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# The Impact of Prototyping Strategies on Computer-Aided Design Behavior

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## ABSTRACT

Prototyping is central to the engineering design process. Physical prototypes facilitate learning about a design concept's functionality, feasibility, etc. at various stages of the engineering design process. The relationships between prototyping strategy and modeling behaviors are not well understood. Through a student design competition, the effects of parallel and iterative prototyping strategies on computer-aided design (CAD) behaviors were investigated and compared. To investigate the effects, the feature trees in students' CAD assemblies were recorded and compared using a range of statistical analysis techniques. Results show that designs with less complexity (as captured through the feature trees) were more likely to have a positive performance in the design competition. In addition, results suggest that the two different prototyping strategies had an impact on participant usage of CAD package functionality. These results showcase what features students in an introductory engineering graphics course are most likely to use to model their design concepts. Overall, this work contributes to a growing body of knowledge on how an iterative or parallel prototyping strategy impacts the engineering design process.


## 1 INRODUCTION

Prototyping is important during the engineering design process. Prototypes allow engineers to communicate their design ideas, test functionality, and get valuable feedback from stakeholders. For physical products, the prototyping process often involves computer-aided design (CAD) to model solutions or perform analyses. Most undergraduate mechanical engineering students take a CAD course during their studies. Further, research has shown that instruction on CAD tools has a positive impact on students' development of spatial reasoning skills [1]. The prototyping process and the use of CAD tools are often interwoven during engineering design, particularly when designing physical artifacts.

Depending on the nature of a design problem, an engineer can approach the prototyping process in different ways. An iterative approach is typically taken because it allows for testing, refinement, and incremental improvement and has been shown to improve design outcomes [2]–[4]. Many textbooks also encourage an iterative approach [5], [6]. With an iterative approach, prototypes can move linearly from "proof of concept" to "proof of product" to "proof of process" to "proof of production" [7] in a way that gives stakeholders a clear development narrative. However, a parallel approach may allow for rapid and broad exploration that helps identify viable solutions earlier in the design process [8]–[10]. Parallel prototyping typically refers to the development of multiple solutions simultaneously during the design process until one solution proves to better meet design requirements. The prototyping approach taken can depend on the availability of time and resources. In many cases a parallel approach requires more time and resources, though may significantly shorten the total development cycle since the solution space can be more fully explored. On the other hand, iteration can be costly if a design concept proves to not be feasible late in development. In practice, a parallel prototyping approach is more feasible for design teams since team members can focus on different solution concepts. A blend of iterative and parallel strategies that allows for broad exploration and ample refinement likely leads to the best design outcome.

This paper explores how an iterative or parallel prototyping strategy impacted students' use of CAD during a design competition in an introductory mechanical engineering course. The results in this paper build from prior work that investigated how the two prototyping approaches affected competition performance, engineering design self-efficacy, solution space exploration, and design satisfaction [11], [12]. This paper specifically addresses how the prototyping strategies impacted design complexity and CAD software feature use and is compared to competition performance. In this work, CAD features refer to the specific operations that a designer specifies within the software space to create a model. The overarching aims of this research are to understand how novice engineers are using CAD tools for prototyping and to investigate the relationship between prototyping strategy and designer behavior.

The authors hypothesized that student participants using an iterative prototyping strategy would explore fewer of the features available in the CAD software (H1) because their focus on a single design concept would not encourage broader solution exploration therefore requiring less CAD features. On the other hand, students using a parallel strategy would likely explore a broader set of available features since designing two different conceptual solutions would likely require different feature usage within the CAD software. The authors also hypothesized that students who implement fewer unique CAD features in their models would perform better in the design competition (H2). Given that participants consisted of novices, models with less complexity would likely be associated with improved competition performance because greater complexity would likely increase cognitive load during testing, revision, and refinement.

## 2 BACKGROUND

Prior research has explored how iterative and parallel approaches to the design process impact outcome. Dow et al. investigated the relationship between time constraints and iteration, finding that participants that iterated despite time constraints outperformed those who did not iterate [2]. Dow et al. also explored a parallel approach to prototyping and found that those who designed web advertisements with a parallel process outperformed those with a purely iterative process [9]. As a final continuation, Dow attempted a similar study for physical prototypes, but the results were largely inconclusive [10]. Dahan and Mendelson have attempted to expand the basic dichotomy (iterative vs. parallel) to include one-shot, sequential, parallel or hybrid prototyping approaches [13]. Within this model, one-shot refers to situations where the prototype is the actual final design itself, sequential is synonymous with iteration, parallel describes exploration of multiple solutions simultaneously, and hybrid blends the sequential and parallel approaches. Dahan and Mendelson argue that a parallel approach to the prototyping process is best suited to situations with high production costs and short project timelines [13]. Beyond approaches to the prototyping process itself, six prototyping heuristics have been identified as iterative, parallel, scaling, subsystem, requirement relaxation, and virtual prototyping [14], [15]. Menold et al. developed a prototyping framework known as "Prototype for X (PFX)" that consists of framing, building, and testing to support novice designers prototyping process [16]. These ideas have been

explored in industry settings as well. For example, parallel prototyping was identified to occur at points during the design process where major conceptual shifts were present [17].
There is disagreement in the literature about what exactly a prototype is. Some seminal texts specifically define a prototype as a physical artifact [5], [6], [18] while others suggest that sketches, mathematical models, or simulations can also be considered prototypes [19]. Published research commonly includes CAD models into the definition of a prototype [14], [20], [21], considering that they are essentially 3D renderings of the physical product itself. These different definitions for a prototype are largely interchangeable, and likely pertain to specific contexts. For the study presented in this paper, prototypes refer to the physical artifacts created by the students for the design competition and the CAD models are not considered to be prototypes.

Some research has explored how novice designers engage with CAD during the engineering design process. For example, Summers et al. examined how different input devices impact CAD modeling behavior and found that mouse inputs led to shorter completion times and fewer errors compare to direct or indirect tablet input [22]. In addition, the inclusion of a predictive manufacturing time tool into CAD software reduced final predicted part mass but did not significantly increase modeling time [23]. The majority of published work focuses on supporting students using CAD software [24], [25] or the differences between CAD and sketching [26]–[28] instead of investigating student behavior while interfacing with CAD tools. In contrast, the work presented in this paper focuses on students' CAD models and how prototyping process impacts their design behaviors. Ultimately, the results of this work contribute to the existing literature and set a foundation for future studies that explore how students actually use digital modeling tools and how these tools impact the engineering design process.

## 3 METHODOLOGY

The following subsections describe the university context, student participants, design competition, and study design. Terminology used throughout the results and discussion sections are also defined.

### 3.1 Study Context

This study was conducted in a 1st-year undergraduate engineering course focused on free-hand sketching skills and CAD modeling techniques. This study took place at a competitive research-focused public university in the southeastern United States. The design competition took approximately 7 weeks to complete towards the end of the 15-week semester. These seven weeks spanned from when the initial assignment instructions were provided to when the competition took place and final design reports were due. All aspects of this research study were approved by the university's institutional review board (IRB).

### 3.2 Participants

Participants in this study consisted of undergraduate mechanical engineering students enrolled in the course. Of these students, 46 gave voluntary consent to participate in the research study with 23 randomly assigned to the iterative condition and 23 randomly assigned to the parallel condition. On an initial demographics survey, 11 of these students self-reported as female and 35 self-reported as male. For the results presented in this paper, sample sizes slightly differed due to the availability of complete CAD models at the end of the design competition with n = 22 in the iterative condition and n = 21 in the parallel condition for a total of 43 student participants. Some CAD models had to be discarded for analysis because they were either corrupt or incomplete.

### 3.3 Design Competition

Students in this study participated in a design competition. Participants were tasked with designing a device to launch a small foam ball into a target of concentric cups 10 feet away (as shown in Figure 1). These cups were arranged in a hexagonal pattern and were color-coded by filling them each with colored beads that corresponded to the possible point values. These beads also helped weigh them down during testing, as well as reduced the possibility for the small foam balls to bounce out of the cups. This setup was produced on a large piece of paper to ensure alignment and fairness during the design competition.

The device designed by the students would be physically produced by the research team (the authors of this paper, research assistants, and course instructors) using a fused deposition modeling (FDM) additive manufacturing method. Students were not allowed to print their own iterations (e.g., in the university makerspace). A maximum build volume of 4” x 5” x 4” was required for the prototypes. The designs were also required to have two stable states (e.g., when loaded with the foam ball and after launching the foam ball). Prototypes could have multiple components. Other than the provided foam balls and standard-size 33 rubber bands, no other materials were allowed for construction of their prototypes such as glue, tape, bolts, etc. to encourage exploring the capabilities of additive manufacturing. In only a few cases, some students were allowed to glue/tape parts back together that broke during the design competition.

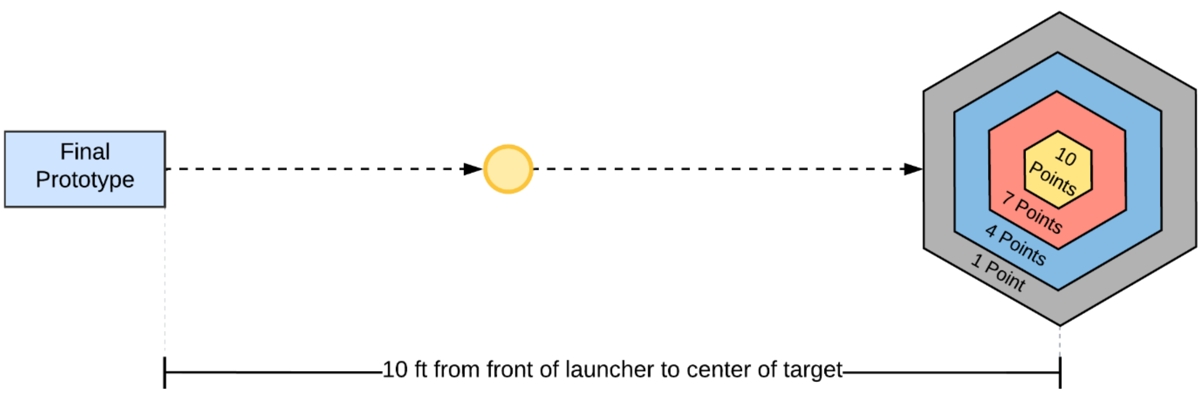


*Figure 1: Top-down view of competition setup with point values increasing closer to the center of the target.*

Scoring during the competition was determined from the best three of five attempts. Scores were comprised of a raw score (more points closer to the center of the target), a distance score (more points closer to the 10-foot requirement), and an attempt score (the summation of the distance score and the raw score). After all trials, each student’s top three attempt scores were summed for their final competition score. The distance scores were determined as provided in Table 1. A comprehensive description of the competition setup, scoring details, and design task can be found in prior work by the authors [11], [12].

***Table 1****: Points awarded for the distance score based on how proximity to the 10-foot requirement.*

| 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 |

## 3.4 Prototyping Conditions

Participants in this study were randomly assigned to one of two prototyping conditions: the iterative condition or the parallel condition. Each student worked individually on this project. Notably, due to curricular constraints, all student participants were in the same course section and were aware of the two prototyping conditions. While this may have introduced bias into the results of this study (and the related study), prior published results showed that this may have led to an unexpected learning outcome, where students appreciated the benefits of both an iterative and parallel approach to prototyping stating that they planned to use a combined strategy for future projects [12]. Prior work also shows that students strongly preferred an iterative approach regardless of condition or competition performance [12]. Working with the university's institutional review board (IRB), great care was taken to ensure that the educational experience was equivalent and fair for students in either prototyping condition. Their performance in the competition did not directly impact their grade in the course, whereas project deliverables were considered course content.

Students in the iterative condition (Figure 2, right) produced a model using CAD in 1.5 weeks and submitted it to the research team. After production, prototype 1 was returned to students for testing. They were then allowed to make any revisions or changes to their models that they wanted using provided rubber bands and foam balls for testing. After testing, they adjusted their CAD models for resubmission, which was called prototype 2. The research team again produced their prototypes and returned them to the students after completion. A similar round of revisions was allowed before submission of the final prototype, which would be used during the design competition. Students were allowed to make any changes (including an entire conceptual shift) between each of these stages.

Students in the parallel condition (Figure 2, left) produced two CAD models in 2 weeks before submitting them to the research team. Students were instructed that these models could be completely different concepts, variations on the same concept, or anything in-between. Because students in the parallel condition had to submit two CAD models simultaneously, they were given a later deadline for submission. The research team produced both of their prototypes (prototype 1 and prototype 2) and returned them to the students for testing. The students could then make any revisions before submission of the final prototype, which would be used for the design competition. Students were informed that their final prototype could be derivative of their prototype 1 or prototype 2. They could also combine ideas from each or produce an entirely new concept. All prototypes for both conditions were produced using a fused deposition modeling additive manufacturing method.

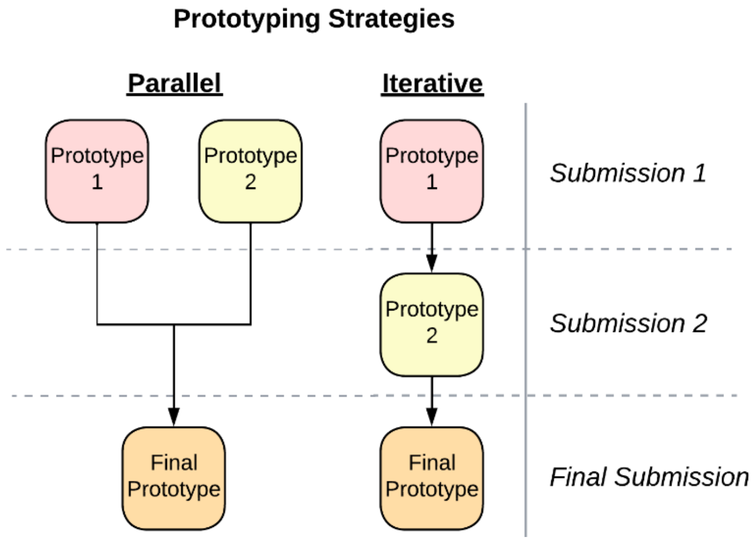


***Figure 2****: Prototyping process for the parallel and iterative conditions in the study. The parallel condition produced Prototype 1 and 2 simultaneously while the iterative condition produced them sequentially.*

Since prototype production at every stage was controlled by the research team, learning occurred at distinct points throughout the project. These distinct points of learning were fundamentally different between the two prototyping conditions. This allowed for comparisons to be made between the two prescribed strategies since learning occurred either sequentially for the iterative condition (after prototype 1 and then after prototype 2) or simultaneously for the parallel condition (after receiving both prototype 1 and prototype 2 at the same time). Because students were not allowed to produce their own prototypes (e.g., makerspace usage was not allowed for this project), participants in the parallel condition learned from their first two design concepts simultaneously whereas students in the iterative condition learned from their designs sequentially. Learning through testing is a key part of prototyping and controlling that learning cycle in this study allowed for comparisons to be made between an iterative vs. parallel approach to the prototyping process.

## 4 RESULTS

The results explore a few different aspects of CAD usage in comparison to assigned prototyping condition and competition performance. Given that “sketches” are inherent to all CAD models in this study, this software feature has been omitted for analysis, which does not affect the statistical results. All results in this study stem from Solidworks feature trees extracted from students CAD models for their final prototype used in the design competition. Unique features refer to a distinct modeling process in the CAD software (e.g., Plane, Mirror, Chamfer, etc.).

### 4.1 Parallel vs. Iterative Average Unique Feature Usage

After extracting feature trees from the final CAD models, the average usage of unique features by each participant in both conditions was determined and compared as shown in Figure 3. Averages are presented with +/- 1 standard error.

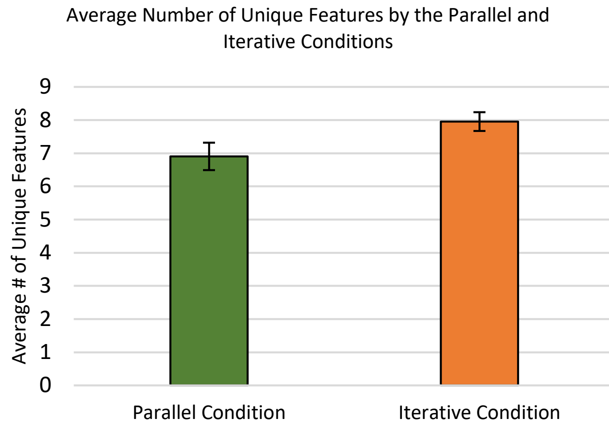


***Figure 3***: *Average unique feature use between the parallel and iterative conditions with +/- 1 standard error.*

On average, students in the parallel condition used fewer unique CAD features (6.90 features) than students in the iterative condition (7.95 features) with a difference of 1.05 features as shown. Sample sizes for these results are n = 21 and n = 22 for the parallel and iterative conditions respectively. This data passes a Shapiro-Wilk test for normality. A two-tailed t-test yields a significant difference between the two conditions ($t(41) = -2.11$, $p = .041$), with the parallel condition using significantly fewer unique features. This result has a medium effect size using Cohen's d ($d = 0.642$). This initial result implies that the prescribed prototyping strategy had a measurable effect on CAD software usage.

### 4.2 Scoring vs. Non-Scoring Average Unique Feature Usage (Parallel Condition)

Unique feature usage for students who scored points in the competition vs. students who did not score points was also considered. Only participants from the parallel condition are considered in this subsection (Figure 4). This same analysis was completed for the iterative condition but is not presented because of small sample sizes of n = 3 (scoring) and n = 19 (non-scoring). Students in the parallel condition had more balanced sample sizes of n = 8 (scoring) n = 13 (non-scoring).

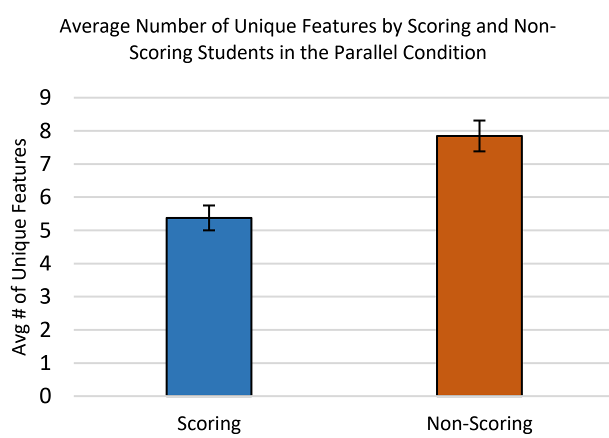


***Figure 4***: *Average unique feature usage between those in the parallel condition who scored points vs. those who did not score points in the design competition with +/- 1 standard error.*

As shown, students in the parallel condition that scored points in the design competition used fewer unique CAD features than those who did not score points on average (Figure 4). Those who scored points averaged 5.38 unique features (n = 8) whereas those who did not score points averaged 7.85 unique features (n = 13) for a difference of 2.47 features. This data passes a Shapiro-Wilk test for normality. A two-tailed t-test shows a significant difference in average unique feature usage by those who scored points vs. those who did not score points in the parallel condition ($t(19) = -3.718$, $p = .001$). This result has a very large effect size using Cohen's d ($d = 1.762$). When only considering students in the parallel condition, average unique feature usage is significantly lower for those who scored points in the design competition.

### 4.3 Scoring vs. Non-Scoring Average Unique Feature Usage (Both Conditions)

Building from the previous analysis, the same comparison was made but includes all students from both conditions (Figure 5). Average unique feature usage by scoring and non-scoring students is considered regardless of random condition assignment.

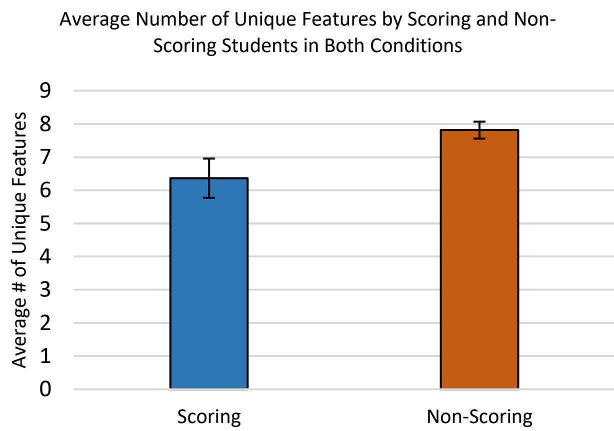


***Figure 5**: Comparison of average unique feature usage including both conditions between those who scored points vs. those who did not score points in the design competition with +/- 1 standard error.*

When considering both conditions, students that scored points in the competition similarly had a lower average of unique feature usage (6.36 features) than those that did not score points (7.81 features) with a difference of 1.45 features (Figure 5). Sample sizes for the parallel condition and iterative conditions were n = 11 and n = 32 respectively. As previously mentioned, this difference in competition performance is explored in prior work [11]. This data does not pass a Shapiro-Wilk test for normality, so non-parametric statistical measures were implemented. A Mann-Whitney U-test shows that students who scored points in the design competition used significantly fewer unique features in their final prototypes ($z = 2.213$, $p = .027$). This result has a large effect size using Cohen's d ($d = 0.840$). These results show that those who scored points in the design competition used significantly fewer unique CAD features than those who did not score points. Notably, this result is dominated by the parallel condition (of the 11 who scored points in this analysis, 8 were assigned to the parallel condition). However, the increased sample sizes reinforce the finding that there is a relationship between unique feature usage and design success.

### 4.4 Top 5 Most Frequently Used Features

Cumulative feature usage was also recorded. Results from this analysis show the frequency of CAD modeling features used for students' final prototypes in the parallel and iterative conditions. As shown in Figure 6, some features were used much more commonly than others.

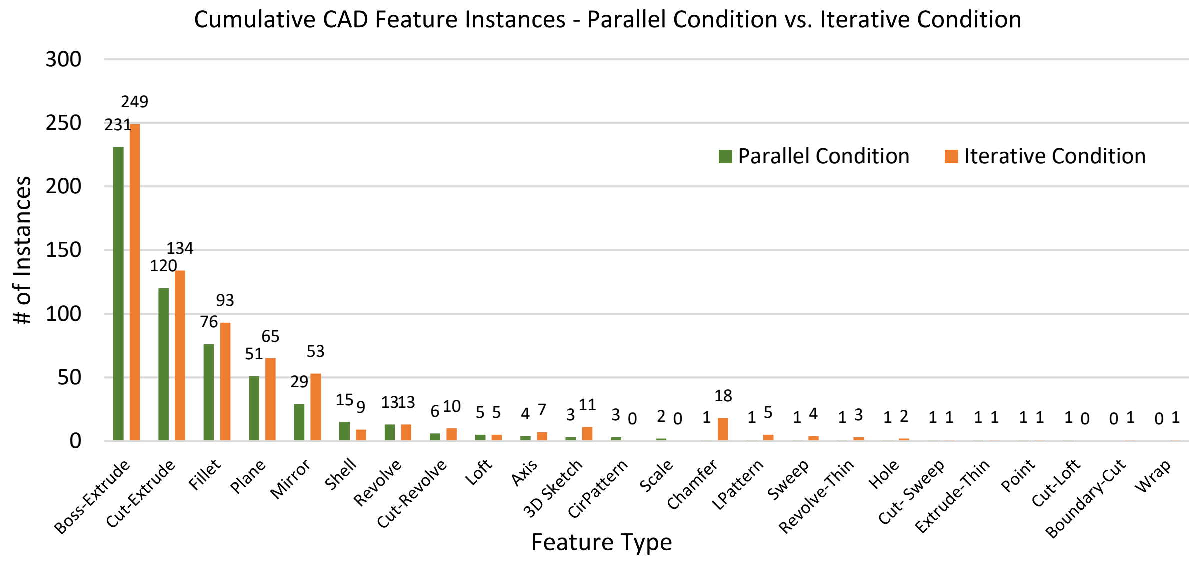


***Figure 6**: Cumulative CAD feature usage by the parallel and iterative conditions in their final prototypes for the design competition.*

Based on this analysis, five CAD features were used the most by both the parallel and iterative conditions: Boss-Extrude, Cut-Extrude, Fillet, Plane, and Mirror. After these first five, feature usage is considerably lower. Boss-Extrude, Cut-Extrude, and Fillet are not at all surprising, and likely routine in most CAD models generated using Solidworks. Many of the features with low frequency were likely implemented in only one or two models from the data set and were specifically useful for the design geometry. Of note, 18 instances of "Chamfer" were observed for the iterative condition. This is likely from only a few models where students prefered the aesthetic of a chamfer over a fillet, but this has not been confirmed qualitatively. Overall, the frequency usage results (Figure 6) could inform curricular content where features used less frequently are emphasized to open up design space possibilities for novice designers. Of course, there are many more possible features that can be used, but were not observed in this dataset.

## 5 DISCUSSION

From the results, prototyping strategy has a significant impact on how students use CAD software. Students in the parallel condition show less unique feature usage by 1.05 features than students in the iterative condition with statistical significance. This result does not support the first hypothesis in the introduction, which states that "student participants using an iterative prototyping strategy would explore fewer of the features available in the CAD software (H1)". This may indicate that parallel prototyping leads to design concepts with lower complexity than iterative prototyping. Iterative prototyping may encourage fine-tuned refinement earlier in the design process as a possible source of this difference. Further, a parallel approach may reduce over-commitment to a single design concept where fine details are not included in the CAD model until after a physical prototype provides some evidence that the concept will satisfy design requirements. In this study, refinement for those in the parallel condition would occur during modeling of the final prototype. In practice, the design of physical artifacts will inherently always include some form of iteration. These results do not necessarily suggest that a purely parallel approach should be taken over an iterative approach, but rather that a parallel prototyping strategy may reduce the complexity of a final design.

Considering only those in the parallel conditions, results show 2.47 fewer unique feature usage by those that scored points in the design competition than those who did not score points with statistical significance. This suggests that lower complexity is correlated with design success. It is important to consider that participants in this study were novices to engineering, CAD, and engineering design. Novices may not be able to successfully design prototypes with high complexity with increased cognitive load from exposure to new software, learning about the engineering design process, and juggling two possible conceptual solutions given the imposed parallel prototyping strategy. It may also be that students in the parallel condition felt time pressure to complete two models, which led to the design of less complex CAD models. In addition, research has shown that novice designers use physical prototypes to rationalize design shortcomings [29] where a parallel approach to prototyping may mitigate this effect and reduce design fixation [30]. Maria Yang showed that prototypes designed with fewer parts overall and fewer added parts during development typically lead to improved design outcomes [31]. The results were consistent when considering both conditions for analysis. Those who scored points in the design competition (in either the parallel or iterative condition) created models with 6.36 fewer unique features than those who did not score points with significance. Notably, this analysis leads to a larger difference in unique feature usage (6.36 features) than when only considering those in the parallel condition (2.47 features). This reinforces that increased complexity may negatively impact design success. Of those that scored points in the design competition, nine of twelve were in the parallel condition, which may contribute to the lower complexity observed overall. Statistically significant differences in unique feature usage by competition success were not observed when only considering those in the iterative condition. The difference in design success by prototyping strategy is described in detail in a published journal article [11]. Taken together, these results support the second hypothesis from the introduction, which states that “students who implement fewer unique CAD features in their models would perform better in the design competition (H2).”

Feature usage frequency may inform curricular content. Specifically, it may be beneficial to focus curricular content on features with lower observed frequency. By understanding how to use more features, the solution space may widen for novice designers. The top five features used (Boss-Extrude, Cut-Extrude, Fillet, Plane, and Mirror) were consistent between the iterative and parallel conditions, implying that these modeling features are likely inherent to most CAD models, or at the very least common for the problem space provided within the context of this design competition. Understanding how curricular coverage of the CAD features with lower observed frequency impacts design outcome is left to future work.

The results presented in this paper are subject to a few limitations. First, the outcomes from the design competition may change depending on participant expertise. In other words, the findings could differ if the design competition was implemented in an upper-level engineering course as opposed to an introductory course. It is expected that performance in the design competition would improve for upper-level students in either prototyping condition given their design experiences throughout an undergraduate curriculum. Second, different instructors, lecture content, or student demographics could lead to different results. However, these preliminary findings set the groundwork to further studies on how prototyping strategy, design complexity, and CAD usage influence each other to ultimately improve undergraduate education.

## 6 CONCLUSION

The results in this paper show that the prototyping approach taken during the design process can impact how student designers use CAD software. Notably, a parallel prototyping strategy led to designs with significantly fewer unique features in the students' models. In addition, a relationship was observed between design competition success and model complexity. Students that scored points in the competition designed models with significantly fewer unique CAD features than students that did not score points. This suggests that increased complexity may negatively impact design success. Finally, no differences were observed in the frequency of CAD feature usage between the two conditions (Figure 6), with a drop-off in frequency after the first five observed features. This might suggest that curricular content should focus on CAD features that are used less often by students, which could broaden the solution space and lead to improved design success.

Building from the results presented in this paper, a few future research directions are promising. First, novices may not be able to wrestle with the cognitive load associated with maintaining two differing conceptual solutions to a design problem, leading to final designs with lower complexity. This may not be the case for students farther along in their degree program, or for practicing designers and engineers with more experience. Second, these results suggest a relationship between complexity and design success with lower complexity leading to better competition performance. Future work could include investigations into other design scenarios to determine whether this observed phenomenon is context specific or to what degree. Lastly, feature usage frequency may inform what instructors should cover when teaching CAD to novices. A study that compares different approaches to CAD education could shed light on how students leverage digital design tools to solve engineering problems.

The findings from this paper are in contribution to a larger research goal that aims to understand how different prototyping strategies impact the engineering design process [11], [12]. These results show that different prototyping strategies have an impact on design complexity and that increased complexity may negatively impact design success. Further, novice designer may be limiting the solution space by only using a core set of the CAD modeling features available to them. The results from this paper help set the groundwork for future research endeavors that explore the role of expertise, the impact of CAD-related curriculum modifications, and how complexity impacts engineering design success through prototyping.

## 7 ACKOWLEDGEMENTS

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