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Student Perceptions of an Iterative or Parallel Prototyping Strategy During a Design Competition

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Student Perceptions of Iterative and Parallel Prototyping Strategies in an Undergraduate Design Competition

ABSTRACT

In engineering design, the prototyping process facilitates learning through testing, evaluation, and refinement. Designer perceptions about different approaches to prototyping may reveal how the benefits and limitations of different prototyping strategies manifest. In this paper, student perceptions of iterative and parallel prototyping approaches are examined through an undergraduate design competition. Student participants' final project reports are analyzed to determine their satisfaction with their assigned prototyping strategy. In addition, themes in participants' perceptions about the two prototyping approaches are assessed by evaluating their reports for emergent theme categorization. Results show a significant preference towards an iterative approach to prototyping despite better design performance by the parallel approach. Participants also recognize the unique benefits of each strategy. Namely, an iterative approach affords minor changes to a concept whereas a parallel approach facilitates solution space exploration. This work showcases how students perceive the benefits and limitations of iterative and parallel prototyping strategies, informing our understanding of how prototyping strategies can affect the engineering design process.

1. INTRODUCTION

Prototyping is an essential part of the design process, providing insight into the form and function of a product or system. Prototyping may take many forms whether it be virtual, physical, or computational, and serves a critical purpose across various disciplines. Often in engineering education, prototypes are core to design course requirements. The *learning by doing* nature of creating a prototype provides students with a contextualized experience facilitating student understanding, offering a means to assess the students' understanding, and creating a reference point to test the product for further design improvement.

Often, an iterative approach is used for prototyping. This idea is supported by many articles for improving the outcome of design projects [1-5]. An iterative prototyping strategy helps plan the design process and structures decision-making [6-9]. But a purely iterative strategy is not the only way to approach the prototyping process. An alternative to an iterative approach to prototyping could be a parallel strategy that encourages exploration of multiple design concepts simultaneously. Some studies have shown that a parallel prototyping provides benefits to the design process [10-13] through novel solutions [10] and radical changes to a design concept [13]. Parallel prototyping enables further exploration of the design space by considering multiple designs simultaneously before deciding on which concept to pursue. This allows designers to combine the best aspects of each concept to create a stronger final design.

Few studies have explored designers' perceptions about the prototyping process, where perceptions are ways in which an individual understands and interprets information. In engineering, designers' perceptions shape how they approach the design process, communicate, and make decisions [14]. In previous studies comparing engineering students' and experts' behaviors during the design process, Atman [15] found major differences between the students and experts. The experts were found to spend more time on the task, especially problem scoping, and overall gathered more information on the problem. However, few studies have directly explored designer perceptions of different prototyping strategies during the engineering design process. Understanding prototyping perceptions could enable us to see how students approach prototyping and compare this to professional engineers in the workplace, exposing potential discontinuities in engineering education.

This paper explores perceptions of prototyping in an introductory engineer design course. Participants were randomly assigned to two difference experimental conditions (the iterative condition or the parallel condition) and participated in a design competition. Participants' satisfaction for their assigned prototyping strategy and their perceptions of the benefits and limitations of each strategy are assessed through qualitative methods. By analyzing participants' final design competition reports for satisfaction and emergent trends, we are able to identify participants' perception of their randomly assigned prototyping strategy. Ultimately, this work aims to answer the question: How do students' design perception compare to their design success?

The authors hypothesized that participants would prefer an iterative prototyping strategy (H1) because iteration is associated with more testing of their design to "perfect" it. Iteration may also be perceived as requiring "less work" since a parallel approach initially requires exploring two concepts as opposed to a single concept before deciding on a final design. Though is it expected that participants will prefer an iterative approach to prototyping, it is hypothesized that a parallel prototyping strategy will have a higher success rate as measured by student performance in the design competition (H2). A parallel approach to the prototyping process may encourage greater exploration of the solution space that provides broader experiential knowledge, which can be leveraged to created more feasible solutions to engineering design problems.

2. BACKGROUND

Prototyping provides a means for designers to communicate, learn, and progress in product development [8]. There is no single definition of prototyping. Dieter and Schmidt [9] explicitly define a prototype as "a physical model of the product," whereas Ulrich and Eppinger [8] include "concept sketches, mathematical models, simulations, test components, and fully functional preproduction versions of the product" as prototypes. Further, Ullman defines prototypes in terms of industry design stages such as "proof-of-concept" or "proof-of-production" [16]. Some make the claim that prototypes can be physical or virtual depending on the context [17-19]. Among seminal literature in the field, there are clearly deviations to what is considered a prototype and how prototypes are used. In this study, a prototype is considered a physical model from which a designer learns about a concept or idea with the goal of finding a solution to a design problem.

Through prototyping, designers gain insight into performance and feasibility of their ideas, facilitating learning through the process [8]. Leifer and Steinert argue rapid prototyping accelerates the rate of learning during design [20]. This can be very significant for engineering novices who have limited experience engaging the design process or for professionals working in new areas or with highly innovative design contexts. Prototypes range along a spectrum of fidelity, or the degree to which a prototype represents the final product. Low-fidelity prototypes have been shown to provide comparable feedback on usability to high-fidelity designs [21] and high-fidelity prototypes support correct and confident design decision making. Further, low-fidelity prototypes are shown to be better suited for determining product functionality [22]. In this study, student participants produced what can be considered high-fidelity, fully functional prototypes in the context of this undergraduate design competition.

Traditionally, an iterative approach to the prototyping process is used for successful design [6, 8, 9]. Iteration has been linked to increased product quality and reduced project time [23] by helping identify errors and meet design requirements [24]. The advantages of an iterative prototyping approach are taught to engineering students across disciplines. However, Buxton argues iteration limits the designer to the evolution of a single design concept instead of considering multiple ideas simultaneously [25]. The process of considering multiple ideas simultaneously aligns with the “parallel” approach utilized in this study. Participants in the parallel conditions did not have the opportunity to learn from their prototypes until two of their concepts were returned to them simultaneously. Based on published the literature, controlling the opportunity for learning most closely aligns with a parallel prototyping approach.

Parallel prototyping has been identified as something that designers should consider when planning a product development cycle [19, 26]. A parallel prototyping approach forces consideration of multiple design concepts simultaneously, therefore likely encouraging broader design space exploration that may converge on more feasible solutions. Camburn et al. [27] demonstrated that a parallel prototyping strategy statistically increased performance on a design task. Dow et al. showed that parallel prototyping led to better online advertisements (considered a virtual design problem), greater solution divergence, and improved self-efficacy [10, 11]. Notably, Dow et al. also investigated these effects for physical prototyping, but with inconclusive results [11]. The parallel prototyping strategy employed by Dow et al. shows some benefits over an iterative strategy, but there is a lack of supporting empirical evidence. The work in this paper aims to provide evidence for the benefits and limitations of these two prototyping strategies through an undergraduate engineering design project for physical products.

Beyond an iterative or parallel approach, researchers have outlined other strategies for an effective prototyping process. Menold et al. [28-30] developed “Prototype for X (PFX)”, a framework for prototyping based on human-centered design. This framework focuses on three phases: Frame, Build, and Test [28] and is shown to increase prototyping awareness [29] and increase design quality among student designers [30]. Other commonly known strategies include the Design Sprint for five-day design cycles [31], Lean Startup focusing on refinement and testing [32], and Agile Design that emphasizes working on smaller pieces from the whole [33]. These three common strategies utilized in an industry context involve an iterative prototyping approach to assist with rapid product develop, where time and cost are critically important factors for design success.

To better understand these strategies and the likelihood that designers will implement them in their future work, we consider designers’ perception of an iterative and parallel prototyping strategy. Salomon has demonstrated that student perceptions are useful in understanding the relationship between technology and students’ learning processes [34]. Students’ perception of the learning context and its purpose has been shown to affect whether the implemented technology impacts their learning [35, 36]. However, there is a gap in the literature on student perceptions of different prototyping strategies for physical prototypes and their perceptions of the design process in general. Through students’ perceptions of an iterative or parallel approach to the prototyping process, we can start to understand the impact these strategies have on student learning, satisfaction, and design success.

3. METHODOLOGY

The methodology section first describes the study context with details about the experimental design in section 3.1. Then, the two methods used to analyze students' final reports are described in sections 3.2 and 3.3.

3.1 Study Context

The IRB approved research study presented in this paper involved a design competition in an introductory undergraduate mechanical engineering course on sketching/drawing and computer-aided design (CAD). The university where this study took place is in the southeastern United States with a research-focused environment. The competition tasked students with modeling a device in a CAD software to launch a small foam ball into an arranged target 10 feet away. The 3D-printed prototypes were produced by the research team for the participants to remove unwanted variables from the experimental design. The only materials allowed during the competition were the 3D-printed prototypes, a rubber band that was provided, and small foam balls that were also provided. This design problem was chosen for its difficulty, which would help highlight learning from the prototypes and offer a wide range of possible solutions. Voluntary student participants (n = 45) were randomly assigned to separate experimental conditions: the iterative condition (n = 23) and the parallel condition (n = 22). The experiment took seven weeks from initial introduction of the design problem, through the prototyping process, participation in the competition, and final submission of reflective design reports.

Participants assigned to the iterative condition created two prototypes and a final design in sequence (Figure 1, left). After the first prototype was 3D-printed and returned to participants in the iterative condition by the research team, they could test their designs before making changes to their CAD model for the next round of production. This process was repeated for their second prototype. After receiving their second iteration, participants in the iterative condition could make changes to their CAD model for their final design.

Participants assigned to the parallel condition created two prototypes simultaneously followed by a final design (Figure 1, right). The research team 3D-printed both prototypes for participants in the parallel condition before returning them for testing. Once both prototypes were returned, participants in the parallel condition made changes to their CAD model for production of their final design. Critically, participants in the iterative condition had two opportunities to learn from their concepts and make changes to their design. In contrast, participants in the parallel condition were only given one opportunity to learn from the concepts and test them before submitting a final design for the competition. Despite this single opportunity, participants in the parallel condition initially learned from two different design concepts instead of one design concept. All participants produced two prototypes and one final design with comparable deadline schedules. No feedback about the design concepts was provided to the participants by course instructors, the research team, or teaching assistants. Notably, the two experimental conditions were aware of each other caused by curriculum constraints beyond the control of the research team.

Clearly defined restrictions were given to the participants. Their design concepts had to fit into a 4” x 5” x 4” build volume. The design could have multiple components, but all components had to be arranged to fit inside of these dimensions. Further, their designs had to have two “stable

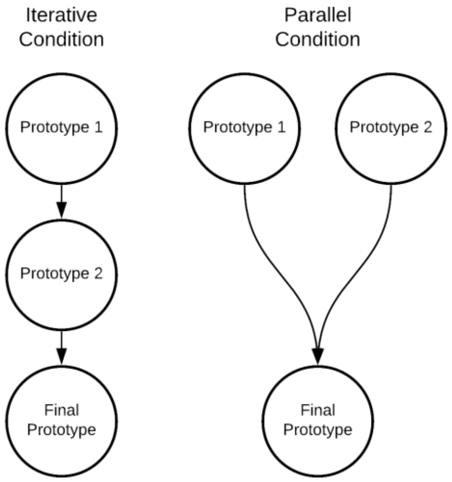

Figure 1*: The two different prototyping processes for the iterative condition and the parallel condition.*

states" (i.e. a "loaded" stated and a "launched" state). This restriction was chosen to prevent an onslaught of slingshots. Other restrictions included: the device had to function from the ground, no outside materials were permitted (glue, tape, screws, etc.), and participants could not print their own prototypes for testing (such as in the university makerspaces). All participants were provided with 3 small foam balls and as many standard-size 33 rubber bands as they desired. The exact document with competition details and design restrictions provided to the participants is forthcoming [37]. For the competition, scoring was determined by the best three attempts of five to hit the target. During each attempt, a "distance score" and a "raw score" were summed together for an "attempt score". The top three "attempt scores" of five were then summed together for a final "competition score". The "distance score" was calculated as shown in Table 1, with less points for straying away from the desired 10-feet requirement. The target was made of unique hexagonal cups arranged concentrically that were color coded and weighted. Foam balls landing at the center of the target would earn more points and earned progressively less points towards the edge of the target (10 points, 7 points, 4 points, and 1 point).

Table 1*: How scores were determined for each attempt of five based on the final prototype's distance from the target called the "distance score".*

Distance Score	**Distance from Target**	
	Too Close	**Too Far**
10 pts	9.5 ft to 10.5 ft	
7 pts	8.5 ft to 9.5 ft	10.5 ft to 11.5 ft
4 pts	7.5 ft to 8.5 ft	11.5 ft to 12.5 ft
1 pts	6.5 ft to 7.5 ft	12.5 ft to 13.5 ft
0 pts	< 6.5 ft	> 13.5 ft

After the competition, participants were required to complete a project report for the competition to capture their experiences, reflect on learning outcomes, and state their satisfaction with their condition assignment (parallel or iterative). In this report, participants were asked to include an answer to the following design reflection questions:

1. *What prototyping condition were you in?*
2. *How did this affect your design process?*
3. *How did this affect your performance in the competition?*
4. *What would you change about your design process in the future? Why?*
5. *Were you satisfied with your condition assignment? Why?*
6. *If you could redo the project, would you use an iterative prototyping strategy, a parallel prototyping strategy, or a combination? Why?*

The results of this paper focus on student responses to these design reflection questions, and primarily on question 2 and question 5. These questions were chosen to capture student perceptions of the two prototyping strategies during the design competition and how they felt about them as strategies for use in future projects throughout their undergraduate careers.

3.2 Satisfaction Sorting

Based on student responses to the questions shown in section 3.1, participants were categorized by two different methods: “permutation sorting” and “emergent themes”. Permutation sorting consisted of eight categories capturing whether the participants scored points and whether they were satisfied with their random condition assignment. The categories are duplicated for each experimental condition for a total of eight. These categories are listed in Table 2. The primary source of data for permutation sorting came from responses to Question 5 of the design reflection questions where the participants were explicitly asked if they were satisfied with their condition assignment.

***Table 2**: Permutation categories for qualitative sorting of student satisfaction.*

	ITERATIVE		**PARALLEL**	
	No Points	**Scored Points**	**No Points**	**Scored Points**
Satisfied	*No Points Satisfied*	*Scored Points Satisfied*	*No Points Satisfied*	*Scored Points Satisfied*
Not Satisfied	*No Points Not Satisfied*	*Scored Points Not Satisfied*	*No Points Not Satisfied*	*Scored Points Not Satisfied*

3.3 Emergent Theme Analysis

Sorting for emergent themes was done primarily using student responses to question 2, but responses to the other questions could be referenced for clarification. This analysis was conducted as exploratory work to generate explanations for the contextualized prototyping activities involved in this study and to reveal hidden meaning from the more quantitative permutation analysis. These results deepen understanding of student perceptions for prototyping strategy in engineering design. The primary research question guiding the emergent themes portion of analysis is:

> *What perceptions are emerging from those in the iterative and parallel condition about the assigned prototyping approach?*

Participants from each experimental condition were sorted into categories through multiple cycles of coding, where the meaning behind participants' responses were investigated, extracted, and categorized. Saldaña defines a code as "most often a word or short phrase that symbolically assigns a summative, salient, essence-capturing, and/or evocative attribute for a portion of language-based or visual data" [38]. After identifying the primary codes, another cycle was repeated to ensure convergence by comparing the data to the identified emergent themes. For this analysis, the experimental conditions were considered independently through two lenses in order to eliminate bias when identifying the emergent themes. Bias could have been introduced through the researchers preconceived ideas about how an iterative or parallel prototyping approach affects design outcome. Further, it was clear which condition each participant was assigned to in the final design reports since this information was often included in their responses to the design reflection questions. Considering the experimental conditions independently helped to remove these sources of bias. The resulting categories from this analysis are described and defined in the results section.

Taken together, these two analysis methods were selected to give different perspectives on student perceptions of each prototyping strategy and capture how those strategies affected their design process. The permutation categorization provides a more explicit analysis whereas the emergent theme categorization provides a more qualitative look at participants' design experience throughout the competition and deepens understanding of the permutation sorting. With both methods, participants' perceptions about the prototyping strategies and how they affected the design process could be assessed and analyzed.

4. RESULTS

Based on answers to the six design reflection questions, participants were sorted into the permutation categories and emergent theme categories by a graduate student studying engineering design theory and methodology. In total, 45 student reports were assessed with 23 in the iterative condition and 22 in the parallel condition. A random sample of 53% of the data (including 12 from the iterative condition and 12 from the parallel condition) was sorted into the permutation categories by a different graduate student studying design theory and methodology for inter-rater reliability. Results showed 100% inter-rater reliability for the permutation sorting, which is attributed to participants' explicit answer to question 5 of the design reflection questions concerning their satisfaction. For the emergent theme analysis, one graduate student sorted the participants based on their responses to the design reflection questions and collaboratively adjusted the language of each theme with the second graduate student. Permutation categorization was compared to participants "competition score" for analysis. Notably, many participants did not earn points in the competition because the design task proved to be more difficult than expected, which is discussed in more detail the discussion section.

4.1 Satisfaction with Prototyping Approach

The permutation categorization showed distinct differences between the iterative and parallel conditions based on their satisfaction with their condition assignment and whether or not they scored points in the design competition. As shown in Figure 2, participants that scored points in the iterative condition were unanimously satisfied with condition assignment, whereas participants in the parallel condition were split (left side of Figure 2). Also shown, participants

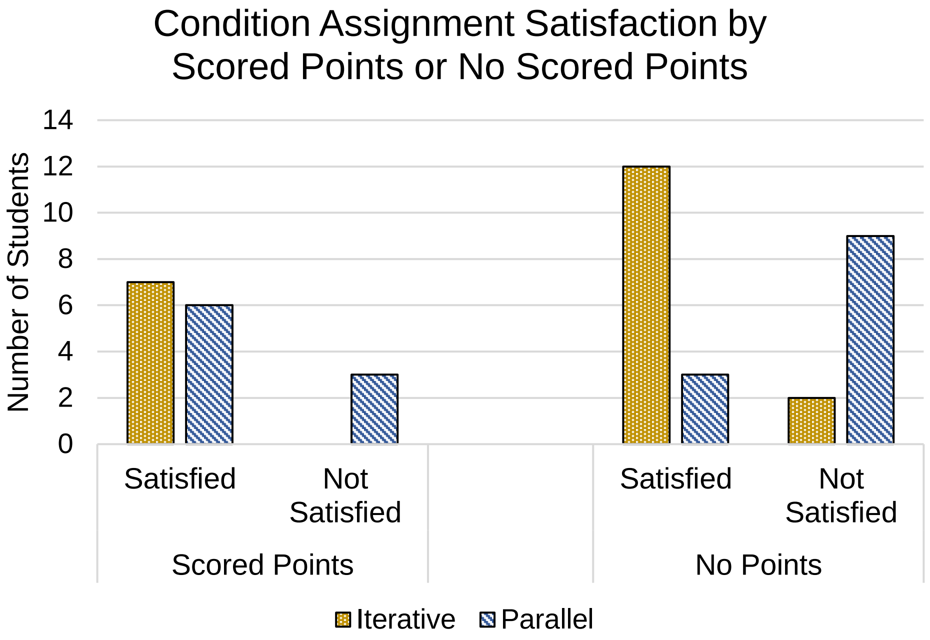

Figure 2*: Comparison of iterative and parallel prototyping strategies based on competition performance and satisfaction with random condition assignment as analyzed by the permutation categories.*

that did not score points in the iterative condition were much more satisfied than participants that did not score points in the parallel condition (right side of Figure 2).

Considering both of these mentioned results, participants showed a natural preference towards iterative prototyping regardless of their success during the design competition. A Chi-squared analysis between condition assignment and satisfaction show a significant difference $\chi^2(1, n = 45) = 13.79$, $p = 0.001$, suggesting that the iterative condition was more satisfied with their condition assignment. This is despite a significantly higher chance for participants in the parallel condition to score points in the competition as measured through a Chi-squared analysis $\chi^2(1, n = 45) = 4.06$, $p = 0.044$. The preference for an iterative prototyping strategy appears stronger than advantages afforded by a parallel prototyping strategy as observed by participants' perceived satisfaction with their random assignment to one of the two prototyping strategies.

4.2 Emergent Themes from the Iterative Condition

For participants in the iterative condition, three emergent themes were revealed that captured their perceptions of the assigned prototyping strategy. The three resulting emergent themes are:

1. *Iterative Approach Limited the Design Process*: Referenced when a student discussed design decisions being "limited." Often due to feeling pressure to continue on with an original idea that didn't work well for the sake of continuity.
2. *Iterative Approach Allowed for Minor Design Improvements*: Referenced when a participant discussed the iterative design process facilitating incremental improvements between iterations such as adjusting tolerances. These participants often discussed the iterative approach encouraging minor improvements rather than major design changes in

order to “play it safe” since they were familiar with the functionality of their early designs.

3. *Iterative Approach Allowed for Testing to Refine Design Concepts*: Referenced when a participant discussed making design improvements through testing after each iteration. This category distinctly references participants that mentioned learning from their design through testing, refinement, or evaluation.

While the vast majority of reports aligned with emergent theme 2 (10 students) or emergent theme 3 (10 students), emergent theme 1 was identified for a small portion of participants in the iterative condition (3 students out of 23) that felt negatively about an iterative prototyping approach. The general positive perception for an iterative approach is consistent with the permutation sorting.

4.3 Emergent Themes from the Parallel Condition

For participants in the parallel condition, two emergent themes were revealed that captured their perceptions of the assigned prototyping strategy. The two resulting emergent themes are:

4. *Parallel Approach Encouraged Design Space Exploration*: Referenced when a participant discussed the parallel approach enabling them to pursue two or more unique ideas and combining the best aspects of each for the final design. Considering multiple concepts simultaneously is taken to mean design space exploration.
5. *Parallel Approach Limited Opportunity for Improvements*: Referenced when a participant discussed feeling limited by the lack of testing and time associated with the parallel approach to make improvements on their design. This does not necessarily imply that students felt limited in their ability to make minor adjustments through the prototyping approach.

Participants in the parallel condition perceived the assigned prototyping strategy either positively (by allowing them to explore the solution space) or negatively (by limiting the opportunity for design refinement). This split was nearly down the middle (10 students for emergent theme 4 and 12 students in emergent theme 5). Again, the results are showing that participants prefer a sequential approach to prototyping over a simultaneous approach that is consistent with the results from the permutation sorting. Notably, about half of the participants in the parallel condition noticed that a parallel approach allowed for broad solution space exploration that facilitated learning about the design problem and the tools being used in this contextualized design process.

4.4 Summary of Results

Based on the results from the permutation categorization and the identified emergent themes, it is clear that students prefer an iterative prototyping strategy. Notice that out of the 24 participants in the parallel condition, 12 participants felt that the approach limited their opportunity for improvement based on the emergent theme analysis. On the other hand, only 3 out of 23 participants in the iterative condition felt negatively about the approach. For positive perceptions, participants felt that an iterative approach facilitated methodical improvement through minor adjustment whereas a parallel approach encouraged design space exploration. In general, the approach used for the permutation sorting shows a strong preference for an iterative prototyping approach that is supported by the identified emergent themes. These emergent themes provide insight into the hidden meanings for why this preference for an iterative approach exists. Further, the identified emergent themes create the groundwork for a what a typology for prototyping perception might look like in future work.

5. DISCUSSION

The permutation sorting clearly shows a significant difference in student satisfaction with their randomly assigned prototyping conditions. Participants in the iterative condition are significantly more satisfied than participants in the parallel condition regardless of their success in the design competition, which supports the first hypothesis (H1). This is despite the parallel condition being more likely to score points in the design competition, which supports the second hypothesis (H2). Participants showed a preference towards an iterative approach to the prototyping process even though a parallel approach yielded better design success. An iterative approach to engineering and design is prevalent through engineering pedagogy, which may contribute to this difference in satisfaction since students are likely more comfortable with this approach and likely uncomfortable utilizing alternative strategies that they are not familiar with.

For example, one student in the parallel condition noted:

> *"No, I am not satisfied with my group assignment. Had I been with the Iterative group I think I would have been able to produce a design that would have performed much better in the competition."*

While a student in the iterative condition said:

> *"I was glad to have been Iterative because it allowed me to better learn from my mistakes and fix them with a greater efficiency."*

In general, the emergent theme categorization led to similar conclusions as the permutation sorting, although it sheds light onto why participants might prefer an iterative approach beyond the simple explanation of familiarity. Participants in the iterative condition largely felt that an *iterative approach allowed for minor design improvement* and *allowed for testing to refine their design concepts*. Notably, the iterative and parallel conditions tested the same number of prototypes before settling on a final design. Students' perception that iteration facilitates small incremental improvement through testing towards some optimized solution is not supported by the results of the design competition where the parallel approach outperformed the iterative approach. Students might make small adjustments that steer their designs farther from an optimal solution as opposed to towards it. Further, what the participants called "minor adjustment" might in reality instead be termed "tuning" for additive manufacturing. Considering that this competition was conducted in an introductory course, many students do not have prior CAD experience or knowledge of the limitations of additive manufacturing. Their adjustments may have been primarily focused on concepts such as tolerancing or print-orientation as opposed to conceptual changes to their designs. A closer analysis of the participants' physical prototypes is left to future work.

For the parallel condition, the participants were split about whether a parallel approach *encouraged design space exploration* or *limited the opportunity for improvement*. Of the 10 participants that perceived a parallel approach as encouraging design space exploration, 6 scored points. Of the 12 participants that felt a parallel approach limited the opportunity for improvement, only 3 scored points. Scoring points in the competition affected the participants' perception of parallel prototyping where success may have changed their preconceived notions of how engineering design should be conducted. The resulting emergent theme categories from the parallel condition support that students have a natural preference towards iteration and are hesitant to change their perceptions about design strategy. This result might suggest that broad solution space exploration is not taught in engineering curricula or is a cognitively taxing activity. Notably, the highest scoring student in the design competition from either condition felt negatively about the parallel prototyping strategy saying:

> *"I believe it hindered [my design process] compared to iterative, because it didn't allow me to test my prototype one more time."*

Interestingly, there were a handful of participants that expressed appreciation for both an iterative and parallel approach to prototyping, even indicating that they might blend the two strategies in future design projects. Students were asked to report whether they would use an iterative, parallel, or combination approach in future design projects. Only 2 reported that they would use an exclusively parallel approach. While 14 reported that they would use exclusively an iterative approach, 30 students reported that they would use a combination approach that incorporated elements of both strategies. Using a Chi-squared analysis, this result is statistically significant $\chi^2(2, n = 45) = 24.40, p < 0.001$. From a pedagogical perspective, there is value in exposing students to different design strategies as they learn what is most appropriate for a given design problem. In their final reports, some participants wrote:

> *"If I could redo this design process, I would likely opt to be in a combination of parallel and iterative groups as this group would allow me to explore different ideas more than the iterative group did; however, both groups produce different strategies and strengths in the final product." [Iterative Condition]*
>
> *"If I could redo the project, I would use a combination of both the iterative and parallel strategies. I feel it would be best to start with a handful of designs (like I did for my first two models) and find which one best worked within the requirements of the competition. This plan would also allow for more than one iteration to be printed before the final, so I could adopt a "trial and error" method in order to see what worked and what did not." [Parallel Condition]*

One possible explanation for the preference towards an iterative approach may be that refinement and incremental change is engrained throughout our lives. Many school, work, and hobby projects are completed with an iterative approach (such as the process of revising a conference paper). Having two concepts, or prototypes, may be perceived as a waste of time despite the benefits, especially in cases where a concept or idea is completely abandoned. In addition, applying a well-rehearsed strategy to a new, novel problem may offer an initial level comfort. A parallel approach, being less common, could create an added degree of unfamiliarity that is frustrating and simply less preferred. In this study, student participants showed a clear preference for an iterative prototyping approach despite better competition success by those using a parallel approach. While the iterative condition was able to "refine" their design twice (between the first and second prototype, then between the second prototype and final design), the parallel condition had a single opportunity to "refine" their design (before the final design). As previously noted, both conditions produced the same number of prototypes.

This experimental study is subject to a few limitations. First, the two experimental conditions were aware of each other, which unfortunately could not be avoided by the research team given the context of the study. Knowledge of the other condition could have influenced perceptions about the participants' assigned prototyping approach negatively or positively, but ultimately beyond what the research team could capture in the collected data. Knowing that the iterative condition had an extra opportunity for "refinement" may have contributed to the preference for an iterative prototyping approach. Keeping the two experimental conditions isolated from each other is left to future work. Second, the design problem proved to be more difficult for the participants than expected. The research team hoped to see a wide range of competition performance that could be analyzed through quantitative methods. Instead, analysis was conducted on whether or not participants scored any points at all.

In future work, a design task more suited to an introductory undergraduate course could yield higher granularity in quantitative differences between an iterative or parallel prototyping strategy, whereas the design problem implemented in this study may be more suitable for upper-level courses or for graduate students. In addition, future work includes analyzing students' perceptions through a single investigative lens as opposed to the two independent lenses utilized in the emergent theme analysis. This would include generating a set of codes that could capture both negative and positive perceptions across experimental conditions. The work presented in this paper provides the groundwork for this future analysis.

6. CONCLUSION

This study examined student perceptions of two prototyping strategies: an iterative approach and a parallel approach. Results showed that students preferred an iterative prototyping strategy regardless of whether or not their assigned prototyping strategy led to design success (scoring points in a design competition). Further, participants were categorized through "emergent themes" based on their answers to design reflection questions in their final report. These emergent themes showed that some participants preferred a methodical, iterative prototyping approach where small changes could be made to a single concept, while other participants gained appreciation for the design space exploration afforded by a parallel approach. The general preference for an iterative prototyping strategy contradicts statistically significant findings that a participant in the parallel condition was more likely to score points in the design competition. In summary, students prefer an iterative prototyping strategy despite the advantages of a parallel prototyping strategy.

The results presented in this paper contribute to our understanding of designers' preferences for different prototyping strategies in an engineering design context. Of particular interest, analysis of students' reports revealed perceptions that an iterative approach offers repeated testing and refinement opportunities, while a parallel approach encourages exploration of the solution space. These two ideas taken together are critical for effective design success. This study has also shown student apprehension for the application of new design strategies than what they are likely most accustomed to. As we continue to understand how prototyping strategies affect design outcomes, we can determine the benefits and limitations of different design strategies to find unique approaches for specific problems that lead to novel, innovation designs.

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