraints for small-to-medium sized enterprises in East Africa, *Dev. Eng.*, **3**, pp. 117–124, 2018.
63. V. Viswanathan and J. Linsey, *Design Fixation in Physical Modeling: An Investigation on the Role of Sunk Cost*, American Society of Mechanical Engineers Digital Collection, pp. 11–130, 12 June 2012
64. K. T. Ulrich and S. D. Eppinger, *Product design and development*, 5th ed, McGraw-Hill/Irwin, New York, 2012.
65. M. Carfagni, L. Fiorineschi, R. Furferi, L. Governi and F. Rotini, Usefulness of prototypes in conceptual design: students' view, *Int. J. Interact. Des. Manuf.*, **14**(4), pp. 1305–1319, 1 December 2020.
66. J. P. A. von Thienen, W. J. Clancey and C. Meinel, Theoretical Foundations of Design Thinking. Part III: Robert H. McKim's Visual Thinking Theories, *Des. Think. Res.*, Springer International Publishing, 2021.
67. R. H. McKim, *Experiences in Visual Thinking*, Brooks/Cole Publishing Company, Belmont, California, 1972.
68. C. Arndt Hansen and A. G. Özkil, "You Cannot Test It Before It Is Verified. When It Is Verified You Cannot Change It": Prototyping Challenges in Industry, *Vol. 8 32nd Int. Conf. Des. Theory Methodol. DTM*, American Society of Mechanical Engineers, Virtual, Online, p. V008T08A043, 17 August 2020

Hannah D. Budinoff is an Assistant Professor of Systems and Industrial Engineering at the University of Arizona. Her research interests include additive manufacturing, geometric manufacturability analysis, design for manufacturing, and engineering education. She completed her PhD in 2019 in mechanical engineering at the University of California, Berkeley, where she was awarded an NSF Graduate Research Fellowship. She is the recipient of a 2021 American Society for Engineering Education Educational Research and Methods Division Apprentice Faculty Grant.

Julia Kramer, MPH, PhD, is a Research Fellow in the Department of Mechanical Engineering at the University of Michigan. She received her BS in mechanical engineering from the University of Michigan and completed her PhD in mechanical engineering and her master's in public health at the University of California, Berkeley. Her research focuses on engineering approaches to support social justice and promote equity, particularly through the development and investigation of products, services, and systems that improve access to health care in low-resource settings. She also studies and teaches human-centered design methods that support diverse participation in equity-oriented work.