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PHYSICAL VERSUS VIRTUAL PROTOTYPING AND THEIR EFFECT ON DESIGN SOLUTIONS

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Abstract: Physical and virtual prototypes are widely used throughout industry in the development of engineering designs. There have been many studies documenting the benefits of both. This work discusses and tests three key areas within this topic: Does the use of virtual prototyping early in the design process lead to design outcomes with poorer functionality? Does the use of virtual prototyping in product development lead to more complex design outcomes? Does early physical prototyping improve design efficiency? To examine these questions, a controlled experiment was conducted that involved nine designers tasked to design a device to protect an egg when moving down an incline and dropped from a table. The results drawn regarding complexity were inconclusive due to low sample size. Other results found that solutions developed using physical prototyping methods possessed superior functionality and fewer features that required rework.

Keywords: *Virtual prototyping, physical prototyping, design methods, design creativity*

1. Introduction

The design process involves the utilisation of many development and evaluation methods including sketching, physical modelling and virtual modelling. The rapid improvement and adoption of new technology methods has led to Computer Aided Design becoming a key part in development. This paper will evaluate weather this adoption has unintentionally weakened overall design outputs due to the reduction in physical prototyping.

The aim of this project was to define the effect that virtual and physical prototyping methods have on final design solutions. The stage of the design process in which a certain prototyping method is used may directly affect the outcome. Prototyping has the most influence over a project during the initial and development phases of the design process. Therefore, this project will focus to its use at this stage. This paper seeks to compare these two methods in regards to their influence on these design outcomes. This will be achieved through the evaluation of aspects of design solutions produced by participants in a controlled experiment. These aspects will be chosen to match a set of hypotheses stated after an in-depth evaluation on previous literature in the subject area. Results will be documented and analysed to form a conclusion.

2. Background

2.1. Design Fixation and Sunk Cost

One way in which the type of prototyping method used could affect design outcomes is whether one may cause the designer to created more fixated designs. Design fixation is when a designer unintentionally limits the number of ways they are able to solve a problem. This is generally believed to be a negative phenomenon as it may lead to a reduction in novelty and creativity of ideas. This is an area of design research that has been evaluated in detail in previous works (Walker, 2010).

Another phenomena that occurs during the generation and development of new designs is the theory of sunk cost. Viswanathan's (2011) work describes the theory of sunken cost as; '*the reluctance to choose a different path of action once significant money, time or effort is invested in present one.'* This is a negative phenomenon that can lead to design fixation. Changing a physical prototype requires more resources that a virtual CAD model. This may suggest that there will be a higher design fixation rate in physical prototyping. Although it is also stated that it is difficult to gain an accurate result regarding sunk cost in a controlled environment as there is very little of the participants own cost sunk into the experiment when compared to real life situations. Therefore, observational studies are more accurate in this area.

The evaluation of design fixation improved the understanding of how prototyping methods may affect design outcomes. Although, no testing will be done in this project regarding the presence of design fixation. To fully test for the presence of design fixation a specialised experiment is required to be conducted such as in Viswanathan's (2012) work. This required a simplistic design problem to allow the participants to create as many solutions as possible to measure the percentage of functional ideas and subsequently categorising them in terms of novelty. Many papers have already investigated the effect and cause of design fixation in great depth (Crilly, 2017), whereas, there is little investigation into the effect on functionality, efficiency and complexity. The evaluation of design fixation would interfere with the testing of these other metrics.

2.2. Design Outcome Functionality, Efficiency and Characteristics

The functionality of a final design is dependant on its ability to fulfil the purpose it was designed for. A set of requirements for a design is often known as a Product Design Specification (PDS) (Pugh, 1987). Functionality of a product can be measured through its conformance to the PDS. If the final design is fit for purpose and performs optimally there will be fewer repairs resulting in lower maintenance costs in post-production, as well as improved customer satisfaction. On a similar note, design efficiency is a measurement of the time required to create a successful design. This metric is of importance as the objective of design efficiency is to minimize cost (Aas, 2002). Designers work is costly, if a quality solution can be created with less time overall process costs are reduced. The success of a low-cost product relies on its manufacturability. This is something that also depends in its design characteristics. These characteristics include; geometric complexity of components, product size, number of parts and types of material used. Design for Manufacture and Assembly guidelines state that these can directly influence the ease with which a product can be manufactured (Boothroyd, 1994). If a component possesses complex geometry such as asymmetric or irregular shapes, more processes are required to manufacture it. It is proposed that prototyping methods may have an effect on final design characteristics, which is an understudied area of design evaluation. If a certain prototyping method is found to have more chance of developing products with high functionality and desirable characteristics, this may be valuable to industry to save production costs.

2.3. Physical Prototyping

One form of model making is the physical model, which can involve rough visual and shape representations to fully functional physical prototypes. These can be created through traditional manual techniques, rapid prototyping or a combination of these processes. The advantages of utilising physical models in various stages of the design process has been widely documented. Large automotive companies such Toyota uses the to find problems in design before the production process (Ward et al., 1995). Walker (2010) and Viswanathan (2011) have stated that their use early in the process improves feasibility and quality of designs as well as supplementing mental models. Benefits of physical prototypes have also been found in teaching. Lemons (2010) found that model building helped engineering design students generate, visualise and evaluate ideas. It's use also resulted in improved creative thinking and made students more aware of their own design strategies.

Existing literature has conflicting results regarding physical prototypes effect on design fixation. Walker (2010) states that physical prototyping has no effect on design fixation from a test involving the design of an energy harvesting device with mechanical engineering students. Viswanathan (2011, 2012, 2014) received varying results from three separate runs of a similar experiment. This experiment consisted of participants designing paperclips in order to investigate the effect of physical prototyping on fixation and functionality when compared to sketching. The first experiment found that early physical prototyping increases design fixation but increase final design functionality. The next experiment found no effect on fixation and an increase in design functionality. A final test found physical prototyping to reduce design fixation and have no effect on design functionality. These conflicting results highlight the need for further evaluation into the effects of physical prototyping, especially in comparison to CAD development.

2.4. Virtual Prototyping

Virtual prototyping is an essential tool that is used throughout the design process. Virtual models can refer to any prototype created entirely in a virtual space that does not involve physical contact with the object being designed (with exception to the use of haptic devices in virtual environments). Virtual prototyping consists of computer-aided design (CAD), computer-automated design (CAutoD), computer-aided engineering (CAE), and Virtual Reality (VR).

3D modelling packages that are widely used in industry to create design solutions will be evaluated in this paper. These models are often used extensively before physical prototypes are made to reduce production time and costs due to their ease to make iterations (Chua, 1999). Robertson (2009) investigated the impact of CAD tools on creative problem solving and found that the use of CAD improves visualisation and communication when compared to solely sketching. It was also found to increases premature fixation when used in early in the ideation phase when not supplemented with additional creative processes such as sketching and group discussion. Other researchers also suggest drawbacks of the use of CAD in product design. Fadel (1995) stated that the visual hand co-ordination that is required to truly asses and understand the way that a design operates is not possible when viewed on a computer screen. Although the CAD technology has advanced considerably since these papers were written, they state the cognitive advantages of a physical model and how the lack of targetability in CAD may lead to poorer quality outcomes. This is something that has remained unchanged by technology with exception to virtual reality. This is a type of virtual prototyping where the designer creates a model in a virtual environment (Arastehfar, 2013). Due to its higher technology and resource requirements VR is not as widely used in industry at present.

2.5. Summary of Key Theory's

Studies evaluated have generally conflicted in regards to design fixation with some suggesting that fixation decreases with the used of physical modelling and others finding an increase. Most sources agree that functionality is increased as a result of physical prototyping. Many sources compare virtual reality to physical prototyping using experimentation. The negative effect that VR has on design perception was stated (Mengoni, 2009) along with the drawbacks of standard CAD that are also related to perception (Chua, 1999). Others state the many benefits of CAD that include reducing production time and costs due to easy editability (Walker 2010).

These studies have compared physical and virtual methods separately to other forms of visualisation such as sketching, using design fixation and functionality as metrics for evaluation. There is an absence of recent studies that compare these two methods directly using experimental investigation. This is likely due to the difficulty of comparing virtual and physical solutions accurately. A study that compares these two methods regarding outcome functionality and design fixation would be useful. In addition to these metrics for evaluation, a comparison between the solutions characteristics such as complexity would also be valuable to investigate their influence on production costs. The papers described in this study explore the influence that the type of prototyping method has on final design outcomes. From the background research conducted, the following hypotheses were drawn:

- *Hypothesis 1* - The use of virtual prototyping early in the design process leads to design outcomes with poorer functionality.
- *Hypothesis 2* - The use of virtual prototyping early in the design process leads to design outcomes with more complex geometry's.

- *Hypothesis 3* - Early physical prototyping will reduce the overall design process time by preventing rework in later stages.

3. Method

3.1. Overview

Hypotheses were evaluated through a controlled experiment at the University of Strathclyde designed to directly compare physical and virtual prototyping methods. The participants are tasked to design and test a final physical prototype to solve a design problem. The experiment contained three separate controlled conditions for which participants were randomly assigned. The first condition represented a circumstance where the designer primarily uses physical prototyping to develop their solution before creating a final design. The second condition simulated a designer using virtual prototyping in the early stages of the process to develop their design before going on to build a final solution based off this design. The final condition acted as a control where the participant was not limited. The final prototypes were photographed before and after testing and evaluated against criteria created to test the hypotheses.

3.2. Design Problem and Materials

Participants were asked to build and test a device that will protect an egg from breaking when moved down a 10-degree incline and dropped from a table 90cm tall. This problem is derived from the classic team building exercise that involves building a device that will prevent an egg from breaking when dropped (Ermer, 1996). To add levels of complexity the device was required to move down an incline and allow the egg to be removed without damaging the device. This prevented participants from simply wrapping the egg in a soft material to complete the task. A PDS (Pugh, 1987), defined in section 2.2, with these details was provided to participants. This test was chosen as it has a large area for creativity and solutions can be both complex and simple. The level of success can be determined by the severity of the breakage as well its compliance to the PDS. This design problem aimed to emulate the entire design process on a small scale. The participants were permitted to use any materials and tools available in the department workshop. This includes a range of resources, from structural building material such as timber and plastic tubing to softer materials such as soft foam and bulwark for shock absorption. Participants were given a tour of the workshop to refresh their memories about what was available.

Table 1. Time restrictions

Physical Condition	**Virtual Condition**	**Time (mins)**
Initial Sketching	Initial Sketching	10
Sketching/Rough Prototyping	Sketching/CAD Development	30
Build Final Model	Build Final Model	40
Test Final Model	Test Final Model	5
Survey	Survey	5

3.3. Procedure

Overall nine participants took part in the experiment, allowing for three in each condition. Participants were all individuals with at least 5 years of training in design engineering. Participants had experience in a workshop environment and were competent with the CAD software Solidworks accordingly they could be placed randomly in any of the conditions. After a pilot study was conducted to identify any major problems with the experiment, the study was conducted over a two-week period with three groups of participants. Due to practical experimental limitations, a time limit was set for the test of 90 minutes per group. The first two tests had time restricted periods set for brainstorming, development and final building. These timings were kept as similar as possible to prevent bias. Participants were notified of time limits, they were allowed to complete each stage early or were moved on to the next phase when the time ran out. The third group were not restricted and acted as a control. A survey was presented to the participants at the end of the experiment to gain additional information about the test. Additional instructions were given to the participants that encourage different ideas and prevented excessive use of material. This made the challenge more difficult as the participant had to make efficient use of material. **Error! Reference source not found.** shows the structure for the two restricted experiments.

3.4. Testing Periods and Conditions

Before beginning this set was given a tour of the materials available in the workshop so that participants had an idea of what is available. Both restricted environments included this stage. It is meant to represent the concept generation period of the design process where participants convert their mental models into quick sketches. They were given the required resources to do this (paper, pens and pencils). The pilot experiment found that 10 minutes was sufficient sketching time due to the simplicity of the challenge. Participants were allowed to use any brainstorming method they were familiar with. They were told to explore as many ideas as possible and choose a single solution by the end of this section. Participants were allowed to change their idea in later stages if the initial idea was not found to be feasible. Sketching was also permitted throughout the experiment to supplement prototyping methods. In the physical prototyping condition, the participants could spend 30 minutes on developing their chosen solution using rough prototyping in the workshop. An egg was provided to measure sizing but participants were not permitted to test until their final design was completed. After this period, they were asked to begin building their final prototype from scratch. This eliminated any advantage that might be gained by this group having a longer build time then the virtual prototyping group. After 40 minutes, they were asked to present their final product for testing.

In the virtual prototyping condition the participants were required to develop their selected design using the 3D modelling CAD package Solidworks. This package was chosen as it is most commonly used in the department and every participant had experience with this software. Once their model was completed they were asked to create a fully functional prototype of their design in the workshop. Technical drawings were created to allow the participant to easily measure the designs dimensions. Participants were asked to keep the design as similar to the CAD model as possible. Small changes were allowed but they were asked to note down what they were and state why the change was made in the survey at the end of the experiment. The time provided in this section for development and final building was the same as the physical prototyping environment to prevent bias.

The control condition had no time or method restrictions. This allowed the participant to spend as much time on each stage as well as the freedom to utilise any method for the development stage. The exact time spent on each section was recorded using a stopwatch. This information will be compared to the other conditions to see if participants would have benefited from additional time in a certain stage. Each method that was chosen was also recorded for later evaluation.

3.5. Metrics for Evaluation

The successfulness of a design problems outcome can be measured in several ways which will be discussed in detail in this section. All environments were required to complete a final model by the end of the process. This allowed each result to be evaluated based on tangible criteria, eliminating the need for expert judgement or simulation, which could result in inaccuracies or bias. These tangible evaluation metrics include; conformance to PDS, design characteristics, and time spent.

To measure functionality, a brief PDS was provided to the participants at the start of the process. These required the device to move, allow the egg to be removeable without breaking the device, and prevent egg fracture. Each completed designs ability to conform to these PDS was used to directly measure their functionality. The result of first two of these points can be determined with yes or no whereas the egg breakage was measured in multiple ways. First the severity of the break from 1-5 for which a scale with examples shown below in Figure 1.

1 2 3 4 5

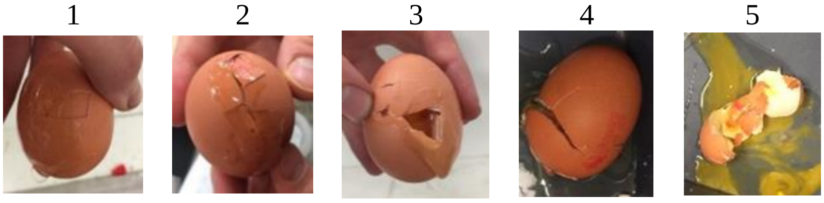

Figure 1. Egg breakage severity scale

The number of times that the egg could be dropped without breakage was also used to measure each designs conformance to this PDS point. If a design could prevent the egg from breaking three times testing was ended and it was assumed to be able to continually perform successfully. These assessments were noted at the time of testing on an evaluation sheet.

Mentioned earlier, the success of a final product often depends on its ability to complete the purpose it was designed for and its cost efficiency. These are directly related to the chosen characteristics for evaluation. These included; geometric complexity, number of components, number of types of material, and the overall size of solution. To measure these design characteristics; the number of components and material types were counted at the time of testing and noted on an evaluation sheet. The complexity and size evaluations are rated through comparing results with other designs. This was achieved once all testing was completed by observing pictures taken of each completed design. Examples of designs at that show the overall range of complexity are shown below in Figure 2.

Figure 2. Examples of designs with differing complexity.

The time efficiency was measured using a stop watch to measure the exact time that was spent on each section. This was used during the control tests and if the participants completed a stage early. If participants could successfully meet the design criteria in a lower time this signified design efficiency.

4. Results and Discussion

In relation to hypothesis 1 (refer to page 4) to understand the overall functionality of each ideas the mean number of successful drops and breakage severity are studied. The variation for each condition is shown in Figure 3. Highly functional designs will score a high number of successful drops and a low breakage severity as this better satisfies the PDS given to participants. Evident in Figure 3, the solutions developed using Physical Prototyping methods scored better functionality (high drop success without breakage and low breakage severity) compared to virtual prototyping. In addition to this, all solutions satisfied the PDS points that required the egg to be retrievable without breaking the device and move down the incline except one device in the physical condition that was not able to move. These results indicate that the use of physical prototyping improves the overall functionality and success of design solutions compared to virtual prototyping. This confirms the first hypothesis stated earlier. The control condition participants primarily used physical methods but failed to perform to the same level as the physical condition. This introduces some inconsistency to the findings.

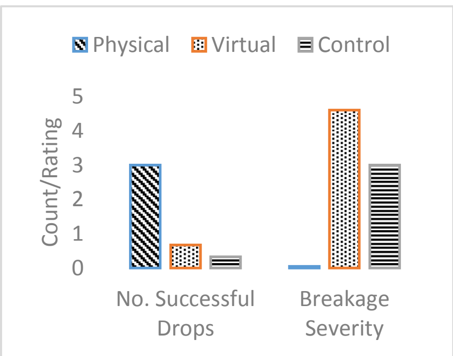

Figure 3. Graph of functionality results

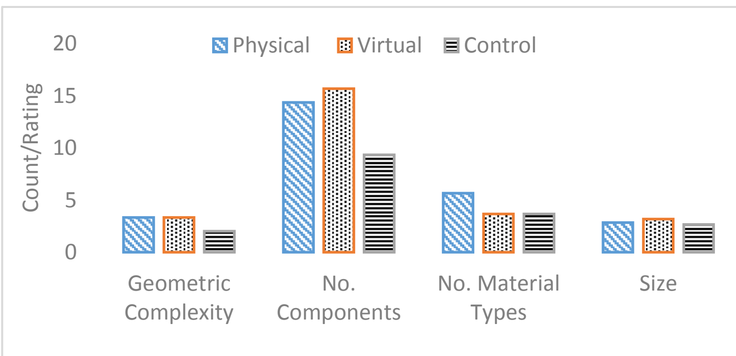

Figure 4. Graph of complexity results

In regards to hypothesis 2 (refer to page 4), participants created a large range of designs that had varying levels of complexity and size. Detailed earlier, each designs' overall complexity was

evaluated using four separate metrics that were analysed once experimentation was completed. This data is presented in Figure 4. In each metric, higher values result in overall higher design complexity which will correlate to higher manufacturing costs.
The results produced no clear indication of either method causing the creation of more complex solutions. Both prototyping techniques resulted in the same geometric complexity. Whereas other metrics indicated that design developed using virtual prototyping will contain slightly more components with fewer types of materials. The prototyping method used was not found to have an influence on size of final solution.
Hypothesis 3 (refer to page 4) was evaluated using two metrics, time and reworked features. The time spent by participants on each stage was recorded using a stopwatch. The number of features that were reworked were split into two sections, after the development phase had finished and what the participants would rework if they had more time after tests. This information was gained in the post-experiment survey. The higher the mean rework value the lower the overall design efficiency as it is assumed that rework will increase process time and cost. The numbers presented in Figure 6 and Figure 5 are mean values. The development and final build segments in the control group are represented with a gradient as participants stated did not have a clear development phase and were developing their idea while simultaneously building a final solution. This is also why there is a smaller post-development rework value for the control as some participant did not have a clear development phase.

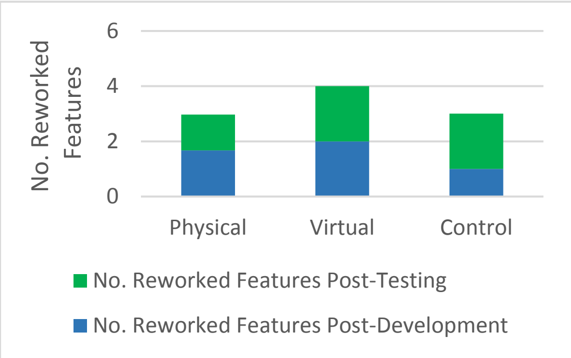

Figure 6. Graph of no. reworked features

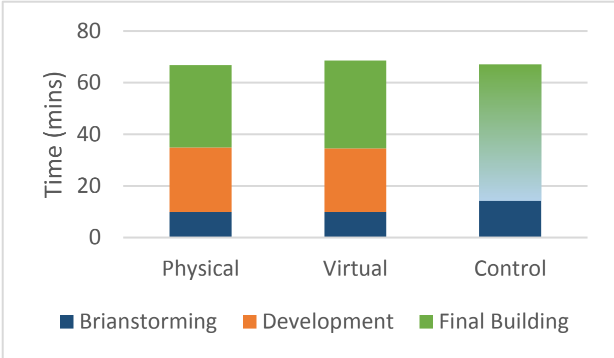

Figure 5. Graph of time spend in each stage

These results found that participants that developed their solutions using virtual prototyping reworked slightly more features than ones developed using physical prototyping. Overall, the restricted conditions took the same amount of time as the controlled conditions. This suggests by moving participant on to the next stage of the process without preparation had no effect on the overall time spent. In the control groups, less time was spent on development. Physical prototypes resulted in solutions with fewer features requiring rework in the same development time. According to this experiment, physical prototyping slightly improves design efficiency. This confirms the previously stated hypothesis.

5. Discussion and Conclusion

Previous research papers have analysed a prototyping methods effect of design fixation and functionality of simple solutions. This project presented experimentation that evaluated the effect that the use of a prototyping method in the development phase has during a semi-complex design problem. The experiment evaluated a previously uncovered effect on final designs. The results found that designs developed using physical prototyping methods created more functional solutions that resulted in fewer features needing to be reworked. These findings agreed with two hypotheses that were developed from the review of current literature in the area. The experiment also evaluated the level of complexity of the final designs produced through a number of metrics for which results were inconclusive. The primary limitation to this study is the large variance in results caused by the low sample size collected. Time and resource limitations prevented the use of advanced manufacturing methods and materials. This may have prevented participants from creating more complex solutions.

Furthermore, the results of this study cannot be fully equal to a real-life engineering problem in industry as the design problem was simple in comparison. This could produce results with increased simplicity and functionality in a faster time. This may have produced results with increased simplicity and functionality in a faster time. While the complexity of the design challenge may impact the overall solution properties, it will not influence the difference between solutions created by each group. As a whole, this experiment was extremely informative and brought forward findings that indicate a benefit to further study of the topic. These future studies could directly compare the impact that prototyping methods have on design fixation as well as developing a more objective method of evaluating component complexity. This could incorporate a systematic approach analysing geometries that increase manufacturing costs such as asymmetry or sharp edges.

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