The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #41580

A Weighted Design Matrix Approach for Informing Digital vs. Physical Prototyping Options

Dr. Daniel D. Jensen, Westmont College

Dr. Dan Jensen is the Westmont Endowed Professor of Engineering and the Director of the Engineering program at Westmont College. He was a Professor of Engineering Mechanics at the U.S. Air Force Academy for 21 years. He received his B.S. (Mechanical Engineering), M.S. (Applied Mechanics) and Ph.D. (Aerospace Engineering Science) from the University of Colorado at Boulder. He is a Fellow at the International Design Center (Co-located with Singapore University of Technology and Design and MIT). Dr Jensen has authored over 140 refereed papers and has been awarded (with collaborators) approximately $4.5 million of consulting and research grants.

Elijah Cicileo
Jonah Kai Swanson
Gregory Reich

©American Society for Engineering Education, 2024

A Weighted Design Matrix Approach for Informing Digital vs. Physical Prototyping Options

Jensen, D.[1], Reich, G.[2], Cicileo, E.[1], Swanson, J.[1], Loh, T.[1],Wozniak, J.[1], Jensen, L.[3]
[1] Engineering - Westmont College, Santa Barbara, CA
[2] Air Force Research Laboratory, Wright Patterson Air Force Base, Dayton, OH
[3] Creo Consulting, Santa Barbara, CA

Abstract

Prototyping, a critical part of an engineering design process, can be used in a wide variety of manners to enhance that process. They can be used early in the design process for initial stakeholder feedback and in the middle of a design process for increasing ideation innovation. Further into the design process they may be used to begin to evaluate meeting design requirements and checking interface requirements. In many design processes, they are used repeatedly for stakeholder feedback as the design concepts mature. In later stages of design, they might be used to evaluate manufacturing processes or improve marketing strategies. Strategies for prototyping that include numerous variables that describe the details of how prototyping will take place can assist the designers to make the prototyping process more efficient and effective. One particular part of a prototyping strategy is determining if digital or physical prototypes (or both) will be used. This research reports on a detailed method for informing designers in physical vs. digital prototyping options. Designers from across the engineering industry were interviewed giving the first insights into the method. The method involves use of a weighted design matrix (WDM) that correlates digital and physical prototyping options with cost, schedule and performance variables. Inclinations toward digital or physical prototyping are then weighted by considering the flexibility of cost, schedule and performance parameters as well as the resources and capabilities of the designers. The WDM method was used to successfully inform digital vs, physical prototyping decisions for three different product designs. Feedback from engineering designers on the potential use of the WDM method for future designs was very positive.

1.0 Introduction

Prototyping is a key aspect of engineering design. A prototyping strategy describes the process and methods used to accomplish the prototyping process. Many variables comprise a prototyping strategy including how many different concepts will be prototyped in parallel, will the prototypes be scaled, what manufacturing techniques will be used to create the prototypes, how many iterations in a concept will be needed, what design requirements are being evaluated by each model, will subsystems be prototyped separately, and will digital or physical prototypes be used (or both). Our previous research indicates that engineering design teams often follow the same prototyping strategy used in their previous design efforts. However, research also shows that this is not always the best decision. Careful consideration of the prototyping strategy, based on specific characteristics of a design project, can lead to significant benefits for the outcome of the design.

This current work provides a method for informing the engineering design team regarding decisions on when to use digital and/or physical prototypes. Physical prototyping, in this context, refers to any physical embodiment of the product or system. Digital prototypes in the current context are any digital representation of the product or system including CAD and/or any digital analysis or simulations. The decision regarding use of physical and/or digital prototyping needs to be evaluated not only for the entire product or system being designed, but often for each subsystem. With the increasing use of additive manufacturing (3d printing) to create physical prototypes, combined with the ever-increasing capabilities and availability of digital prototyping capabilities, the decision of when to use digital vs. physical prototypes is an evolving target.

The development of the current strategy for evaluating decisions on digital vs. physical prototyping came as a result of an extensive interview process with numerous engineering design teams. These interviews were used to evaluate the ways that the design teams made prototyping decisions and then used this information to create a prototyping strategy or process. In this current work, a weighted design matrix (WDM) approach is used to inform the design team regarding digital/physical options. This is done for the entire product or system and also for key subsystems as can be seen in Figure 1 below which shows one part of the WDM.

The current work correlates aspects of cost, schedule, and performance with advantages for either digital or physical prototyping. The category of performance is divided into two subcategories of "performance best assessed by" and "model delights the stakeholder". This division will be described in more detail later in the paper. The core part of the matrix, as shown in Figure 1, contains this initial or CORE portion of the method. Numbers will be entered into the body of the matrix, in a process described below, resulting in bar graphs in the far-right columns of the matrix that provide a visual indication of inclinations toward either digital or physical prototyping.

A second or SUPPLEMENTAL part of the method, as can be seen in Figure 2, adds the aspect of flexibility of the cost, schedule, and performance variables as a refinement of the matrix output. This idea of using flexibility of cost, schedule, and performance was originally developed by Moe et. al [4]. Finally, aspects of the organization's capabilities in terms of resources and team skills specifically associated with either digital or physical prototyping are incorporated. The incorporation of capabilities and resources came from our interview process. All these factors can be seen in the second or supplemental portion of the WDM as seen in Figure 2 below. Numbers from the CORE part of the WDM (Figure 1) are combined with entries in the SUPPLEMENTAL body of the matrix (Figure 2) in a process described below. This again results in bar graphs in the far-right columns that provide a visual indication of inclinations toward either digital or physical prototyping.

0-3 Scale		List of design requirements that are critical to the function of the Sub-Subsystem	Programmatic Factors				Stakeholder/Performance Factors				Bar graph showing which direction Cost, Schedule, and Performance lean	
SubSystems	**Sub-Subsystems**	**Critical DRs**	**Low Cost**		**Short Schedule**		**Performance (DR) Best Assessed by**		**Model Delights Stakeholder**		**Cost, Schedule, Performance Bar Graph**	
			Digital	**Physical**	**Digital**	**Physical**	**Digital**	**Physical**	**Digital**	**Physical**	**Digital**	**Physical**
Car	Car body	3D-printable, easy assembly, self thread screws, aesthetic/fun									#DIV/0!	#DIV/0!
	Motors	good torque/speed in 1:1 Config, easily mounted									#DIV/0!	#DIV/0!
	Wheels	good diameter to pair with motor torque and speed, grip on any surface									#DIV/0!	#DIV/0!
Controller	Controller/grip	comfortable in hand, mounting points for electronics, visually appealing									#DIV/0!	#DIV/0!
	Circuitry / Electronics	simultaneous independent montor control, 9V batt, easy for kids to wire - breadboard wiring									#DIV/0!	#DIV/0!

Figure 1 – Initial CORE Section of the Weighted Design Matrix for Digital vs. Physical Prototyping Decisions

Flexibility Factors - On a scale of 1-10 rate how flexible each of the following parameters are. 1 is very flexible and 10 is very rigid			Team/Company Factors				Bar graph showing which direction Cost, Schedule, and Performance lean		
Cost	**Schedule**	**Performance**	**Existing Resources to Prototype**		**Existing Team Skills to Prototype**		**Cost, Schedule, Performance Weighted Bar Graph**		**Key**
			Digital	**Physical**	**Digital**	**Physical**	**Digital**	**Physical**	
							#DIV/0! #DIV/0!	#DIV/0! #DIV/0!	Original Weighted Original Weighted Original Weighted Comfort Zone
							#DIV/0! #DIV/0!	#DIV/0! #DIV/0!	Original Weighted Original Weighted Original Weighted Comfort Zone
							#DIV/0! #DIV/0!	#DIV/0! #DIV/0!	Original Weighted Original Weighted Original Weighted Comfort Zone
							#DIV/0! #DIV/0!	#DIV/0! #DIV/0!	Original Weighted Original Weighted Original Weighted Comfort Zone
							#DIV/0! #DIV/0!	#DIV/0! #DIV/0!	Original Weighted Original Weighted Original Weighted

Figure 2 – Second SUPPLEMENTAL Section of the Weighted Design Matrix for Digital vs. Physical Prototyping Decisions

2.0 Review of the literature

As a crucial and often primary part of the engineering design process, prototyping both in physical and digital forms and the methodologies for determining aspects of the prototyping process comprise a very extensive literature. For this reason, we will focus the scope of this background section on the literature dealing specifically with salient differences between physical and digital forms of prototyping, as well as covering the broad strokes of previously formulated methodologies for guiding the prototyping process. According to RAND, 'Although the term "prototyping" captures a wide range of activities, all prototyping has several elements in common, including the design and fabrication of one or more representative systems (hardware or software) for limited testing and demonstration prior to a production decision' [20].

Many questions arise during the prototyping process, such as, "Do simpler prototypes mean a more successful design? Does the amount of time spent on a project, both overall and on different activities over a project cycle, relate to design success? And does it matter when this time is spent?" [25]. Although prototyping efforts across industries, and even companies, can have degrees of cultural dependence [3,23], certain factors seem to inevitably arise to begin to answer these questions as the prototyping process progresses over a multitude of iterations [3,23]. Prototyping often comprises a large dedication of both time and budget in the initial stages of a product's design [1], and as such companies that have a clear decision-making strategy in that process gain a marked advantage over their competitors. For this reason, a multitude of taxonomic criteria sets have been developed, some more industry-specific and some with more universal applicability [5]. When considering the overall objectives of a prototyping strategy, Camburn et al [7,8,9] have done an extensive literature review of over 300 articles and weighted the importance of four emergent objectives from the literature, shown in Figure 3 below.

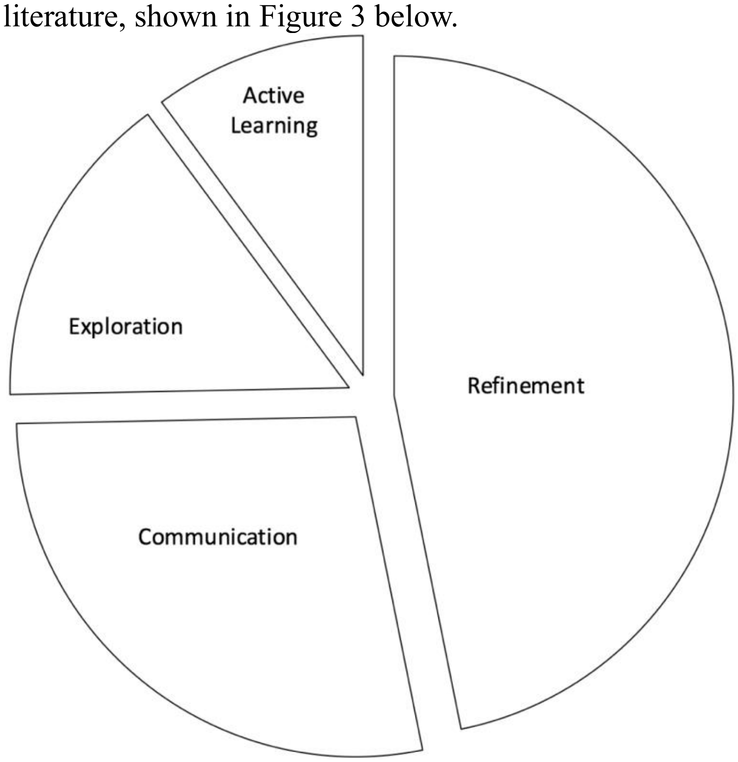

Figure 3 – Objectives of Prototyping [7,8]

Refinement, or the process of improving upon each iteration, was weighted in this study as the highest objective, with communication, exploration, and active learning being sequentially less weighted but still important goals of the prototyping process. The core objective then being gradual improvement, the questions quickly turn to the decisions that ought to be made for how a product can be made better, more economical, and add value to its consumers. An immediate lack of methodologies and strategies to account for the numerous variables has been recognized in many corporate design labs in the previous decades. While companies often invest in the fabrication of advanced prototypes, little attention is given to the strategic knowledge that ensures the prototypes create value in the design process. Similarly, formal teaching of strategic prototyping skills is usually not emphasized in the education of design engineers [12].

Prototyping often entails repeatedly trying ideas and getting feedback. A canonical prototyping iteration comprises four steps: envisioning possibilities, creating a prototype to embody a possibility, getting feedback about the prototype, and reevaluating constraints. However, time constraints often lead organizations and individuals to focus on realization rather than iteration [41]. Studies into strategies to prototype efficiently and effectively often have a specific focus such as rapid prototyping [2,17,22,34,39], planning [6,8,10], conceptualization [11,14,15,21,29] or how prototyping fits in the overall design process [5,9,16,18,22,24,27,30,33,35,36,37,40,41,44].

While several methods have been devised to bridge the gap between digital and physical prototyping in specific contexts [2,10,15,17] such as rapid prototyping, few efforts have been made to codify a method for the decision-making process between digital and physical prototypes at each stage of the design journey. In exploring the physical design space, several studies have confirmed that because many concepts in the ideation phase turn out to be unfeasible, rapid physical prototyping can help narrow down the solution space to assist designers in developing more feasible solutions [19,28,38], yet at the same time also confirm the 'Fixation Hypothesis', namely that once a physical prototype is developed, designers can tend toward becoming fixated on that narrow solution space and potentially miss out on creative solutions that may have presented themselves more abundantly while prototyping in the digital space [13,19,28].

Other efforts to understand the specific topics related to either digital or physical prototyping have also been explored [12,26,31,32,42,43]. While these researchers provide insight into different aspects of digital and physical prototyping, with the exception of Hammon [10], the goal is not to assist in the digital vs. physical decision. Hammon's work used a simple matrix approach which was focused on asking questions regarding variables such as accuracy and efficiency of digital and physical prototyping options. The focus of many of the other papers in this area is on the cognitive aspects associated with physical prototypes [19, 26, 28,32]. Of course, some of the previous work on prototyping strategies in general is applicable to this digital vs. physical question, but a systematic method, applicable across multiple product domains, to assist in this specific part of product development appears to be lacking.

3.0 Research questions and research process

3.1 Research Questions

The specific research questions that drives this work are stated below.

Research Question #1: Can a method be created that can inform engineering designers in their decisions regarding digital or physical prototyping options?

Research Question #2: Can utility of the method for informing designers regarding digital vs. physical prototyping be demonstrated?

3.2 Research Process

The process used to investigate this research question began by interviewing numerous engineering designers across multiple engineering domains. Approximately 12 different practicing engineers were interviewed regarding their use of prototyping in their work. We asked what sort of prototyping strategy they employed and what the goal of prototyping was in their case. We asked for details regarding how they determine if they will use digital or physical prototyping (or both). Initially, we thought we might be able to take this interview data and develop a set of heuristics to guide the virtual vs. physical decisions. This proved to be difficult mainly because the process was quite different depending on the nature of the design. As an example, one interview revealed that when designing logic circuits, this engineer exclusively used digital prototyping until the design was ready for small scale production. However, designers working on development of novel drone technology used a mixed approach as digital prototyping of some of the second order aerodynamic effects is quite time consuming. Our work interviewing engineering designers therefore led to a need to develop a method that relies on key aspects that are common across many different types of design efforts. Since cost, schedule, and performance are common across a large variety of product development work, these variables were chosen as core variables for our work.

Many of the engineers we interfaced with were using a user-centered design process. Aspects of design thinking and systems engineering that focused heavily on stakeholder co-creation were often seen to be key to the success of the product. In order to capture this focus in our method, we chose to split the performance aspect of the WDM into two parts: 1) Performance (Design Requirements) Best Assessed by and 2) Model Delights Stakeholder. This split allows differentiation between meeting a DR and delighting a stakeholder. Our interviews informed us that while not meeting a DR most often implies the stakeholder will not be delighted, the opposite is not necessarily true. There are important cases where a DR is met, but the design concept does not delight the stakeholder. This could be for example due to a stakeholder's sense of a latent need such as aesthetics or a perception of novelty of a design.

While understanding, and quantifying, the options of digital vs. physical options as they relate to cost, schedule, and performance was found to provide helpful insight into the prototyping process, we determined that other aspects of the design environment also needed to be accounted for. Many times, cost, schedule, and performance are either flexible or rigid. Moe's work describes how this can impact design strategy [4]. For this current work, if one of these three aspects is more rigid then other aspects, then it makes sense to weight that aspect more heavily. This is taken into account in the “supplemental factors” part of the WDM Method. Also, knowing the resources and skills of the design team might impact the decision on digital vs. physical. For example, even if considerations of cost, schedule and performance indicate that digital prototypes should be pursued, if the design team has no expertise in digital modeling, it becomes problematic to develop the digital models. Therefore, we integrate team resources and team skills into the supplemental sections of the WDM. Details will be shown below through an example.

4.0 Implementation of the weighted design matrix

Figure 4 - Remote Controlled Car Educational Kit

The Weighted Design Matrix, in its current embodiment, should be used after the ideation process when a final concept idea, or multiple ideas, have been chosen to pursue prototyping. The goal of the WDM is to help the designer or design team to understand the benefits and drawbacks of pursuing digital and/or physical prototypes in the initial prototyping phases. After using the WDM, the design team can expect to better understand the implications of prototyping physically or digitally for a concept, or subsystems of a concept. The explanation of its use will be aided by the example use of the WDM in a project for design and implementation of a STEM educational kit intended to teach STEM concepts to children in Ecuador. The education kit shown in the example is a remote controlled (RC) car powered through an Arduino and controlled with directional buttons on the controller as shown in Figure 4.

Core Factors												
0-3 Scale			Programmatic Factors				Stakeholder/Performance Factors				Bar graph showing which direction Cost, Schedule, and Performance lean	
Sub-Systems	Sub-Sub-systems	Critical Design Requirements	Low Cost		Short Schedule		Performance (DR) Best Assessed by		Model Delights Stakeholder		Cost, Schedule, Performance Bar Graph	
			D	P	D	P	D	P	D	P	D	P
Car	Car body	3D-printable, easy assembly, self thread screws, aesthetic/fun	3	0	3	1	3	1	3	2		
	Motors	good torque/speed in 1:1 Config, easily mounted	1	3	1	2	1	3	0	3		
	Wheels	good diameter to pair with motor torque and speed, grip on any surface	2	1	2	3	0	3	1	3		
Controller	Controller/ grip	comfortable in hand, mounting points for electronics, visually appealing	2	3	2	1	1	3	1	3		
	Circuitry / Electronics	simultaneous independent montor control, 9V batt, easy for kids to wire - breadboard wiring	3	1	3	2	2	3	1	3		

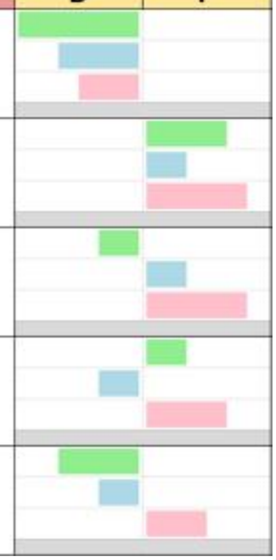

Figure 5 - Remote Controlled Car Weighted Design Matrix - CORE

As can be seen in Figure 5, each row of the WDM is a sub-subsystem representing an individual portion of a subsystem for the RC car design. However, this is flexible, as a team may choose to only apply the WDM on the subsystem level. The subsystems are listed in the first column and the sub-subsystems are listed in the second column, grouped with their parent subsystem. The design team begins by determining the project's subsystems, and sub-subsystems. In the example, the team chose to go all the way to the sub-subsystem level; the subsystems being the car and the controller and the sub-subsystems being the car body, the motors, the wheels, the controller body/grip, and the circuitry/electronics.

Each row of the third column of Figure 5 houses a list of the critical design requirements (DRs) for each sub-subsystem. As the team determines the subsystems and sub-subsystems, they should also identify the critical design requirements based on stakeholder needs and requirements of the sub-subsystems and the overarching concept and list them in the third column.

Note that the prototyping factors of cost schedule and performance are each given a column for D=digital and P=physical. Also, note that, as described above, the performance factor is broken into two parts, one for "Performance (DR) Best Assessed By" and the other for "Model Delights Stakeholder". These digital and physical columns for each separate factor are where each sub-

subsystem is rated on a scale of 0-3 on how well that form of prototype would accommodate the given factor. For example, a 0 in the digital column would mean a digital prototype would not accommodate that factor for the given sub-subsystem, and a 3 would mean it would excel as a digital prototype with respect to the given factor.

		Supplemental Factors							
0-3 Scale		Flexibility Factors - 1 = flexible, 10 = rigid			Team/Company Factors				Bar graph showing which direction Cost, Schedule, and Performance lean
Sub-Systems	Sub-Sub-systems	Cost	Schedule	Performance	Existing Resources to Prototype		Existing Team Skills to Prototype		Cost, Schedule, Performance Weighted Bar Graph (D / P); Key
					D	P	D	P	
Car	Car body	7	10	10	2	3	3	1	
	Motors	2	6	3	1	3	3	1	
	Wheels	3	9	5	2	3	3	3	
Controller	Controller/ grip	10	3	6	2	1	3	1	
	Circuitry / Electronics	7	6	9	2	3	3	1	

Figure 6 - Remote Controlled Car Weighted Design Matrix - SUPPLEMENTAL

As mentioned previously, the prototyping factors are split into core and supplemental factors. This distinction is made because the core factors (Figure 5) are based on the industry standard benchmark variables of cost, schedule, and performance which are left unweighted in this core section of the WDM to allow the raw data to be assessed. The supplemental factors (Figure 6) include a section for the team to rate their flexibility in cost, schedule, and performance for each sub-subsystem. This rating is then used to weight the data from the core factors to better represent the specific needs of the design team. A final pair of prototyping factors, designated "Team/Company Factors" in the Figure 6, allow the team to consider how they are best trained and equipped to prototype.

Bar graphs visually indicate the preference for digital vs. physical based on both the core (Figure 5) and supplemental (Figure 6) rankings. The first of the core factors are the programmatic factors: *Low Cost (green)* and *Short Schedule (blue)*. Next are the DR performance and stakeholder delight factors: *Performance (DR) Best Assessed by* and *Model Delights Stakeholder (red).*

In terms of specific implementation of the WDM, following the completion of the first three columns in Figure 5, the design team should discuss and score the core factors – filling in the "D" and "P" columns for the cost, schedule and 2 performance factors for each sub-subsystem. The bar charts in Figure 5 are created automatically through coding of the Google sheet. A key benefit of using the WDM is the space that it affords for discussion and debate over how to score each prototyping factor. This deliberation can lead to significant insights into how to proceed in prototyping. While the WDM provides actual scoring for digital and physical alternatives, it may be advisable to do both digital and physical prototyping or to split depending on the subsystem. The WDM should be seen as informing the decision process, not mandating either digital or physical options.

After the design team or designer has rated a given sub-subsystem in each of the core factors a color-coded bar graph is automatically generated representing how the sub-subsystem is biased in terms of its predisposition towards digital or physical prototyping. The bar graphs are generated through scripts written for the Google sheet. Each of the three core factors, with the two stakeholder/performance factors being combined, are represented by a bar. A bar on the left side, represents a bias towards digital prototyping and a bar on the right represents a physical prototyping bias. The side that the bar is graphed on, and the length of the bar are determined by the difference between the digital and physical rating for each of the design factors, with the two stakeholder/performance factors being averaged.

Following development of the core factor portion of the WDM, the supplemental factors beginning with the flexibility factors for cost, schedule, and performance are addressed (Figure 6). These supplemental factors provide additional information that design teams have found assist in interpreting the output from the core factors in figure 5. Here the design team rates their flexibility in each category on a scale of 1-10. With a 1 being very flexible and a 10 being very rigid. The team then scores two Team/Company Factors: *Existing Resources to Prototype* and *Existing Team Skills to Prototype.* Each of these is again split into digital and physical columns with a 0-3 scale. After the team has filled out the supplemental factors a new set of bar graphs is automatically generated. The newly generated bars utilize the Cost, Schedule, and Performance flexibility rating to weight the length of the bars. These bars (graphed in darker colors below the originals) have the potential to be twice the length of their original. A bar that is twice the length of the original corresponds to a flexibility rating of 10 meaning that category is very rigid, and the bias needs to be more significantly considered. For example, in the RC car sub-subsystem of the controller grip the team was not very flexible on the cost with a score of 10, but they were flexible on the schedule with a score of 3. Therefore, in the graph the darker green cost bar doubled in length and the darker blue schedule bar shrunk, showing the rigidity of the team on cost and the flexibility of the team as far as the schedule variable of this sub-subsystem (Figure 6).

The Team/Company factors in Figure 6 are used to generate an additional set of bars graphed in both the digital and physical columns and representing the comfort/capability zone of the design team or company for digitally or physically prototyping the product. These are the black bars that are the lowest bars for each sub-subsystem. If a bar for cost, schedule, or performance shows a bias towards digital or physical prototyping, but that bar is shorter than the comfort/capability bar the team should consider investing in improving the capability (resources or team skills) of the team/company or pursuing the opposite prototyping strategy. The RC car example shown demonstrates a case in which none of the prototyping biases (green, blue and red bars) fell outside of the team's comfort and capability zone (black bars).

5.0 Evaluation of the impact of using the weighted design matrix

To assess the method, the WDM approach is applied to three engineering design projects. Two of these were art of a 1 semester design class taken during the junior year. The third design project was a personal project a student was working on. The first junior design project is the design of a remote-controlled (RC) car (previewed above) and the second junior design project is a Heli-Launcher. Both of these designs were designed to be used as part of a STEM educational experience for children in developing countries. For these first two projects, the WDM method was used retroactively, after the design was finished, as described below. The third project was the design of a game controller as a personal student project. For this project, the WDM methods was used early in the design process an aided in the development of the prototyping process.

The Heli-Launcher and the RC car designs were completed BEFORE the WDM method was developed, so their use as evaluation design projects for the WDM method is done retroactively. Specifically, because we already knew how these two design teams did the prototyping, we could evaluate the output of the WDM and indicate if the insight gained from the WDM aligned with the prototyping process that was used, or if it did not. This is obviously not the intended manner for use of the WDM method. The purpose of this retroactive process is therefore evaluation of the WDM method, not the intended use of assisting the design team in creation of their prototyping strategy. This retroactive use was done, in part, because the engineers who created those two designs (Heli- Launcher and RC car) were also part of the team working on the WDM research. This gave them the required knowledge of both the WDM method and of the two product designs. Results from this retroactive application of the WDM method to the two designs could be that the path for prototyping suggested by the WDM was followed, or that it was not followed. This outcome can be evaluated for each sub-subsystem in each design. If the prototyping strategy (i.e. digital or physical preference) suggested by the WDM was followed, then the evaluation is a reflection on whether that appeared to be a good decision or not. If the WDM's suggestion for a sub-subsystem was not followed, then the team asks if they believe, in retrospect, that it would have been helpful to have implemented the prototyping path suggested by the WDM.

For each project, as described above, variables of cost, schedule, and performance are used as evaluation criteria mapped against digital or physical prototyping impact. In general, the design teams found the method relatively easy to understand and use. The CORE results of the implementation of the WDM are a set of suggestions for digital vs. physical prototyping options for both individual subsystems and for the entire product/system. This is followed by more nuanced results that take into account the flexibility of the cost, schedule and performance variables and also the resources and skill set of the designers in the SUPPLEMENTAL part of the WDM. The design teams found the numerically based suggestions and associated bar graphs to be very helpful in interpreting their prototyping strategy.

5.1 RC car design as an evaluation tool

For the RC car design, the system components can be seen in Figure 4 and the WDM can be seen in previous Figures 5 and 6. The educational kit included about 20 individual parts which the children assembled using a set of detailed, but simple, instructions. Younger children assembled shafts and wheels onto the car's body while older children worked to program the Arduino that controlled the system. Each team of 3-6 children was successful in assembling a functional RC car. The children learned STEM principles such as how gears trade rotational velocity for power and some very basic Arduino programming skills. The completed RC cars were used to run a timed obstacle course, which the children found very exciting.

The Figure 5 shows preferences for the car body to be prototyped digitally and the motor system to be explored physically. The team followed these suggestions and found that CAD modeling of the body enabled easy quick alterations, which was very helpful. The motor system and its connection to the wheels to enable movement of the RC car did indeed benefit from physical modeling (as suggested by the WDM) as both the power vs velocity requirements and traction capability were challenging. The other suggestions from the WDM were generally followed for the other sub subsystems with similar positive results. From the supplemental factor section of the WDM (Figure 6), it can be seen that both the flexibility and resource/skills adjustments to the output, as seen in the darker bar graphs and the black bottom bar, align well with the initial output seen in Figure 5. The sub-subsystem of the controller, however, shows resource/skills could be an issue for the physical implementation. This is likely because the team is comprised primarily of mechanical engineers and the controller system needs expertise in electronics and programming.

5.2 Heli-launcher design as an evaluation tool

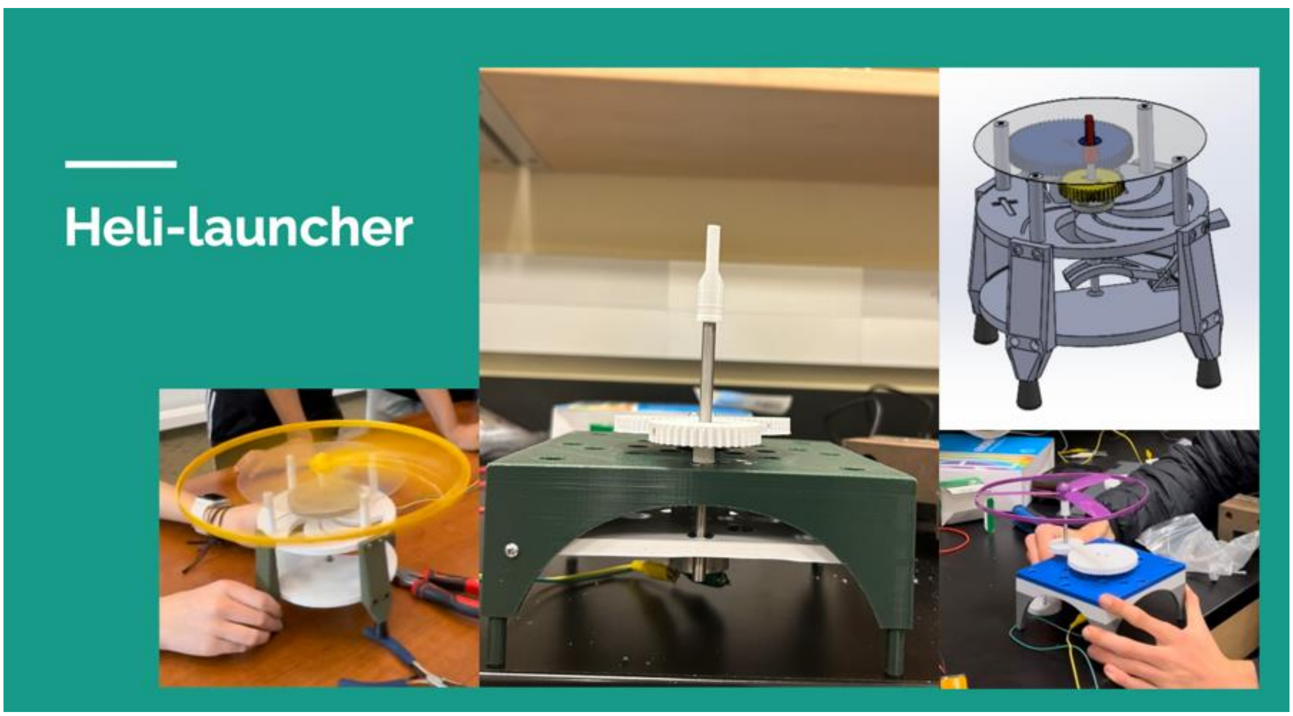

Figure 7 – Heli-Launcher System

The Heli-launcher system is intended to teach STEM concepts such as circuit design, gear ratios and most importantly power density. The system as shown in Figure 7 is assembled from a kit of approximately 20 parts. Three power sources are available as input through the gear system to spin, and potentially launch, the disk. Sufficient power enables the disk to launch and insufficient power only spins the disk slowly, which does not enable launch. The three power inputs are a hand crank mechanism (lower right in Figure 7), a solar cell array and a battery. Only one power input is used at a time. In general, the power from the small solar cells we chose did not have sufficient power to launch the disk, the hand crank was sufficient only when turned very aggressively and the battery could easily launch the disk. This allowed the children to get a “feel” for power density from a variety of sources.

Subsystems for the design included the Heli-disk launcher, the hand crank generator and the circuit system. Sub-subsystems for each of these three can be seen in Figure 8. The green, blue and red bars in Figure 8 show the WDM suggestions for digital or physical prototyping. In many cases the suggestions from the WDM were followed with positive results. There were, however, cases where the suggestions were not followed. For example, the WDM suggests digital work for the Hand-crank generator subsystem in the areas of sub-subsystems of “Hand crank” and “Gears” based on schedule (blue) concerns. While these systems were digitally modeled in CAD, they were then 3d printed without additional digital work such as kinematic or FEA based displacement/stress modeling. The team encountered significant difficulty getting these systems to work properly. The gearing in the system needed to be altered to meet design requirements of torque and rotational speed. Tolerances are critical in this design in order for the gear meshing to work correctly. The gear support system needs to be rigid in order to keep the gears meshing correctly. All these design requirements could have been checked, and design changes made digitally, using CAD and FEA. Instead, multiple iterations of 3d printed models were used, which took a long time and put the design in jeopardy. In retrospect, if the team would have had and followed the WDM, these issues could have been mitigated.

Figure 9 shows the supplemental factor matrix for the Heli-launcher. Note that for the Hand-crack generator’s sub-subsystem of “gears” the rigidity of the schedule variable emphasizes the suggestions for digital prototyping by showing the darker blue line extending leftward of the lighter blue line in the gears row. In addition, the bottom black line in that same row and column indicates sufficient resources and skills to do that digital work, which is verified by the team as they have stated that they had sufficient CAD capability to check tolerances and sufficient software and skills to accomplish the FEA needed for displacement analysis.

0-3 Scale		List of design requirements that are critical to the function of the Sub-Subsystem	Programmatic Factors				Stakeholder/Performance Factors				Bar graph showing which direction Cost, Schedule, and Performance lean	
SubSystems	**Sub-Subsystems**	**Critical DRs**	**Low Cost**		**Short Schedule**		**Performance (DR) Best Assessed by**		**Model Delights Stakeholder**		**Cost, Schedule, Performance Bar Graph**	
			Digital	**Physical**	**Digital**	**Physical**	**Digital**	**Physical**	**Digital**	**Physical**	**Digital**	**Physical**
Heli-disk launcher	Motor slide	Fits motor, fastens properly to base, slides without much friction	3	0	3	1	1	3	3	2		
	Launcher base	Minimal vibration and movement upon launching heli-disk, structurally sound	3	0	2	1	3	1	2	3		
	Shaft and heli disk	good diameter to pair with motor torque and speed, grip on any surface	2	2	3	1	1	3	1	3		
Hand-crank generator	Hand crank	comfortable in hand, smooth rotations, doesn't easily fail by shearing	2	3	2	1	1	3	1	3		
	Gears	mesh properly, connect well to shafts	2	3	3	1	2	3	1	3		
Circuit system	Circuit elements	Proper values meet specifications for voltage, current, and resistance	1	3	1	3	1	3	1	3		
	Solar panels	Supply sufficient voltage to circuit system	1	2	2	1	1	3	1	3		

Figure 8 – Heli-Launcher System Weighted Design Matrix - CORE Factors

0-3 Scale		Flexibility Factors - On a scale of 1-10 rate how flexible each of the following parameters are. 1 is very flexible and 10 is very rigid			Team/Company Factors				Bar graph showing which direction Cost, Schedule, and Performance lean		
SubSystems	Sub-Subsystems	Cost	Schedule	Performance	Existing Resources to Prototype		Existing Team Skills to Prototype		Cost, Schedule, Performance Weighted Bar Graph		Key
					Digital	Physical	Digital	Physical	Digital	Physical	
Heli-disk launcher	Motor slide	5	7	9	2	3	3	1			Original Weighted Original Weighted Original Weighted Comfort Zone
	Launcher base	2	6	8	1	3	3	1			Original Weighted Original Weighted Original Weighted Comfort Zone
	Shaft and heli disk	3	9	9	2	3	3	3			Original Weighted Original Weighted Original Weighted Comfort Zone
Hand-crank generator	Hand crank	10	3	8	2	1	3	1			Original Weighted Original Weighted Original Weighted Comfort Zone
	Gears	6	7	9	2	3	3	1			Original Weighted Original Weighted Original Weighted Comfort Zone
Circuit system	Circuit elements	10	3	8	2	1	3	1			Original Weighted Original Weighted Original Weighted Comfort Zone
	Solar panels	7	6	9	2	3	3	1			Original Weighted Original Weighted Original Weighted Comfort Zone

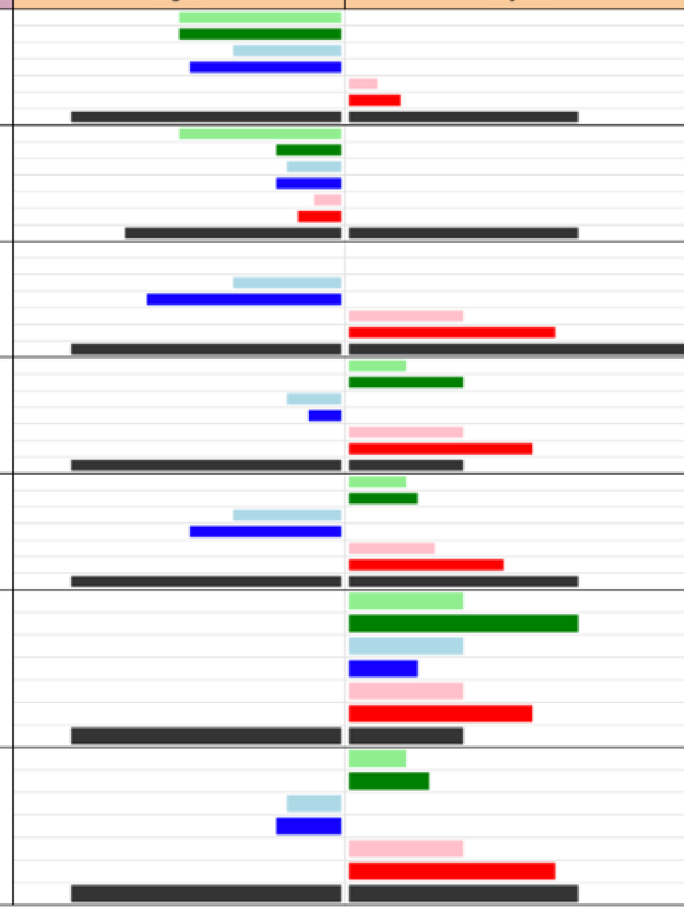

Figure 9 – Heli-Launcher System Weighted Design Matrix – SUPPLEMENTAL Factors

5.3 Design of a custom game controller as an evaluation tool

Figure 10 – Alpha Prototype - Custom Game Controller

Figure 11 – Beta Prototype - Custom Game Controller

The final design evaluation for the WDM used the design of a custom game controller. Figure 10 shows the Alpha prototype embodiment of the device while Figure 11 shows the evolved beta prototype. Four subsystems were identified for the device: Middle Console, Sliders, Charging Station (which has the circuitry) and the Grip. For this design work, the WDM was used after initial ideation (with some limited embodiment) so that the WDM could inform the prototyping process.

Figure 12 shows the WDM for the product. The WDM output for the "Middle Console" (top row in the matrix body) suggests physical prototyping except for the cost consideration. Since eventually the design would need to be physically prototyped, the lower cost of the digital prototype was overridden, and this subsystem was prototyped physically. The WDM suggests digital prototyping, from both cost and schedule standpoints, for the "Slides" subsystem. Initially, before employing the WDM, the plan had been to 3d print the slides with a "best guess" at dimensions. The WDM's suggestions for digital prototyping for this subsystem helped the designer to realize that a digital focus could help get dimensions correct early in the process where tolerances could be addressed between this part and the adjacent parts. This greatly assisted in design efficiency.

The "Charging System" row in the WDM indicates a preference for digital prototyping from a cost standpoint. This was helpful insight as the pre-WDM plan had been to do exclusively physical prototyping for the circuitry part of this subsystem. However, digitally prototyping the circuit to ensure the functionality before ordering and assembling the circuit parts helped make the design more efficient. Finally, the prototyping strategy for the "Grip" subsystem was initially planned (pre-WDM) to be fully digital with the hope that the CAD model could be used, without alteration, for the 3d print of the final part. However, based on insight from the WDM, it became apparent that a very simple physical prototype could help with schedule issues by displaying the human interface and tolerance design requirements. Thus, a simple paper physical model was first produced followed by the CAD model.

Overall, the implementation of the WDM significantly changed the initial plan for prototyping of this system. The designer expressed that creating the WDM helped organize the prototyping process in ways that dramatically improved efficiency and ultimate effectiveness of the prototyping strategy.

Based on this initial assessment, we plan to use the WDM in all of our engineering design classes in the future. Preferred implementation for courses like our senior design courses would occur immediately after initial ideation and down select; therefore right before detailed concept prototyping occurs. However, it might be interesting to implement the WDM earlier, when the teams are doing some initial prototyping as part of their ideation. We hope to explore these options in the near future.

0-3 Scale		List of design requirements that are critical to the function of the Sub-Subsystem	Programmatic Factors				Stakeholder/Performance Factors				Bar graph showing which direction Cost, Schedule, and Performance lean	
SubSystems	**Sub-Subsystems**	**Critical DRs**	**Low Cost**		**Short Schedule**		**Performance (DR) Best Assessed by**		**Subsystem Model Delights Stakeholder**		**Cost, Schedule, Performance Bar Graph**	
			Digital	**Physical**	**Digital**	**Physical**	**Digital**	**Physical**	**Digital**	**Physical**	**Digital**	**Physical**
Controller	Middle Console	The center of the controller that connects the two slides together	3	2	2	3	3	3	2	3		
	Slides	Holds Joycons, No sliding once locked in	3	1	2	1	3	3	3	3		
	Charging System	Must fit in console	3	1	1	3	0	3	1	3		
	Grip	Comfortable, stays in hand with no slip,	3	2	1	3	3	3	3	3		

Figure 12 – Custom Game Controller Weighted Design Matrix

6.0 Discussion and further evaluation

The research team was given the opportunity to present the WDM method to a group of engineers and scientists at the Air Force Research Laboratory (AFRL) in Dayton, OH. Two meetings, each approximately 90 minutes, provided time to gain valuable insight into the possible utility of the WDM method. Overall, the response to the method was very positive. Since the main demonstration of the implementation of the method was on very simple systems (the RC car system and the Heli-launcher system), questions about the applicability of the method to larger projects were discussed. Specifically, aircraft systems being designed by AFRL for very high speeds (hypersonic) were considered. Physical models of some components of these systems were displayed by AFRL to aid the discussion. The consensus was that, due to the dependance of the WDM method on cost, schedule, and performance variables, which are key variables for any product development process, the WDM would likely have applicability to these more complicated systems. Applicability to a different, highly innovative aircraft system was also discussed resulting in a similar conclusion that the WDM method would likely provide helpful insight into prototyping decisions.

The idea of including the supplemental factors of flexibility of the 3 primary variables (cost, schedule, and performance) as well as team resources and team skills was well received. In an organization like AFRL, the team skill set will often be very broad, and the team will likely be full of domain expertise. Therefore, the variable of "team skill set" might not be as important for that group. However, the reviewers indicated that they understood the possible and important applicability of these supplemental factors across engineering design teams in general.

There were also some important questions and suggestions provided during this discussion. The breakdown of the system into sub-subsystems is somewhat ambiguous. It may be helpful to provide additional thoughts on how this breakdown should occur as part of the method. Furthermore, the matrix could potentially become very large for a complicated system like a full aircraft, and that could render the WDM method too time consuming. Also, the scoring of the different parts of the matrix is somewhat ambiguous. However, it was noted that as long as the scoring was done consistently throughout the matrix, the absolute values of the scoring are not as important because the scores are relative and intended to show preferences for the "D" vs. "P" categories.

7.0 Conclusions and acknowledgements

A weighted design matrix (WDM) approach is presented to assist engineering design teams in decision regarding digital vs physical prototyping options. The matrix evaluates different sub systems of a product using variables of cost schedule and performance to provide insight and suggestions for digital vs physical prototyping decisions. The WDM method is evaluated using three designs of small products with positive results. In addition, the method was presented to a group of engineers at the Air Force Research Lab for evaluation. The utility of the method was verified by these reviewers in addition to them providing useful suggestions for improvement.

This work has been supported by the Air Force Research Laboratory through the Aerospace Systems Directorate. Westmont College also provided additional support through its undergraduate research program.

8.0 References

1. K. Otto and K. Wood, "Product design: techniques in reverse engineering and new product design," ed: Prentice-Hall, 2001.
2. L. Sass and R. Oxman, "Materializing design: the implications of rapid prototyping in digital design," *Design Studies,* vol. 27, pp. 325-355, 2006.
3. M. Schrage, "The culture (s) of prototyping," *Design Management Journal (Former Series),* vol. 4, pp. 55-65, 1993.
4. R. Moe, D. D. Jensen, and K. L. Wood, "Prototype partitioning based on requirement flexibility," in *ASME-IDETC*, 2004, pp. 65-77.
5. B. A. Camburn, B. U. Dunlap, V. K. Viswanathan, J. S. Linsey, D. D. Jensen, R. H. Crawford*, et al.*, "Connecting Design Problem Characteristics to Prototyping Choices to Form a Prototyping Strategy," presented at the ASEE Annual Conference and Expoisition, Atlanta, GA, 2013.
6. B. U. Dunlap, C. L. Hammon, B. A. Camburn, R. Crawford, D. Jensen, M. G. Green*, et al.*, "Heuristics-based prototyping strategy formation: development and testing of a new prototyping planning tool," presented at the ASME IMECE, Montreal, Canada, 2014.
7. B. A. Camburn, B. U. Dunlap, R. Kuhr, V. K. Viswanathan, J. S. Linsey, D. D. Jensen*, et al.*, "Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment," in *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2013, pp. V005T06A033-V005T06A033.
8. Camburn, B., Green, M., Dunlap, B., Jensen, D., Gurjar, T., Crawford, R., Hamon, C., Otto, K., Wood, K., “A Systematic Method for Design Prototyping”, ASME Journal of Mechanical Design, 137(8), Aug 01, 2015.
9. Camburn, B., Viswanathan, V., Linsey, J., Otto, K., Crawford, R., Jensen, D., Wood, K., “Design Prototyping Methods: State-of-the-art in Technology, Strategies and Heuristics”, Design Science Journal, April, 2017.
10. C. L. Hammon, M. G. Green, B. U. Dunlap, B. A. Camburn, R. Crawford, and D. Jensen, "Virtual or Physical Prototypes? Development and Testing of a Prototyping Planning Tool," presented at the ASEE Annual Conference and Exposition, Indianapolis, IL, 2014.
11. T.-J. Nam, S. Park, and J. Verlinden, "A model to conceptualize interactivity," *International Journal on Interactive Design and Manufacturing (IJIDeM),* vol. 3, pp. 147-156, 2009.
12. D. A. Schön, "Designing as reflective conversation with the materials of a design situation," *Knowledge-based systems,* vol. 5, pp. 3-14, 1992.
13. J. Jang and C. D. Schunn, "Physical design tools support and hinder innovative engineering design," *Journal of Mechanical Design,* vol. 134, p. 041001, 2012.
14. R. I. Campbell, D. J. D. Beer, L. J. Barnard, G. J. Booysen, M. Truscott, R. Cain*, et al.*, "Design evolution through customer interaction with functional prototypes," *Journal of Engineering Design,* vol. 18, pp. 617-635, 2008.
15. Y.-K. Lim, E. Stolterman, and J. Tenenberg, "The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas," *ACM Transactions on Computer-Human Interaction (TOCHI),* vol. 15, p. 7, 2008.

16. D. T. Stowe, "Investigating the role of prototyping in mechanical design using case study validation," Master of Science, Clemson University, 2008.
17. V. S. Gordon and J. M. Bieman, "Rapid prototyping: lessons learned," *IEEE software,* vol. 12, pp. 85-95, 1995.
18. V. K. Viswanathan and J. S. Linsey, "Build to learn: effective strategies to train tomorrow's designers," presented at the ASEE Annual Conference and Exposition, San Antonio, Texas, 2012.
19. V. Viswanathan and J. Linsey, "Understanding physical models in design cognition: A triangulation of qualitative and laboratory studies," in *Frontiers in Education Conference (FIE)*, 2011, pp. S3F-1-S3F-6.
20. J. A. Drezner and M. Huang, *On Prototyping: Lessons from RAND Research*: RAND, 2009.
21. M. Buchenau and J. F. Suri, "Experience prototyping," in *Proceedings of the 3rd conference on Designing interactive systems: processes, practices, methods, and techniques*, 2000, pp. 424-433.
22. J. Daugherty, Y.-T. Teng, and E. Cornachione, "Rapid Prototyping Instructional Design: Revisiting the ISD Model," *Online Submission - ERIC,* 2007.
23. V. Krishnan and K. T. Ulrich, "Product development decisions: A review of the literature," *Management science,* vol. 47, pp. 1-21, 2001.
24. T. Hess and J. D. Summers, "Case study: Evidence of prototyping roles in conceptual design," in *DS 75-1: Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol. 1: Design Processes, Seoul, Korea, 19-22.08. 2013*, 2013.
25. M. C. Yang, "A study of prototypes, design activity, and design outcome," *Design Studies,* vol. 26, pp. 649-669, 2005.
26. T. Hess and J. Summers, "Protocol analysis: studying physical manipulatives during conceptual design," presented at the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Buffalo, NY, 2014.
27. C. Elsen, A. Häggman, T. Honda, and M. C. Yang, "Representation in early stage design: an analysis of the influence of sketching and prototyping in design projects," in *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Chicago, IL, 2012, pp. 737-747.
28. V. K. Viswanathan and J. S. Linsey, "Physical models and design thinking: A study of functionality, novelty and variety of ideas," *Journal of Mechanical Design,* vol. 134, p. 091004, 2012.
29. D. Faas, Q. Bao, and M. C. Yang, "Preliminary sketching and prototyping: comparisons in exploratory design-and-build activities," presented at the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Buffalo, NY, 2014.
30. A. Römer, M. Pache, G. Weißhahn, U. Lindemann, and W. Hacker, "Effort-saving product representations in design—results of a questionnaire survey," *Design Studies,* vol. 22, pp. 473-491, 2001.
31. R. J. Youmans, "The effects of physical prototyping and group work on the reduction of design fixation," *Design Studies,* vol. 32, pp. 115-138, 3// 2011.

32. M. Carulli, M. Bordegoni, and U. Cugini, "An approach for capturing the voice of the customer based on virtual prototyping," *Journal of Intelligent Manufacturing,* vol. 24, pp. 887-903, 2013.
33. B. A. Camburn, K. H. E. Sng, K. B. Perez, K. Otto, D. Jensen, R. Crawford*, et al.*, "The Way Makers Prototype: Principles of DIY Design," presented at the ASME-IDETC, draft submitted, Boston, MA, 2015.
34. K. B. Perez, D. Anderson, and K. L. Wood, "Crowdsourced Design Principles for Leveraging the Capabilities of Additive Manufacturing," presented at the ICED, draft submitted, Milan, 2015.
35. B. A. Camburn, B. U. Dunlap, R. Kuhr, V. K. Viswanathan, J. S. Linsey, D. D. Jensen*, et al.*, "Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment," in *ASME 2013 IDETC*, Portland, 2013.
36. E. J. Christie, D. D. Jensen, R. T. Buckley, K. K. Ziegler, and R. H. Crawford, "Prototyping strategies: literature review and identification of critical variables," presented at the ASEE Annual Conference and Exposition, San Antonio, TX, 2012.
37. S. Thomke and D. E. Bell, "Sequential testing in product development," *Management Science,* vol. 47, pp. 308-323, 2001.
38. K. Yamazaki, "Approach to Human Centered Design Innovation by Utilized Paper Prototyping," in *Human Centered Design*, ed: Springer, 2009, pp. 367-373.
39. J. Dutson, K. L. Wood, J. J. Beaman, R. H. Crawford, and D. L. Bourell, "Application of similitude techniques to functional testing of rapid prototypes," *Rapid Prototyping Journal,* vol. 9, pp. 6-13, 2003.
40. S. P. Dow, K. Heddleston, and S. R. Klemmer, "The efficacy of prototyping under time constraints," in *ACM conference on Creativity and cognition*, 2009, pp. 165-174.
41. S. P. Dow, A. Glassco, J. Kass, M. Schwarz, D. L. Schwartz, and S. R. Klemmer, "Parallel prototyping leads to better design results, more divergence, and increased self-efficacy," *ACM Transactions on Computer-Human Interaction (TOCHI),* vol. 17, p. 18, 2010.
42. U. Cugini, M. Bordegoni, and R. Mana, "The role of virtual prototyping and simulation in the fashion sector," *International Journal on Interactive Design and Manufacturing,* vol. 2, pp. 33-38, 2008.
43. M. Bordegoni, U. Cugini, G. Caruso, and S. Polistina, "Mixed prototyping for product assessment: a reference framework," *International Journal on Interactive Design and Manufacturing (IJIDeM),* vol. 3, pp. 177-187, 2009.
44. Hansen, C. A. (2021). Design by Prototyping: Strategic support for prototype-driven product development. Technical University of Denmark. DCAMM Special Report No. S308