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**“THUS, I HAD TO GO WITH WHAT I HAD”: A MULTIPLE METHODS
EXPLORATION OF NOVICE DESIGNERS’ ARTICULATION OF PROTOTYPING
DECISIONS**

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ABSTRACT

Effectively communicating designs to stakeholders or end users is a critical step in the design process yet can be a difficult challenge for engineers. Prototypes are unique tools that can enhance communication between these two groups, as prototypes are physical manifestations of the designer’s mental model. Previous work has demonstrated that novice designers often struggle to use prototypes as communication tools. We argue that it is critical that engineering students learn to fully leverage prototypes, and thus the current work sought to understand the relationship between argumentation, prototyping, and design decisions. In order to understand the communication patterns of novice designers during a prototyping task, a controlled study was conducted with a total of 46 undergraduate engineering students. The analysis of quantitative and qualitative data point to the intricate linkages between how students make material decisions and how they justify those decisions.

1 INTRODUCTION

Given the increasingly technical nature of global threats (e.g., cybersecurity) there is an urgent need for designers and engineers to clearly articulate technical decisions and explain the design of complex systems. There is no lack of calls for engineers to communicate more clearly; however, most communication competencies at the undergraduate level focus on technical writing (of laboratory reports or similar) and giving research presentations. Prototyping is also commonly taught at

the undergraduate level, yet there is little emphasis on how to effectively utilize prototypes for design communication. As entrepreneurial and design-focused skills are increasingly valued by industry employers, there is a need to understand how undergraduate students learn to interpret the needs of a design review audience, make rhetorical choices that leverage prototype attributes, and appropriately scope a pitch to effectively meet the audience’s needs.

In engineering education, the development and use of physical models or prototypes is critical to the development of design skills for engineering students [1]. Prototypes are useful educational tools that enable engineering students to critically evaluate and reflect upon their work throughout the design process [2,3]. The creation and subsequent testing of prototypes by students has been shown to supplement their understanding of complex engineering systems [4], technical design [5] and ill-defined problems [6–8]. Although critical to engineering design, previous research has shown that novice designers struggle to use prototypes effectively to communicate design concepts to stakeholders [9,10]. However, when used effectively, prototypes can be strong communication tools and can help generate stakeholder buy-in for risky or uncertain design ideas [11]. It is critical that engineering students develop strong communication skills and learn to leverage prototypes throughout the entirety of the design process. The current work examined the intersection of design, argumentation, and prototyping through a study in

which first-year engineering students were given a prototyping task.

1.1 Design and Argumentation

In human-centered design, argumentation and narrative are essential to how designers and engineers communicate the intent of a design to stakeholders or customers [12,13]. However, education on prototyping in design has typically focused on creation and visualization of a solution over the ability to communicate that solution to others [14]. Gray found in his work that when design students were encouraged to think of a scenario involving a user, instead of thinking exclusively about the design process, that their solution was presented in a more convincing manner with increased depth and understanding [15]. Moreover, documentation of a design in terms of argumentation and rationale can provide significant context to support redesign and component reuse [16].

Within multidisciplinary design teams, argumentation also plays an important role in intra-team communication. Detienne et al. [17] conducted a field study in which they studied several teams engaged in co-design tasks. Argumentation was linked to the viewpoints of different sub-disciplines. Such multidisciplinary and multi-functional design teams are commonly plagued by a variety of communication issues [18,19] which could be mitigated by more effective argumentation and communication strategies.

Typically, the design argumentation literature focuses on the “what” part of the rationale or argument. However, as noted by the literature cited above, it is also important to study “how” students are approaching their justifications, which to date has been studied by few scholars in the engineering design and engineering education communities. Bucciarelli [20] and Dym [21] note that engineering design has its own language, one that should be extended from the object space into jottings, sketches, and other artifacts to better interpret the design process. The language of design has explicitly been studied. Atman et al. [22] investigated student use of design terminology as they enact the design process and describe solutions, finding that students became more proficient at using design terminology through authentic design processes, moving from a solution-oriented approach at the beginning of the project to a process-oriented justification at the end of the project. However, this study focuses on the “what” part of the justification (what *design words* are being used) rather than focusing on tone or what the focus of the justification is when students articulate their decisions, processes, and solutions.

1.2 Prototyping and Self-efficacy

Prototypes lie at the intersection of people and product, and the technical knowledge developed through each prototype adds to both the technical skills [5,23–25] and tacit knowledge [3,20,26] of the designer. Here a physical prototype is defined as any physical pre-production model, regardless of fidelity, that serves as a representation of the design or features of the design. Physical prototypes have been shown to be useful tools for boosting design performance [27,28], influencing stakeholder buy-in [11,29], improving design team communication [3,30,31]

and supplementing designers’ mental models [32]. Prototypes enable the development of knowledge through hands-on experiences [33] and are useful boundary objects [20,34] that have the ability to create shared tacit knowledge amongst design teams [31]. The rapidly evolving technical knowledge of the designers, developed through prototyping, is used to revise and refine the set of design requirements that guide the development of solutions [35]. The process of refining requirements through prototypes, has been linked to increased understanding of complex engineering systems [27] and ill-defined problems [36–38]. Few studies, however, have attempted to distill or quantify the experience gained through the use of prototypes [8]. We highlight this as a significant gap in the existing literature. Without a thorough understanding of the interaction between the prototype and the engineering designer we cannot begin to understand the larger effects of prototyping behaviors on the design process as a whole.

Carberry et al. [1] highlight the utility of task specific self-efficacy beliefs to assess experience level and self-concepts towards engineering design tasks. Self-efficacy refers to an individual’s assessment of his/her ability to arrange and complete courses of action for a given task [39], and has been shown to be critical in engineering design [40]. Increased self-efficacy beliefs have been linked to increased retention rates of minority and underrepresented populations in engineering education [41]. Previous studies in engineering education and engineering design have explored the relationship between self-efficacy beliefs and engineering design experiences. For example, [42] found that “designettes”, or “brief, vignette-like design challenges” can improve learning and lead to increased design self-efficacy amongst undergraduate engineering students. [43] studied the impact of authentic learning experiences in undergraduate engineering computer courses, highlighting the ability of such experiences to increase students’ self-efficacy beliefs. [44] used an adapted version of Carberry et al.’s engineering design self-efficacy scale [1] to highlight gains in innovative engineering design self-efficacy from extracurricular design project involvement. While these studies have linked increased self-efficacy beliefs with design experiences, few studies have explored the relationship between self-efficacy beliefs and prototyping behaviors specifically. Gerber [29] found that creating low fidelity prototypes allowed professional design teams to reframe failures as opportunities and increased self-efficacy beliefs amongst team members. Additionally, [24] demonstrated that parallel prototyping activities can lead to increased task-specific self-efficacy beliefs. Outside of these two works, however, there is little exploration of the effect building physical prototypes has on self-efficacy beliefs. While prototyping has been linked with increased technical understanding little has been done to explicitly link this with self-efficacy. Researchers have highlighted the necessity of *both* will and skill to achieve design outcomes [1] and the effect of prototyping on students’ will and motivation, both outcomes of improved efficacy beliefs, has not been studied in any satisfying depth.

1.3 Research Objectives

Based on the existing literature, there are significant gaps that exist at the intersection of engineering, design, and prototyping. These are highlighted in the following research questions:

1. *What drives novice designers' decisions of prototyping material and tool use?*
2. *How do novice designers articulate their decisions to use various materials and tools in a design challenge?*

The remainder of the paper is organized as follows. Section 2 details the experimental design and setup. Section 3 presents analysis from both quantitative and qualitative perspectives. Section 4 synthesizes the quantitative and qualitative results to offer an integrated perspective on tool and material choice in prototyping and the accompanying argumentation strategies. Finally, Section 5 concludes with a summary of major findings and proposed directions for future work.

2 METHODOLOGY

To answer these research questions, a controlled study was conducted with a total of 46 undergraduate engineering students through a first-year engineering design course. This section serves to summarize the methodologies used in this study.

2.1 Participants

The participants of this study were undergraduate students from an engineering design course at a large public university. 46 students (21 female, 25 male) in total participated in the study; participants were recruited from two sections of a first-year engineering design course wherein the fundamentals of engineering design are emphasized through hands-on projects. Prior to the experiment all students had received safety training in a basic woodworking shop and were exposed to safety procedures for bandsaws, hand tools, miter-saws, sanders, and other tools.

2.2 Procedure

At the start of the study, the purpose and procedures were discussed with the students and all questions were answered. Next, consent of participants was obtained following IRB procedures. Each student worked individually to sketch and create their design. Questionnaires were completed throughout the building process to provide feedback on material, use of equipment, and engineering design.

This study consisted of 4 phases, illustrated in Figure 1: pre-survey, ideation, prototyping, and post-survey. At the start of the study, students were provided with a brief overview of the study procedure and the design challenge. Students were then instructed to fill out an online survey; this survey asked students to answer items from both the Engineering Design Self-Efficacy Scale [1] and the Tinkering Self-Efficacy scale [45] along with general demographic information. Students were given 10 minutes to complete this survey.

5 mins		Introduction
Pre-Survey	10 mins	Participants answer demographic questions, and scale items for TSE and EDSE scales
Ideation	10 mins	Participants are instructed to brainstorm tower designs
Prototyping	45 mins	Participants are instructed to select and build the optimal design. Participants are reminded to fill out the tool choice survey every ten minutes throughout the building session.
Post-Survey	10 mins	Participants answer open ended questions about design decisions

FIGURE 1. OUTLINE OF EXPERIMENT.

Once all students had completed the pre-survey, they were provided with the following information regarding the design challenge:

"We are interested in understanding how designers use different prototyping medium when tasked with designing a tower that is as tall as possible, aesthetically pleasing, and able to hold as much weight as possible at the tallest point. You can think about this as your problem statement and customer needs. To construct your tower, you can either choose to use wood or cardboard. For wood, you will be provided with one 2'x2' sheet. For cardboard, you will be provided with two 2'x2' sheets. These material options are functionally identical - either can be used to create a tall, strong, and aesthetically pleasing tower. You will also have access to a variety of tools in the model shop.

These include: scissors, utility knives, rulers, marker/pen/pencils, bandsaws, hacksaws, drill presses, hand tools, hot glue gun, tape, nails, and screws."

After instructions were provided verbally, students were given 10 minutes to complete an in-class brainstorming session. Ideas were recorded using ideation sheets. At the conclusion of the brainstorming session students were instructed to select their final design idea, they were informed that the selected concept could be either a single idea or combination of ideas generated during the ideation session.

Immediately following the brainstorming session students were allotted 45 minutes to create a tower based on a design of their choosing. Although students were constructing a prototype, they were aware of the fact that their prototype was intended to be functional. To construct their towers, each student selected either one sheet of 2'x2' plywood or two sheets of 2'x2' cardboard. In addition to these materials, students had access to a variety of tools including, but not limited to, utility knives, scissors, hot glue guns, nails, hammers, bandsaw, tape, and a variety of hand and power tools. At the start of the prototyping session students were instructed to fill out the tool choice survey after each tool use; the survey was available to students in either digital or paper and pencil form and asked students to select which tools were used from a comprehensive list describing all tools in the shop. Additionally the tool choice survey asked students to describe what the tool was used for, how it contributed to the design, and why they felt the choice of tool was best for the described task. To ensure that students were actively filling out the tool choice survey, the research team reminded the students every 10 minutes to fill out the form as they continued to build.

At the completion of the 45 minutes, students wrote their student identification numbers on their tower, including unfinished work and unused pieces, and stored the projects. Pictures were then taken of each design and the corresponding student ID was recorded for each tower. Representative pictures are included in Appendix A. The final phase of the experiment included a post-survey, that asked students to list the equipment they used throughout the prototyping session. Students were also asked to reflect on their past experiences with all tools available in the workshop and rate their level of experience with each tool, *prior* to the prototyping session, on a scale from 1 to 5 (1 = low, 5 = high). Following this, students were presented with the four open ended questions in order to qualitatively assess the students' decision making processes and argumentation in the context of prototyping and engineering design.

2.3 Data Collection

Data was collected throughout the experiment using Google Forms, an online survey platform. Data were collected through three separate surveys, a pre-survey, a tool choice survey, and a post survey.

Pre-Survey: The pre-survey was comprised of 3 demographic questions, the 9 item engineering design self-efficacy scale from [1], and the 30 item tinkering self-efficacy scale from [45]. Carberry and Ohland proposed a 9-item measure

of engineering design self-efficacy (EDSE) [1] based on the eight-step process for engineering design proposed in the Massachusetts Department of Education Science and Technology/Engineering Curriculum Framework. This design process is similar to design processes proposed by Ulrich and Eppinger [46], and in multiple studies, the EDSE scale has been shown to be a useful measure of the task-specific self-concepts related to engineering design. The instrument asks participants to rank their degree of confidence to perform 9 tasks in engineering design, for example construct a prototype, by recording a number from 0 to 100, with 0 being low, 50 being moderate, and 100 being high. The scale can typically be completed within 5 minutes. The tinkering and technical self-efficacy scale developed by Purzer et al. [45] is a 30 item measure of "confidence and belief in one's competence to engage in activities often associated with engineering such as manipulating, assembling, disassembling, constructing, modifying, breaking and repairing components and devices, (e.g. assembling a bicycle or taking apart a computer)" [45]. The instrument asks participants to rate how descriptive each statement was of themselves on a scale from 0 to 5, 0 being not very descriptive and 5 being very descriptive. Example statements include "I want to know how things work" and "I do not work well with my hands".

Tool Choice Survey: A tool choice survey was created for this study to capture the behaviors of students throughout the prototyping session. This survey served as an Ecological Momentary Assessment of students' prototyping behavior. Ecological Momentary Assessments (EMA) are common in clinical psychology and involves the repeated sampling of subjects' current behaviors or experiences in real time, minimizing recall bias and enabling the investigation of micro-processes [47]. The tool choice survey asked students to select every and any tool used in the previous design task and what the tool was used for, how it contributed to the design, and why they felt the choice of tool was best for the described task. These questions were asked in order to compare the narratives made by students during the prototyping activity to the narratives created by students during the reflection activity in the post-survey. It was assumed that students completed this survey after the completion of every task within the prototyping session, where a task was defined as any discrete construction activity that contributed to the completion of the tower. This assumption is recognized as a limitation of the study, as it cannot be guaranteed that students completed the tool choice survey at the conclusion of every discrete construction activity.

Post Survey: The post-survey was distributed at the close of the experiment and asked students to select all equipment used throughout the prototyping session. The post-survey also asked students to rate their experience with all available tools in the workshop, prior to the prototyping session; this experience question was asked after the completion of the prototyping session so as not to bias any of the students in tool or material selection prior to the experiment. Previous experience and tacit knowledge of tools, equipment, and materials has been shown to impact both technical quality of designs and self-efficacy beliefs

[24]. Thus, it was essential to measure previous experiences with tools, equipment, and materials used throughout the study. It should be recognized that these were self-reported and retrospective perceptions of familiarity which might have been influenced by experiences during the experiment. Students were also presented with the following four more open-ended questions:

1. Why did you choose the materials and tools that you used?
2. How did your design change throughout the prototyping process? Please list any experiences, thoughts, or behaviors that influenced your design along the way.
3. Please argue why your tower has the best combination of aesthetics, height, and strength.
4. Is there anything else that you would like to tell us about your design experience that helped you succeed?

These four questions were asked in order to understand the rationale and justifications of students' design decisions made throughout the prototyping session. The questions were specifically designed to encourage participants to construct arguments justifying the attributes of their prototypes. Responses to each of these questions were recorded and abductively coded as described in Section 2.5.

2.4 Quantitative Analysis

This paper reports regression analyses to analyze underlying variables that might contribute to material choice, tower height, tower strength, and tower completion. Tower aesthetics, although introduced as part of the problem statement, are yet to be assessed. All regressions utilize an all-possible subsets approach, in which model selection is performed by assessing the information content of all possible subsets of variables [48]. Here, the Akaike information criterion [49] is used to compare between possible models.

2.5 Qualitative Analysis

The qualitative data student responses were analyzed through constant comparative methods with the research team according to a coding schema developed through a pilot study. While several thematic codes were predicted to emerge based on the prompts given to students, through the pilot data analysis several additional emergent themes surfaced. We approached the development of a codebook through an abductive analysis approach [50] which takes into account prior theory and literature (unlike pure grounded theory as per [51]) while also being responsive to data that does not fit into previously determined themes. It was through this abductive method of analysis by which we realized that there were strong linguistic indicators in the ways in which students were approaching their justifications to their design. First, students leaned heavily on passive voice to avoid responsibility for unsuccessful designs. Second, students mediated their claims through rhetorical "hedges" and "boosters" to soften or build up attributes of the designs. One example of the role that linguistic indicators have within argumentation is in the use of "hedges" (language that softens statements or arguments) and "boosters" (superlatives

and other language augmenting some facet of the argument) within justifications. As Hyland [52] promotes, hedges and boosters are commonly found in academic discourse, where writers find it necessary to hedge assertive findings and simultaneously position themselves highly among their academic peers and colleagues. Third, we noticed students' use of language relating to "satisfice," a term that combines the words and meanings of "sacrifice" and "satisfy," coined by [53]. Our finalized qualitative codebook through which the team coded the qualitative parts of the data is shown in Table 1. All coding was done as a team, and all decisions were coded to agreement. The data were allowed to be assigned both a thematic code and a linguistic indicator code; in this way, we could note the ways in which students used language as it pertained to their engineering justifications of design decisions.

TABLE 1. THEMATIC AND RHETORICAL INDICATOR CODEBOOK

Theme	Definition
Material Attributes	Rationale related to the characteristics or properties of materials and tools
Height Attributes	Rationale related to maximizing the height element of the design challenge
Strength Attributes	Rationale related to maximizing the strength element of the design challenge
Structural/Stability Attributes	Rationale related to any aspects of structure or stability of the design
Self-imposed Design Criteria	Rationale related to criteria that were not part of the design challenge
Affective Decisions	Rationale stemming from self-confidence, feelings of ability, or techniques that are "easy" (from the point of view of any particular student)
External Limitations	Mention of limitations outside of those imposed by the technical elements of the design challenge
Rhetorical Indicator	Definition
Passive/External Attribution	Attributed (usually failed) performance to outside actors
Hedges and Boosters	Employed rhetoric to either boost argument or to soften strong claims
Satisfice	Employed language that provided evidence of a tradeoff in terms of the best combination of height, strength, and aesthetics

3 RESULTS

3.1 Quantitative Results

Figures 2 and 3 depict correlation matrices between tool/material familiarity values (captured in the post-experiment survey) and actual tool/material usage (captured through EMA and verified in the post-experiment survey). These matrices are clustered using a hierarchical scheme to indicate grouping of tools and materials.

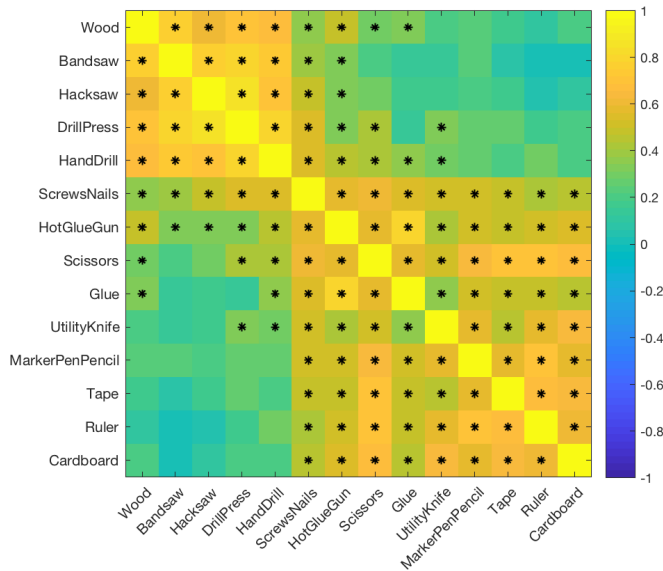


FIGURE 2. SPEARMAN CORRELATION MATRIX OF TOOL/MATERIAL FAMILIARITY. ASTERISKS INDICATE CORRELATIONS SIGNIFICANT WITH $P < 0.05$.

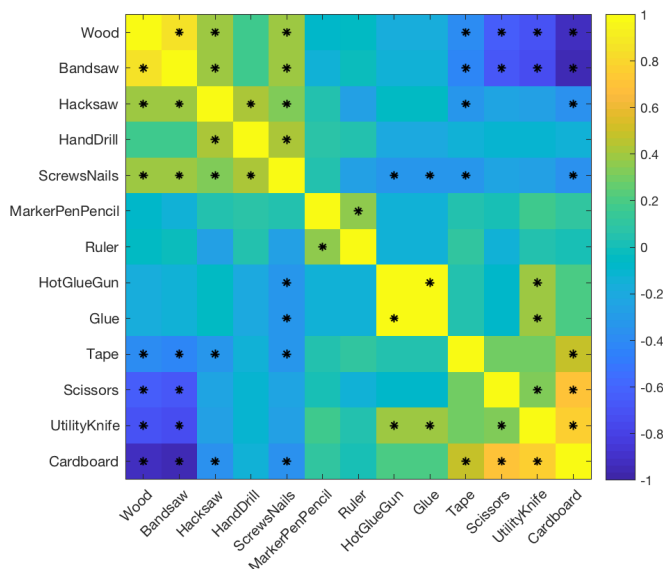


FIGURE 3. SPEARMAN CORRELATION MATRIX OF TOOL/MATERIAL USAGE. ASTERISKS INDICATE CORRELATIONS SIGNIFICANT WITH $P < 0.05$.

In both matrices, a clear grouping develops between light prototyping tools/materials and intermediate prototyping tools/materials. The light prototyping tools/materials are clustered in the lower-right of both plots and include items such as glue, utility knives, cardboard, and tape. The intermediate prototyping tools and materials appear in the top-left and include items such as wood, bandsaws, hacksaws, and hand drills. Figure 2, indicating correlations between familiarity for different objects, generally shows a higher degree of positive correlation between items than Figure 3, which shows correlations between the actual usage of items. In Figure 3, tape usage, scissor usage, utility knife usage are significantly and positively correlated with cardboard usage, but negatively correlated with wood usage. Likewise, bandsaw usage, hacksaw usage, and screw/nail usage are positively correlated with wood usage, but negatively with cardboard. The differences between the two figures and the phenomena noted in Figure 3 underscore the deep, constraining relationship between material choice and tool choice.

An initial automatic linear modeling tool, made available in SPSS version 19, was used to understand the relative importance of each predictor. There were 16 predictors in the original model: 14 variables were related to previous experience with a specific tool and the remaining 2 variables were related to total scores on the Tinkering Self-Efficacy and Engineering Design Self-Efficacy Scales. Since the number of predictors was less than 20, the SPSS automatic linear modeling tool utilizes an all-possible subsets approach, in which model selection is performed by assessing the information content of all possible subsets of predictor variables [48]. This amounted to 65536 regression models (or 2^{16}). This tool returned previous experience with cardboard, previous experience with wood, and Tinkering Self-Efficacy Score as important predictors of material choice.

A binomial logistic regression was performed to ascertain the effects of previous experience with cardboard, previous experience with wood, and tinkering self-efficacy on material choice. A binomial logistic regression was used because the dependent variable, material choice, is a categorical variable; linearity of the continuous variables, familiarity with cardboard, familiarity with wood, and tinkering self-efficacy, with respect to the logit of the dependent variable was assessed via the Box-Tidwell [54] procedure. Based on this assessment, all continuous independent variables were found to be linearly related to the logit of the dependent variable. The logistic regression model was statistically significant, $\chi^2(3) = 27.727$, $p < .000$. The model explained 61.3% (Nagelkerke R^2) of the variance in model completion and correctly classified 77.8% of cases. Of the four predictor variables three were statistically significant, as shown in Table 2. B indicates the logistic regression coefficient values, S.E. is the standard error of the estimate, d.f. is the degrees of freedom for the chi-squared test, and p is the significance value. Increasing familiarity with cardboard was associated with an increased likelihood of cardboard material selection. Increasing familiarity with wood was associated with an increased likelihood of wood material selection. Increasing Tinkering Self-Efficacy score was associated with an increased likelihood of wood material selection.

TABLE 2. BINOMIAL LOGISTIC REGRESSION MODEL FOR MATERIAL CHOICE.

Model Term	<i>B</i>	S.E.	d.f.	<i>p</i>	Odds Ratio
<i>Intercept</i>	-7.548	3.424	1	.028	.001
<i>Cardboard Familiarity</i>	-1.283	.446	1	.004	.277
<i>Wood familiarity</i>	1.158	.398	1	.004	3.185
<i>Tinkering Self-Efficacy</i>	.081	.036	1	.024	1.085

The automatic linear modeling tool, made available in SPSS version 19, was once again used to understand the relative importance of each predictor and perform model selection to predict tower completion. A binomial logistic regression was performed to ascertain the effects of gender, material choice, tinkering self-efficacy, and engineering design self-efficacy on the likelihood that students completed their tower design before the end of the experiment. Linearity of the continuous variables, tinkering self-efficacy and engineering design self-efficacy, with respect to the logit of the dependent variable was assessed via the Box-Tidwell procedure. Based on this assessment, all continuous independent variables were found to be linearly related to the logit of the dependent variable. The logistic regression model was statistically significant, $\chi^2(4) = 13.925$, $p = .008$. The model explained 46.0% (Nagelkerke R^2) of the variance in model completion and correctly classified 88.9% of cases. Of the four predictor variables none were statistically significant, as shown in Table 3.

TABLE 3. BINOMIAL LOGISTIC REGRESSION MODEL FOR TOWER COMPLETION.

Model Term	<i>B</i>	S.E.	d.f.	Sig.	Odds Ratio
<i>Intercept</i>	24.29	8262.0	1	.998	-
<i>Design Self-Efficacy</i>	-.007	.005	1	.167	.993
<i>Tinkering Self-Efficacy</i>	.013	.038	1	.726	1.013
<i>Gender</i>	-21.33	8262.0	1	.998	.000
<i>Material Choice</i>	1.404	1.153	1	.223	4.072

The automatic linear modeling tool, made available in SPSS version 19, was once again used to understand the relative importance of each predictor and perform model selection for predicting tower height and strength. For tower height, the tool returned predictors of hacksaw familiarity and drill press familiarity. The linear regression model with these predictors was statistically significant, $F(2, 42) = 4.217$, $p = 0.021$. The model explained 12.8% (Adjusted R^2) of the variance in tower height. Of the two predictor variables, both were statistically significant, as shown in Table 4. S.E. indicates the standard error of the coefficient estimates, *t* is the test statistic, and *p* is the significance value.

TABLE 4. LINEAR REGRESSION MODEL FOR TOWER HEIGHT.

Model Term	Coefficient	S.E.	<i>t</i>	<i>p</i>
<i>Intercept</i>	27.871	5.926	4.703	0.000
<i>Hacksaw familiarity</i>	-11.939	4.034	-2.904	0.006
<i>Drill press familiarity</i>	9.691	4.111	2.402	0.021

For the tower strength model, the automatic linear modeling tool indicated predictors of engineering design self-efficacy, tinkering self-efficacy, hot glue gun familiarity, bandsaw familiarity, and screw/nail familiarity. The linear regression model with these predictors was statistically significant, $F(5, 33) = 4.430$, $p = 0.003$. The model explained 31.1% (Adjusted R^2) of the variance in tower strength. Of the five predictor variables, three were statistically significant (see Table 5): Design Self-Efficacy score, hot glue gun familiarity, and bandsaw familiarity.

TABLE 5. LINEAR REGRESSION MODEL FOR TOWER STRENGTH.

Model Term	Coefficient	S.E.	<i>t</i>	Sig.
<i>Intercept</i>	27.318	37.746	0.724	0.474
<i>Design Self-Efficacy</i>	0.146	0.04	3.658	0.001
<i>Hot glue gun familiarity</i>	-11.983	4.967	-2.413	0.022
<i>Bandsaw familiarity</i>	9.74	4.406	2.211	0.034
<i>Screw/nail familiarity</i>	8.153	4.85	1.681	0.102
<i>Tinkering SE</i>	-0.633	0.384	-1.648	0.109

The relatively low predictive accuracy for the tower height regression model indicates that the determination of tower height is likely driven by variables not captured in the model. However, the tower strength regression model achieved moderate accuracy with the familiarity and self-efficacy predictors. This is not surprising, since a tall tower may be achieved with little attention to detail, but when a structure is loaded the smallest flaw can lead to failure. Both joining operations (hot glue gun and screw/nail) were selected for this model. Though only one was significant, both potentially contribute to the integrity of a prototype, as structural models commonly fail at joints. Interestingly, hot glue gun familiarity with negatively correlated with tower strength, while screw/nail familiarity was positively correlated. This may indicate that hot glue simply produced weaker joints, or that cardboard (primarily used with hot glue) was not well-fitted for producing strong towers.

3.2 Qualitative Results

The qualitative data collected from the post-design activity reflection questions was analyzed through thematic analysis based on a coding schema developed through the pilot study for this research. The schema, described in Table 1, captured students' justifications for their design decisions. The second part of the schema is composed of linguistic trends that emerged in the pilot data and additionally in the present study, indicating that the novice designers heavily relied on a variety of different rhetorical techniques as they provided rationales for their decisions. Examples of each of the codes are described in the following text.

While the themes related to the design challenge related to materials, strength, and height were expected based on the design challenge and the prompts for students to fill out, there were several qualitative themes that emerged that were unexpected. Specifically, the themes of "Self-imposed design criteria," "Affective decisions" and "External Limitations" were relatively unexpected. In their justifications of why their designs optimized the design criteria, students frequently referred to self-imposed design criteria, rather than the defined design challenge. As examples, one student justified her or his decisions based on the fact that the "tower had an abstract feel to a house shape so provided a homey aesthetic." While aesthetics were part of the instructions, hominess was not. Another student noted "I wanted to use as little glue as possible. So I cut my pieces so that I could fit them together instead of glue them together." Glue usage was not a limiting factor in the design challenge, which, as per the instructions was only based on height, strength, and aesthetics.

The affective domain seemed to be important in the materials that student chose to use, mainly because of the tools they would need to use to manipulate the materials. Several students referred to selecting cardboard due to the fact that it was "easy" to use, and because of their familiarity with cardboard, scissors, tape, and hot glue and relative inexperience using power tools such as bandsaws and sanders: (e.g., "It was quick and easy and did not require me learning a new tool and worrying about safety" and "I chose cardboard because I am more familiar with how to use a box cutter than a bandsaw to cut wood.") In

contrast, many students expressed their comfort in using the tools, like this student: "I chose wood for its rigid structure and high strength. It's relatively easy to work with, and any structural failure is likely due to construction error rather than a weak point in the material such as a wrinkle in a piece of cardboard. The tools I used were the most efficient pieces of equipment available, and I felt comfortable using them." Parts of this quote were coded as Material, Strength, and Structure, and the second part of the quotation indicates the bearing that this student's comfort level (the affective domain) had on the decision to use the materials.

Further, students quickly attributed their lack of successes in the design challenge to outside limitations other than the constraints placed on the amount of material given in the design challenge. Time (or the lack thereof) was one of the most-cited factors in students' ability to fully enact their plans; however, many students attributed their lack of success to other external factors of varying degrees of "truth". For example, one student distanced her/himself from the reasons for design failure: "Some of the measurements weren't exact and the lines weren't straight so I ended up having to adjust and re-glue things and in the end scrap the design all together because I didn't have enough access to a hot glue gun." Rather than owning the inexact measurement, the use of passive voice indicated an outside actor was responsible for the inaccurate measurement and crooked lines. Similarly, one student attributed her/his having to quickly change plans "because my originals were stolen" and another student to "the bandsaw queue." One student explained, "I did not have much time to actually put together my design, due to the large number of students who needed to cut intricate pieces. Thus, I had to go with what I had in the short amount of time." These quotes demonstrate the overall tendencies of students to attribute their lack of success in this design challenge to external actors. Linguistically, these students tended to use passive voice, distancing themselves from their personal decisions that led to a lack of success. While many of the students with unsuccessful designs attributed their failures to external actors (time, materials, other students), the students who performed well owned their successes and failures, typically using active, first-person voice.

Other noteworthy linguistic features captured from student reflections on their prototyping decisions related to the uses of hedges and boosters as students justified their decisions. Some of the reflections were grandiose, yet unimpressive: "My tower maximizes height and strength. It can hold light to moderately heavy objects like a pencil or maybe two pencils. Height-wise, the design is taller than I envisioned I would be able to actually make it, so that is a plus. However, my design is very aesthetically pleasing. The subtle X design hints at modern art pieces you might find at NYC's MOMA." Others used hedging language to make their design seem better as compared to the designs of other students ("My structure is very aesthetically pleasing, as it employs a symmetrical, geometric shape that is unusual but visually attractive. Admittedly it is not as tall as some students' towers, but it still was pretty decently high and can certainly support more weight than other, skinnier towers"),

while other student reflections were simply unclear as a way of justifying a lack of some attribute (“It is tall enough to make it tall, but it is not too tall that it would be too weak to support itself.”)

Lastly, elements of satisfice were present in many student justification processes, often combined with a hedging statement. Examples like “[The tower] had almost maximum height for the time and materials provided. While it looks good, some of the aesthetics were sacrificed for height and strength” and “I utilize[d] the wood to be oriented in a way that produces the best overall structure for strength. It has a symmetrical and triangular shape for aesthetics and it is reasonably tall given the set material amount” show that students were indeed trying to maximize their performance in the three categories, while also understanding that perfection could not be accomplished in the timed design challenge. While many students went to great lengths to justify their design decisions (e.g., this comment: “My tower shines in two of these categories greater than the rest. I had one of the tallest towers and it strongly resembled a stick. Sticks are a part of nature therefore making it quite aesthetically pleasing”), there were some students who did not feel they could or should argue for how their tower had the best combination of attributes. For example, one response to the prompt, “Please justify why your tower has the best combination of aesthetics, height, and strength,” one student wrote, “It most likely was not. Structurally it was somewhat sound and aesthetically it didn’t look too horrible, but when I had to change my original design to fit the time constraint, my aesthetics, height and strength were not my biggest concern.” This comment shows examples of hedging (e.g., “somewhat” and “too horrible”) but in the end the student did not try to claim success.

4 DISCUSSION

One of the interesting results from this multiple-methods design research project of novice engineering students was the role that language played in their technical justifications of the attributes of the towers after a classroom design challenge. In particular, we noted the prevalence of passive voice and external attribution of unsuccessful designs; hedging and boosting tendencies; and elements of satisfice as the participants argued for their designs. While findings related to the ways in which students employ design thinking terminology and processes in their rationales, narratives, and justifications of the problem/solution space have been conducted (e.g., Atman et al. [22]), we found no evidence of an analysis of student usage of hedging and boosting language in the engineering design literature. Applied linguistic techniques are employed in academic writing studies; however, since many students’ justifications relied heavily on boosters and hedging (often in unclear ways), we feel this may be a useful trajectory for future analysis of the ways in which students articulate their decisions. Discussions with students about their use of language may also offer pragmatic professional development opportunities for students in design classes, which are often used to prepare students for “authentic” working experiences. While the linguistic indicators of satisfice are not necessarily groundbreaking, they become more interesting when

paired with other thematic or linguistic indicators. For example, students that used satisficing language while also justifying a design criterion that was not part of the original project (calling to mind the student who decided not to use much glue) leads researchers and instructors to question whether the students can effectively understand customer needs (for example.) Lastly, and potentially the most worrisome, is the tendency of students to attribute the lack of success to outside actors or use language to try to distance themselves from their decisions. For example, language such as “some of the measurements weren’t exact and the lines weren’t straight” indicates that the blame was not with the student (who presumably did the measuring and drawing). This may be an indicator of immaturity in the design process and is problematic when considering that the engineering design classroom is meant to be authentic practice for students.

Pairing qualitative findings with some of the quantitative results adds an interesting perspective to the story. The quantitative results point to clear correlations between material choice, familiarity, and design performance. Logically, students’ choices of material and tools were driven by a pre-determined strategy, but when design decisions proved to be incorrect or resulted in a sub-optimal design, students either a) generated their own design criteria to reframe failure as success or b) blamed external factors, such as time or inadequate material, for design failure. These results reveal argumentation and prototyping to be entwined in a Gordian knot of sorts. Prototyping is likely driven by desired argumentative strategy, yet argumentation is inherently affected by emergent attributes of the solution that are discovered during prototyping.

One unanswered question is associated with the media by which the reflections were gathered. On one hand, most students completed the post-activity justifications via their smartphones, and potentially this venue led students to not think as critically or seriously about their justifications as they would have if they were to do a long-hand or typed reflection. On the other hand, the quick-response format may likely have provided researchers with a more authentic “off the cuff” understanding of students’ justification, capturing the realistic levels of student thought about their decisions, successes, and failure.

5 CONCLUSIONS

This work examined the intersection of design, argumentation, and prototyping through a study in which first-year engineering students were given a prototyping task. A combination of quantitative and qualitative analyses was used to uncover (1) the drivers behind novice designers’ tool and material choices, and (2) how novice designers articulate the rationale behind their choices.

Quantitative analyses revealed that students tend to have experience and familiarity with one of two groupings of tools. Moreover, the choice of material was strongly correlated with the selection of specific tools. The choice of material, conversely, was primarily predicted by material familiarity. Interestingly, design outcomes for tower height and strength were predicted by familiarity with specific tools. Qualitative analyses indicated elements of hedging, boosting, and satisfice

within the justifications provided by study participants. In addition, participants had a tendency to distance themselves from poor or detrimental decisions through passive voice and external attribution. Another finding that is particularly relevant to education is the role that tool/material familiarity and various dimensions of self-efficacy play in determining design outcomes. Tinkering self-efficacy, engineering design self-efficacy, and familiarity with certain tools had some effect on tower performance and material choice. This is an important finding as it demonstrates the importance in engineering education of hands on design projects that have the ability to build tacit knowledge and improve self-efficacy beliefs. Ultimately, this work serves to motivate a combined approach in education that holistically addresses design, prototyping, and argumentation.

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APPENDIX A: REPRESENTATIVE TOWER PICTURES



FIGURE 3. REPRESENTATIVE TOWER #1.



FIGURE 5. REPRESENTATIVE TOWER #3.



FIGURE 4. REPRESENTATIVE TOWER #2.