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Sustainable and Inclusive Design Thinking

by

George Edward Moore II

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Committee in charge:

Professor Alice Agogino, Co-Chair
Professor Kosa Goucher-Lambert, Co-Chair
Professor Bjorn Hartmann

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Abstract

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Design thinking has become increasingly popular in academic, professional, and colloquial communities as a means to address complex problems. In an era where responses to global issues, such as the climate crisis, may have long lasting impressions on the human condition, it is important that the methods for solving these problems are setting solid foundations for future generations. This dissertation investigates sustainable and inclusive factors within the design thinking process based on the premise that these are foundational elements of complex problem solving. Holistically this dissertation studies how design thinking participants perceive success and satisfaction in a design thinking experience. Also, this work includes a particular focus on one of the more tangible stages of the design thinking process -- prototyping -- and uncovers opportunities to improve sustainable practices through drawing insights about the current vulnerabilities in the life cycles of prototyping and making. Key insights from this dissertation include significant struggles at the beginning of the design thinking experiences compared to the end of design thinking experiences (see Chapter 2 and Chapter 3) and suggests that demographic background plays a significant role in how design thinking participants perceive success (see Chapter 2). Notable takeaways about sustainable design thinking practices involve how the lack of transparency in the manufacturing and distribution of needed materials and equipment make it difficult for decision makers to prioritize sustainable, and even social, factors. Instead, cost, availability, and quality remain driving factors for decision making. In addition, the driving purpose for small scale fabrication spaces (such as community, project execution, or skill building) was revealed as an influential factor in sustainable behaviors throughout all stages of the life cycles of small scale fabrication spaces. Overall, future work that aims to reinforce sustainable and inclusive practices in design thinking would benefit from investigating how demographic context and motivation influence perceived value of, and observed behaviors within, design thinking processes.

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1 Introduction

1.1 Why Design Thinking is Important

Skyscrapers, microprocessors, sonar, cellular phones, automobiles, airplanes, and many other cutting edge technologies that have been large influences in this time exemplify what, at one time, may have been unfathomable human capabilities. These tangible manipulations of the world done with the intention of bettering the human condition have paved the way for creating a better future through the use of design, engineering, and technological disciplines.

One would think that as humans have become better at using these strategies to turn dreams into reality, that the world would not be on the verge of climate crises threatening the livelihood of billions and facing a polarity of inequitable living conditions that have never been seen before.

In the recent history of engineering and technological development, perspectives on the most important problems to solve, definitions of success, and how to measure success have failed to account for the complexity of the world – specifically the differentiation of values across global communities.

The point here emphasizes that this era of engineering, design, and technology will be defined by abilities to address wicked problems. Hence, this study engages with wicked problems and its relationship with mechanical engineering and design through investigating design thinking experiences – a common wicked problem solving approach in academia, industry and even the private sector.

Design thinking is a conceptual framework that has taken the world by storm. Part of its genesis is closely tied to addressing what Horst Rittel and Melvin Webber defined as Wicked Problems back in 1973. In fact, they provide "ten distinguishing properties" of wicked problems that have provided a foundation for identifying these kinds of problems: (1) wicked problems have no definitive form; (2) wicked problems can not be stopped; (3) there are no right answers to wicked problems; (4) there are no tests that validate solutions to wicked problems; (5) all attempts to solve wicked problems count significantly – the stakes are always high; (6) there is no definite set of solutions; (7) every wicked problem is unique; (8) all wicked problems are connected to other problems; (9) wicked problems can be described in many ways and the perspective of the explanation sets the trajectory for the problem's resolution; (10) the problem solver has no right to be wrong [1]. With these in mind, it is to no surprise that Rittel and Webber describe approaches to wicked problems that lack multiple perspectives as outdated.

1.1.1 Inclusive Design Thinking

Several disciplines, including business, engineering, anthropology, and design have contributed to the growth and development of the design thinking community, which compliments one of the key tenets of design thinking practices: interdisciplinary collaboration. Some may regard inclusive design thinking as exclusively a moral dilemma to wrestle with. However, considering that collaboration and empathy are seen as exemplary traits of design thinking [2–4], an inclusive approach should be considered essential to optimizing design thinking performance.

Lately, attention to the importance of inclusive design practices within the design thinking process has gained traction. For example, due to a few previous employees speaking up, the lack of inclusive practices at one of the leading design thinking firms in the world caused a stir in the design thinking community [5–8]. Ideally, this serves as a reminder that the design thinking framework, similar to its iterative characteristic in practice, is associated as dynamic in definition – as it always has room for improvement.

1.2 Dissertation Outline

The goal of this dissertation is to investigate the design thinking process in a way that enables a better understanding of where an inclusive experience and sustainable practices are lacking the most and provide suggestions for how to work to amend these shortcomings. Hence, this dissertation includes three research studies that support a greater understanding of participant experiences as they navigate the design thinking process and participant behaviors associated with sustainable prototyping and making. Chapter 2 investigates the virtual design thinking experience for undergraduate students using journey mapping as a method. Chapter 3 investigates the virtual prototype experience of undergraduate students and, also, uses journey mapping as a method for collecting and analyzing their experiences. Chapter 4 explores the life cycles of making through semi structured interviews to better understand pathways to more environmentally sustainable behaviors and practices. Chapter 5 summarizes the key highlights of this dissertation and shares opportunities for future work.

2 Journey Mapping the Virtual Design Thinking Process

2.1 Introduction

Over time, many frameworks and pedagogical approaches have precipitated from the design thinking community (Google Design Sprint, Stanford/IDEOs design thinking process, the Innovation Process, Double Diamond, etc) [9–12]. While the diversity of design thinking methods to choose from has become abundant, that is not the case for metrics and methods used to define their value. Understanding the value of the participant experience as they use these frameworks is still in its infancy. Hence, this work is motivated by the need to shed some light on the effectiveness of these design thinking frameworks in relation to the participant's perspective. The following research questions were used to frame the goals of this study:

R1: How do students' self-reported ratings for (1) individual experience, (2) individual performance, (3) team experience, and (4) team performance change as they navigate through stages in the Design Thinking journey?

R2: How does a student's gender identity or academic discipline shape the trajectory of their self-reported ratings of experience and performance during the Design Thinking journey?

R3: How do students' self-reported ratings of experience and performance observed in their First Design Thinking journey (during the journey itself) compare to ratings reported in their Final Design Thinking journey (after the journey is complete)?

2.2 Related Work

2.2.1 Measuring and Evaluating Design Thinking

As the value of design thinking has become prioritized across academic disciplines, professional industries, and all sorts of problem solving organizational efforts, the need to assess design thinking metrics has surfaced in the discourse. Many conversations about measuring design thinking emphasize mindsets and capabilities, outcomes, and participant experience.

The study of design thinking mindsets and capabilities are arguably among the first to directly address setting foundations for measuring design thinking. Suggested design thinking mindsets and capabilities that have emerged from the field include tolerance for uncertainty, a risk taking mentality, empathy, human centeredness, a holistic perspective, experimentalism, optimism, and a dynamic mindset just to name a few [2–4,9,13,14]. In fact, Chesson, Dosi et al., and Hassi & Laakso have documented an extensive collection of these in their work [2,3,14]. While these traits offer a reference point for measuring design thinking skills, Royalty et al. caution against the binary perspective of design thinking as a skill (or set of skills) that a person possesses or lacks [15].

There is less agreement across design thinking discourse about factors that contribute to design thinking outcomes. Nonetheless, pressure (often from for-profit entities) to prove that a design thinking practice, or similar innovation-based practice, is successful usually results in drawing some correlation to improving the bottom line (return of investment) for a company or organization. Additional expectations that are often reinforced by organizational standards include measuring the project-based efforts at intervals [16]. Validation through external experts, empirical evidence via success stories, and contextualized project-based metrics serve as an approach to pacify those seeking immediate signs of design thinking success in organizational structures [17]. However, attaining measurable proof of design thinking success is generally a difficult task [18]. On that note, Björklund et al. presents the Design Ladder [19], Design Value Scorecard [20], and Design Maturity Matrix [21] as examples of frameworks that measure design thinking progress and outcomes within organizational structures [17]. While these offer a starting point for how design thinking outcomes (and checkpoints along the way) are beginning to be assessed, there is still much to be learned about how to measure design thinking outcomes and which frameworks to choose based on the organization’s goal. Additional examples of performance measurements for design thinking, primarily adapted from organization management research, includes Balanced Scorecard [22] and Du Ponts Pyramid of Financial Ratios [23,24]. From conducting a literature review on performance measurement of design thinking, Haskamp proposes three streams of performance measurement related to (1) innovation, (2) impact, and (3) the organization. Still, there is skepticism and disagreement about the usefulness of performance measuring instruments for design thinking stemming from concerns about how these metrics may lead to less creativity and misleading incentives for participants [24]. Ultimately, the degree of difficulty involved in identifying and engaging with sufficient metrics and measurement instruments for design thinking outcomes makes this a complex problem. Mayer et al. offer a step in the direction towards better trusted solutions by identifying eight challenges related to the measurement of design thinking activities [25]

Efforts to measure the participant experience of design thinking have benefitted from project-based learning and interdisciplinary team research. Participant motivation, conflict, and participative safety are three useful metrics that have proven useful as applications from project-based and team research on design thinking research. Kröper et al. used the experience sampling method (ESM) to measure chronic affect and chronic regulatory focus in design thinking participants as a way of assessing participant motivation. ESM is designed to capture a participant’s immediate conscious experiences by prompting them for responses (via questionnaire) several times a day [26,27]. Jehn frames a definition for three kinds of conflict related to project-based learning: task conflict, relationship conflict, and process conflict. Moreover, Jehn and Ewald et al. provide sufficient rationale to consider participative safety as a key design thinking factor to measure since relationship conflict and process conflict have been significantly linked to negative impacts on team performance, team satisfaction, and team cooperation [28,29]. On a related note, task conflicts are indecisive – meaning there is not significant data to declare a positive or negative impact on team performance, team satisfaction, or team cooperation; specifically, that is without adding context such as when in the conflict occurred during the team life cycle (earlier or later) [29,30]. Edmondson explains team psychological safety (closely synonymous with participative safety) as a "shared belief that the team is safe for interpersonal risk taking [31]." While, participative safety has only been minimally correlated with innovative outcomes – in which some attribute to the "comfort zone effect" – others note that it is important to distinguish between participative safety and similar socioemotional team factors, such as team cohesiveness, that may be also be disguising the value of participative safety in design thinking [29,31,32]. In short, though design thinking, project-based learning, and team collaboration research, there is enough understanding about socioemotional factors to state that failing to cultivate an inclusive environment for each design thinking participant to feel valued and treated as an equal, compromises the impact of the design thinking process [33,34].

2.2.2 Journey Mapping Experiences with Socioemotional Factors

Journey mapping is a human-centered, design research method that is commonly used in exploratory research and testing stages of design thinking as well as in organizations to assess a customer's or user's interaction with their products and services [35]. Recent studies have demonstrated the value of using journey mapping to collect data about experiences where socioemotional factors are important contextual factors [36,37]. Similarly, there have been adaptations of journey mapping being used for academic research purposes in addition to more conventional organizational and commercial research focuses [36,38]. In fact, Dove et al. describes their unconventional lightweight journey mapping method as something that "spans across time, devices, and workflows; and characterizes a complete set of customer interactions with a company [36]." Also, Sinitskaya et al. introduced the combined (linked) journey mapping technique in an effort to capture multiple perspectives of the same experience [38].

This study draws on these examples of journey mapping as a data collection tool to support capturing participant experiences in design thinking.

2.3 Methods

2.3.1 Course Description

The setting of this study takes place during a course at a public research university in the United States. This course was listed as a 2 unit course, spanning a 6 week duration over the summer. All course activities were conducted online via synchronous video conference platforms and included the Mural platform for virtual collaboration. Of 23 enrolled students, 13 chose to participate in this study. There were 10 female and 3 male participants. Also, 7 participants were from non-engineering disciplines while 6 participants were from engineering disciplines.

This course was a project-based learning course that guided students through the five phases of the Human-Centered Design process (Research, Analyze, Ideate, Build, and Communicate). Key deliverables for the course included several activities such as conducting user interviews, framing a problem to solve using “How Might We” statements, brainstorming ideas as a team, creating a final prototype, and communicating the value of a solution through a slide presentation and short video.

2.3.2 Data Collection

This investigation leverages the use of journey mapping to collect self-reported data about design thinking experiences. A key difference in how journey maps are used in this study include a more targeted approach toward understanding the nuance of the participant experience by using direct prompts that refer to a rating system as opposed to what is referred to as the “emotional level” in Chapter 3. The rating system used for this study is more consistent with what has been used in engineering design self-efficacy (EDSE) related work.

Also, this study includes documenting multiple journey maps for the same experience. This was partly inspired by journey map studies where participants got a chance to reflect and, potentially, change responses that they submitted towards the documentation of their journey maps [38].

Two methods were used for collecting the data. They are referred to as the “first” and “final” journey maps. The first journey map involves collecting students’ self-reported ratings about their design thinking journey via Google Form at specified intervals during the design thinking process. The final journey map involves collecting students’ self-reported ratings of their design thinking journey all at once after the process has concluded.

Documentation of the first journey map involved using data collected from students’ “Phase Reflection” assignment. This assignment was delivered via Google Form and was embedded in an online course environment that was to be completed within the first 10 minutes of class following each phase of the Design Thinking process (in this case, each Monday of the course starting on July 19th, 2021). There was one exception: during the final week of the course, the final “Phase Reflection” assignment was due at 12pm on Thursday, August 12th, 2021.

Specific instructions were provided to students in the google form as prompts to document both a self-reported rating and qualitative comment about their individual experience, individual performance, team experience, and team performance. So, a total of four self-reported ratings and four qualitative comments were collected from each student during each phase.

The prompt for students to report individual experience feedback states the following: *“On a scale of 1-10, how would you rate YOUR EXPERIENCE with the activities and assignments required during this phase of the Human Centered-Design process (10 being MOST satisfying and 1 being LEAST satisfying)”*

The prompt for students to report individual performance feedback states the following: *“On a scale of 1-10, how would you rate YOUR PERFORMANCE during this phase of the Human Centered-Design process (10 being MOST successful and 1 being LEAST successful)”*

The prompt for students to report team experience feedback states the following: *“On a scale of 1-10, how would you rate YOUR EXPERIENCE WITH YOUR TEAM during this phase of the Human Centered-Design process (10 being MOST satisfying and 1 being LEAST satisfying)”*

The prompt for students to report team performance feedback states the following: *“On a scale of 1-10, how would you rate your TEAM'S PERFORMANCE during this phase of the Human Centered-Design process (10 being MOST successful and 1 being LEAST successful)”*

Documentation of the final journey map involved collecting interactive plots (created in Google slides) that students submitted through their online course environment as a part of their “Individual Reflection” assignment. This assignment was due on the final day of the course (August 13th, 2021 at 11:59pm).

Specific instructions were provided to students in the google slide deck as prompts to document both a self-reported rating and qualitative comment about their individual experience, individual performance, team experience, and team performance for all design thinking phases. The instructions are provided below:

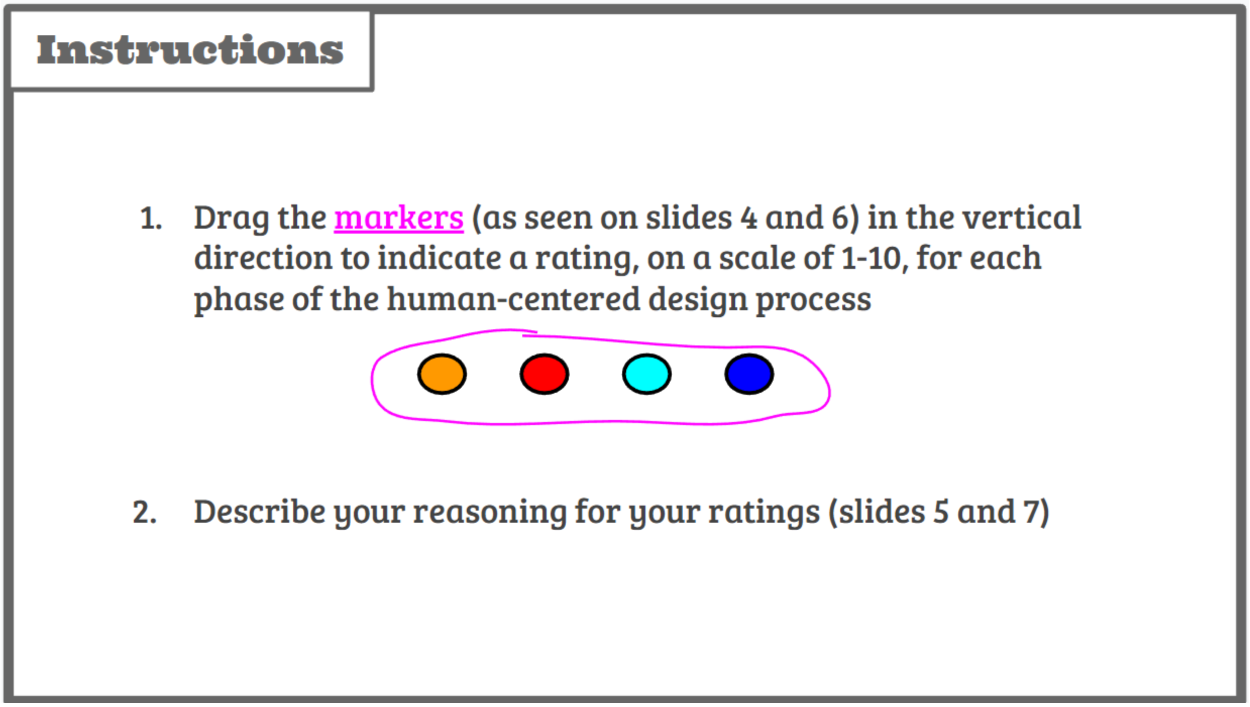
“The purpose of this exercise is to create two Journey Maps that illustrate your journey through the human-centered design process. The Journey Maps should reflect PERSONAL evaluation of

(1) individual success, (2) individual satisfaction, (3) team success, and (4) team satisfaction at the five stages during the human-centered design process.

For each step in your journey map, please associate a rating on a scale from 1-10 that corresponds to how you felt during that stage. For this exercise, a rating of 10 represents the MOST successful and MOST satisfactory experiences, while a rating of 1 represents the LEAST successful and LEAST satisfactory experiences.

1. *Please click through the following example slides (3-7) to understand the goal of this exercise.*
2. *Then, modify slides 9 - 12 accordingly to best represent your experience.*
3. *Once you are finished, download this slide deck as a PDF and upload it to [your course online course environment].”*

Below, Fig. 1 - Fig. 5 illustrate slides 3-7 – referenced as examples in the instructions above.



Instructions

1. Drag the markers (as seen on slides 4 and 6) in the vertical direction to indicate a rating, on a scale of 1-10, for each phase of the human-centered design process
2. Describe your reasoning for your ratings (slides 5 and 7)

Figure 1: Student instructions for submitting final journey map

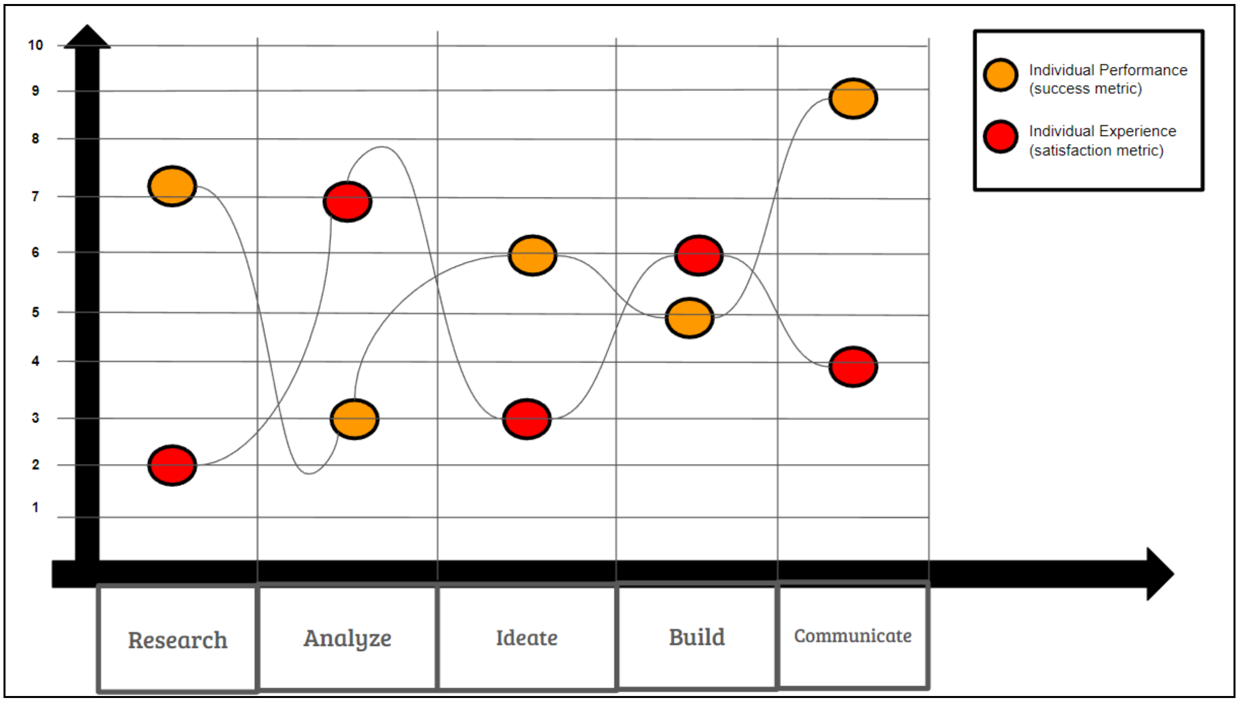
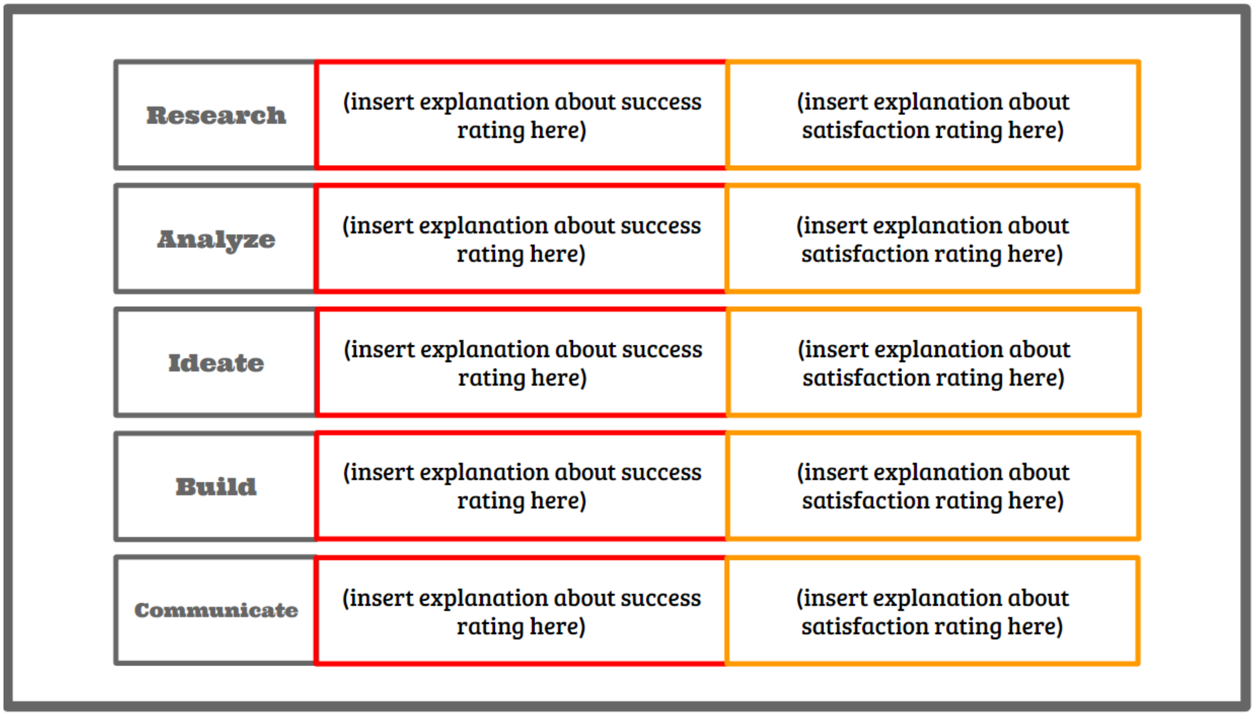


Figure 2: Student instructions for submitting the final journey map. Example of Individual Performance and Individual Experience interactive map



Research	(insert explanation about success rating here)	(insert explanation about satisfaction rating here)
Analyze	(insert explanation about success rating here)	(insert explanation about satisfaction rating here)
Ideate	(insert explanation about success rating here)	(insert explanation about satisfaction rating here)
Build	(insert explanation about success rating here)	(insert explanation about satisfaction rating here)
Communicate	(insert explanation about success rating here)	(insert explanation about satisfaction rating here)

Figure 3: Student instructions for submitting the final journey map. Example of Individual Performance and Individual Experience qualitative feedback prompts

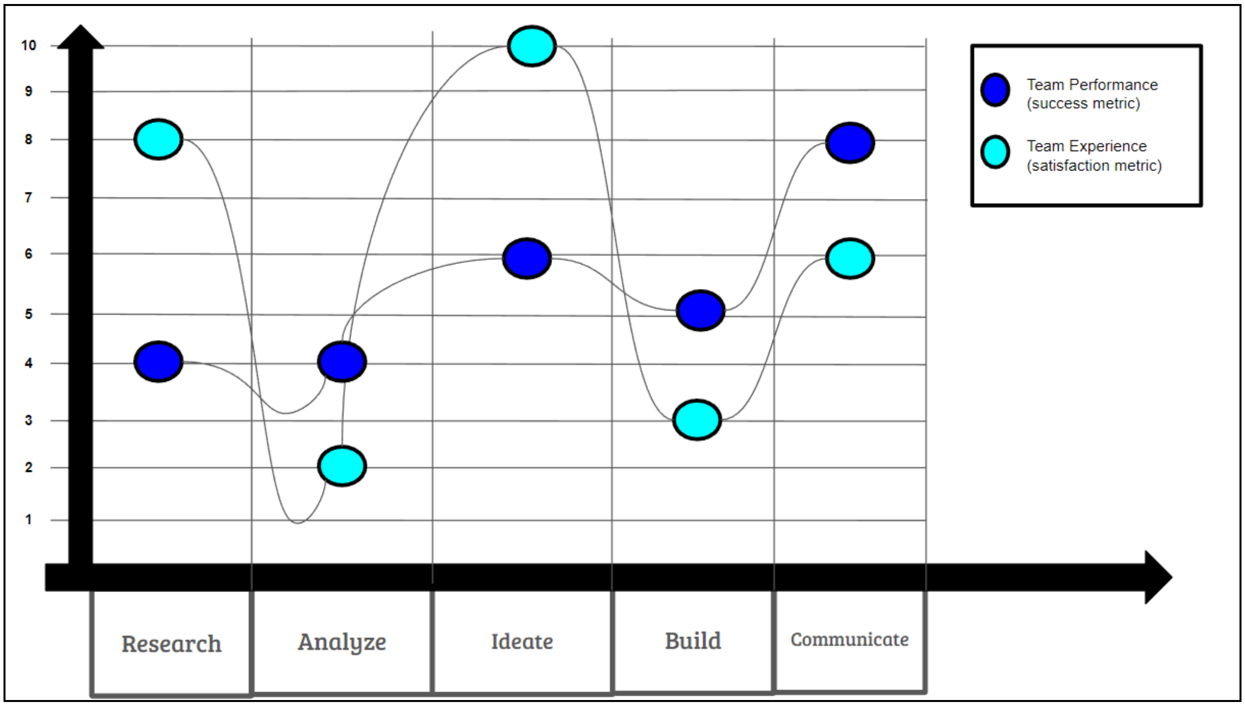
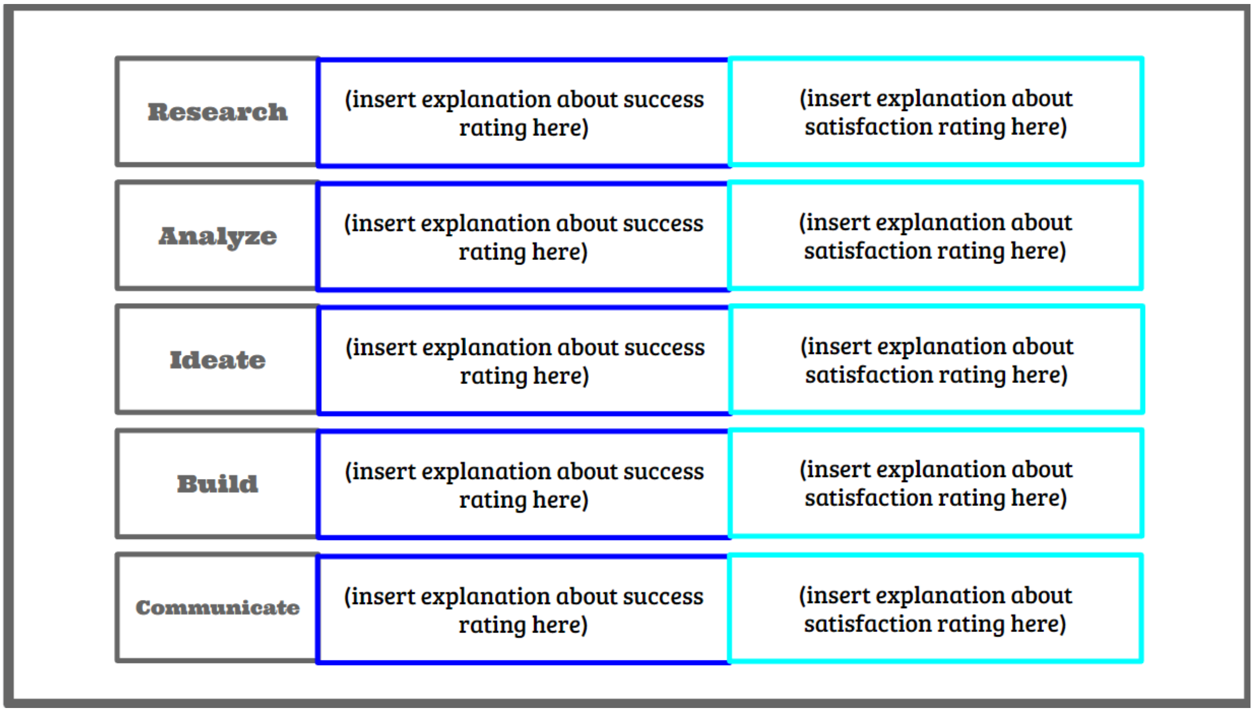


Figure 4: Student instructions for submitting the final journey map. Example of Team Performance and Team Experience interactive map



Research	(insert explanation about success rating here)	(insert explanation about satisfaction rating here)
Analyze	(insert explanation about success rating here)	(insert explanation about satisfaction rating here)
Ideate	(insert explanation about success rating here)	(insert explanation about satisfaction rating here)
Build	(insert explanation about success rating here)	(insert explanation about satisfaction rating here)
Communicate	(insert explanation about success rating here)	(insert explanation about satisfaction rating here)

Figure 5: Student instructions for submitting the final journey map. Example of Team Performance and Team Experience qualitative feedback prompts

Instructions communicated during class for all journey map assignments (related to both first and final) included a reminder that they would be graded for completion and that the content of the submission would not impact their course grade.

2.3.3 Data Analysis

Data for four journeys were collected at each phase of the five design thinking process. This was done during design thinking experience (first journey map) and after the entire experience was over (final journey map). With 13 participants in this study, there were a total of 520 self-reported ratings and 520 qualitative comments to be collected (2 journey collection efforts x 4 types of ratings to document x 5 design thinking phases x 13 participants). In actuality, there were 456 self-reported rating and qualitative comments collected – in which, missing data points were due to students not submitting their assignments.

Steps to analyze the self-reported ratings included beginning with using type III, two-way ANOVA tests to determine which factors (gender, academic discipline, iteration, and design thinking phase) were significantly impacting the self-reported rating submitted by students participating in this study. After identifying which factors were significant, one-way ANOVA tests were performed as post hoc tests to determine which specific factor levels were significantly impacting self-reported ratings. Finally, Shapiro-Wilk's test (test for normality of the data) and Levene's tests (tests for homogeneity of variance) were performed to validate assumptions of the ANOVA model.

Complimentary to statistical methods being used to identify significant factors and factor levels, affinity mapping was used as a technique to extract high level themes that were discussed in the qualitative comments. Themes were sorted based on the design thinking phase and the type of self-reported rating that they were associated with.

2.3.4 Assumptions

The course in which this study was conducted uses the term "Human-Centered Design process" while this study uses the term Design Thinking. These terms are assumed to be synonymous and, in an effort to maintain consistency with the language being used in this dissertation, the term design thinking will be used in reference to course activities.

Regarding academic discipline, students that were listed as studying Computer Science were counted as engineering students although some of them are on a degree path where they will receive degrees from the college of letters and sciences instead of the college of engineering (this distinction has mostly to do with their elective courses).

2.4 Results and Discussion

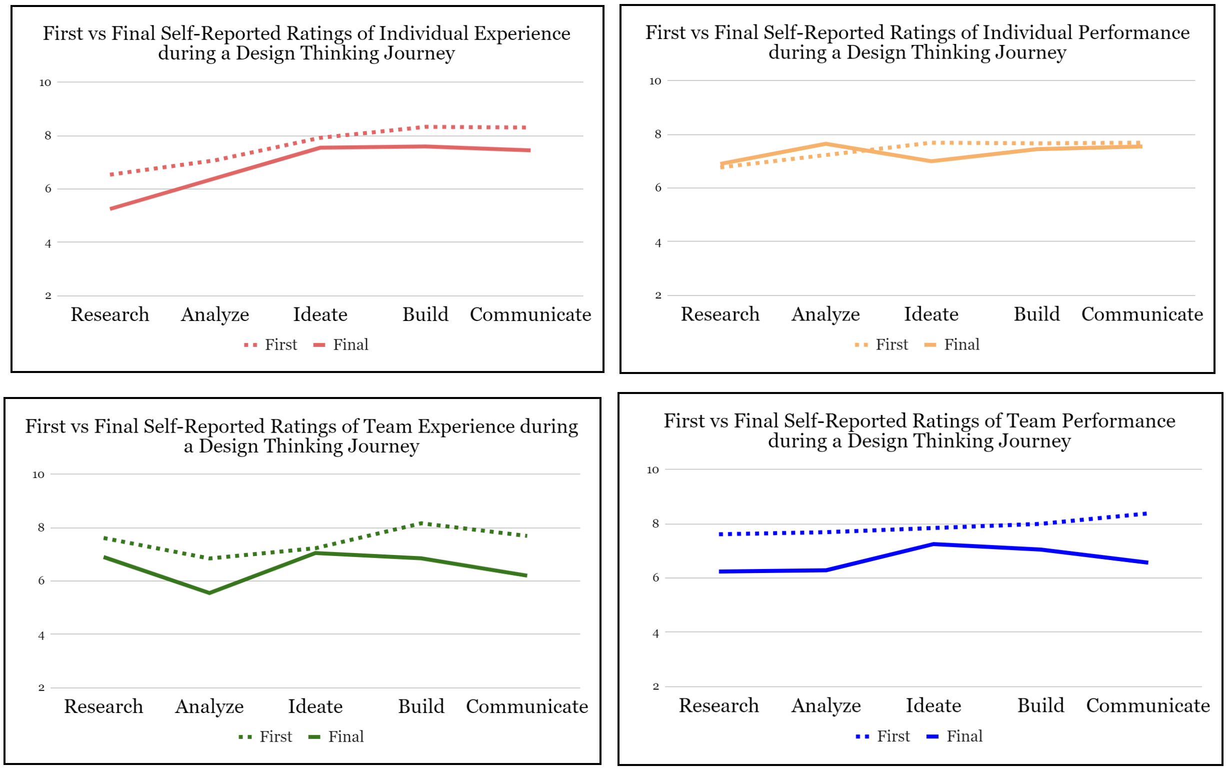
In this chapter, the following results and discussion topics will be presented: (Section 2.4.1) a comparison of the first and final journey maps across all students, by gender, and by academic discipline; (Section 2.4.2) statistically significant factor and factor levels that influence the self-reported journey map ratings; (Section 2.4.3) qualitative data expressing key themes from each design thinking journey across all phases of the design thinking process; and (Section 2.4.4 & Section 2.4.5) finally discussions of limitations and future work, respectively.

2.4.1 First vs Final Self-Reported Ratings during Design Thinking Journey

Below, Table 1 and Fig. 6 illustrate both the first and final design thinking journeys from all students in regards to their self-reported ratings of individual experience, individual performance, team experience, and team performance.

		Research		**Analyze**		**Ideate**		**Build**		**Communicate**	
		mean	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
First	**Individual Experience**	6.54	1.45	7.08	1.38	7.92	1.19	8.33	1.23	8.31	1.65
	Individual Performance	6.77	1.74	7.23	2.17	7.69	1.89	7.67	1.83	7.69	2.25
	Team Experience	7.62	1.19	6.85	2.23	7.23	2.28	8.17	1.85	7.69	2.32
	Team Performance	7.62	1.56	7.69	0.95	7.85	2.41	8.00	2.22	8.38	2.29
Final	**Individual Experience**	5.25	1.84	6.40	2.17	7.55	2.81	7.60	1.78	7.45	1.85
	Individual Performance	6.90	1.97	7.65	1.60	7.00	1.68	7.45	2.09	7.55	2.14
	Team Experience	6.90	1.20	5.55	2.43	7.05	2.52	6.85	2.67	6.20	3.02
	Team Performance	6.24	1.79	6.29	1.98	7.25	1.55	7.05	2.17	6.57	2.31

Table 1: Average Self-Reported Ratings of all Design Thinking Journeys corresponding to Design Thinking Phase


First vs Final Self-Reported Ratings of Individual Experience during a Design Thinking Journey

First vs Final Self-Reported Ratings of Individual Performance during a Design Thinking Journey

First vs Final Self-Reported Ratings of Team Experience during a Design Thinking Journey

First vs Final Self-Reported Ratings of Team Performance during a Design Thinking Journey

Figure 6: First vs Final Self-Reported Ratings of all Design Thinking Journeys

Fig. 7 illustrates the first and final design thinking journey maps from all students through a comparison of gender. Similarly, Fig. 8 illustrates the first and final design thinking journey maps from all students through a comparison of academic discipline.

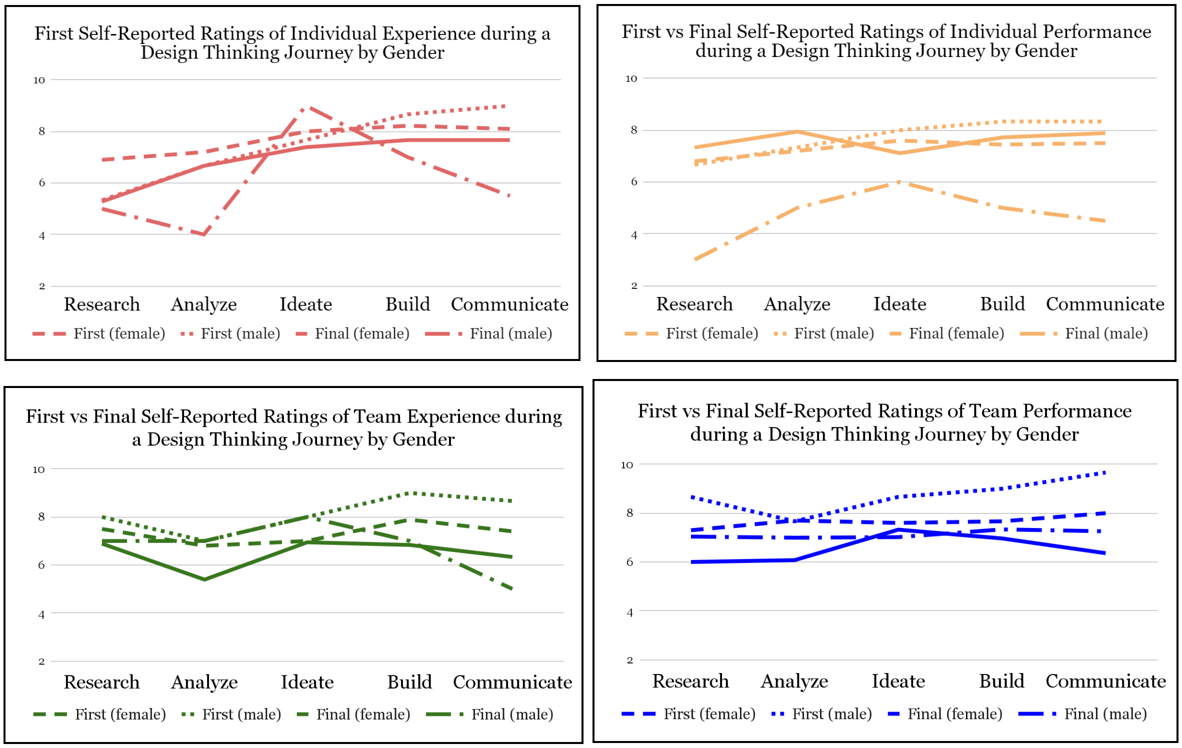


Figure 7: First vs Final Self-Reported Ratings of all Design Thinking Journeys by Gender

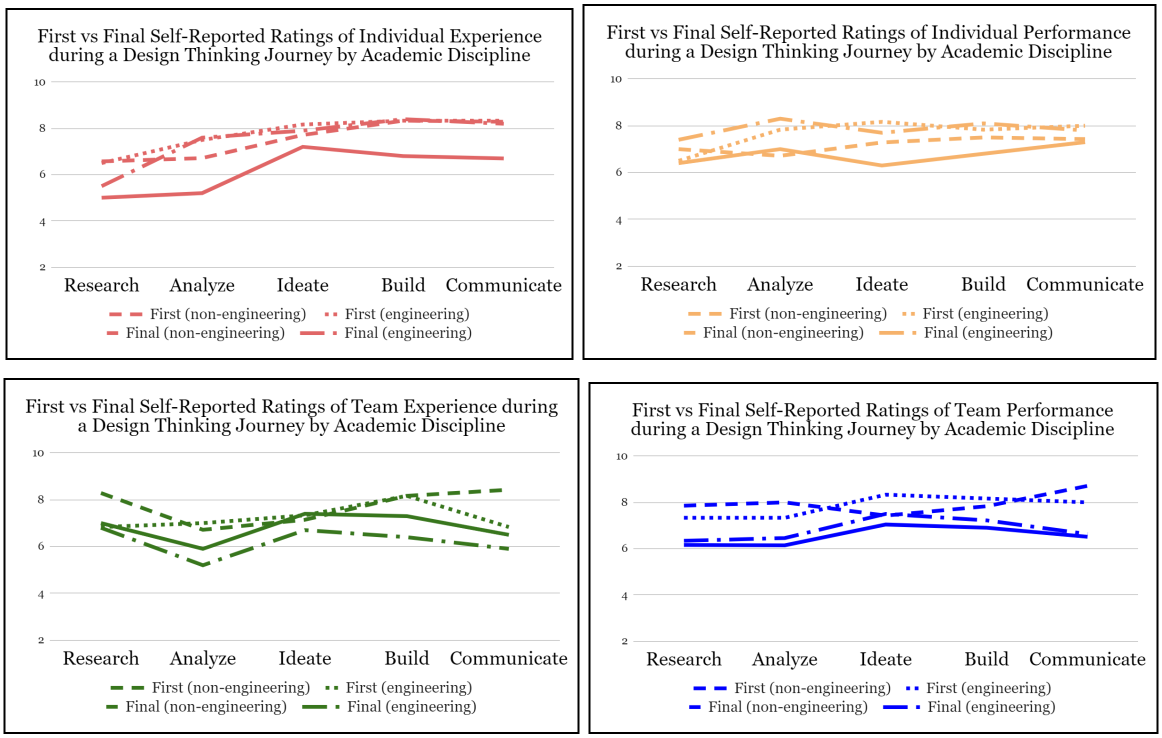


Figure 8: First vs Final Self-Reported Ratings of all Design Thinking Journeys

2.4.2 Significant Factors and Factor Levels Acting on Self-Reported Ratings

Since the journey map data was unbalanced and included several independent variables, several type III ANOVA tests were performed to understand the significance of each variable in relation to each other and the dependent variable – the self-reported ratings of the students. Table 2 represents all of the factors influencing the dependent variable.

Factors	**Gender**	**Discipline**	**Phase**	**Iteration**
Factor Levels	Female Male	Non-engineering Engineering	Research Analyze Ideate Build Communicate	First Journey Map Final Journey Map

Table 2: Factors and factor levels associated with self-reported ratings in each journey map

Next, Table 3 - Table 8 provide the p-values resulting from the type III ANOVA calculations.

	Individual Experience		**Individual Performance**		**Team Experience**		**Team Performance**	
	P-value	**sign**	**P-value**	**sign**	**P-value**	**sign**	**P-value**	**sign**
Gender	0.65	ns	0.32	ns	0.11	ns	0	**
Phase	0	**	0.53	ns	0.64	ns	0.69	ns
Gender:Phase Interaction	0.78	ns	0.88	ns	1	ns	0.95	ns

Table 3: Type III ANOVA tests results for Gender and Phase factors

	Individual Experience		**Individual Performance**		**Team Experience**		**Team Performance**	
	P-value	**sign**	**P-value**	**sign**	**P-value**	**sign**	**P-value**	**sign**
Gender	0.79	ns	0.41	ns	0.28	ns	0.04	*
Discipline	0.39	ns	0.42	ns	0.33	ns	0.16	ns
Gender:Discipline Interaction	0.5	ns	0.46	ns	0.75	ns	0.26	ns

Table 4: Type III ANOVA tests results for Gender and Discipline factors

	Individual Experience		**Individual Performance**		**Team Experience**		**Team Performance**	
	P-value	**sign**	**P-value**	**sign**	**P-value**	**sign**	**P-value**	**sign**
Gender	0.32	ns	0.02	*	0.35	ns	0	**
Iteration	0.05		0.01	*	0.08	ns	0.74	ns
Gender:Iteration Interaction	0.55	ns	0	**	0.68	ns	0.4	ns

Table 5: Type III ANOVA tests results for Gender and Iteration factors

	Individual Experience		**Individual Performance**		**Team Experience**		**Team Performance**	
	P-value	**sign**	**P-value**	**sign**	**P-value**	**sign**	**P-value**	**sign**
Discipline	0.03	*	0.04	*	0.17	ns	0.15	ns
Phase	0	**	0.63	ns	0.39	ns	0.46	ns
Discipline:Phase Interaction	0.78	ns	0.89	ns	0.92	ns	0.99	ns

Table 6: Type III ANOVA tests results for Discipline and Phase factors

	Individual Experience		**Individual Performance**		**Team Experience**		**Team Performance**	
	P-value	**sign**	**P-value**	**sign**	**P-value**	**sign**	**P-value**	**sign**
Discipline	0.02	*	0.03	*	0.18	ns	0.13	ns
Iteration	0.03	*	0.75	ns	0.02	*	0.07	ns
Discipline:Iteration Interaction	0.12	ns	0.39	ns	0.89	ns	0.25	ns

Table 7: Type III ANOVA tests results for Discipline and Iteration factors

	Individual Experience		**Individual Performance**		**Team Experience**		**Team Performance**	
	P-value	**sign**	**P-value**	**sign**	**P-value**	**sign**	**P-value**	**sign**
Iteration	0.02	*	0.79	ns	0.02	*	0.07	ns
Phase	0	**	0.68	ns	0.35	ns	0.42	ns
Iteration:Phase Interaction	0.94	ns	0.91	ns	0.85	ns	0.92	ns

Table 8: Type III ANOVA tests results for Iteration and Phase factors

Results from the type III ANOVA model suggest that phase, iteration, and academic discipline have a significant impact on the self-reported ratings of the individual experience in design thinking journeys. Gender, iteration, and academic discipline have a significant impact on the self-reported ratings of the individual performance in design thinking journeys. Only iteration has a significant impact on the self-reported ratings of the team experience in design thinking journeys. Finally, only gender has a significant impact on the self-reported ratings of the team performance in design thinking journeys. In addition, the gender:iteration interaction (see Table 5) suggests that gender has a significant impact on self-reported ratings of individual performance in the first vs final design thinking journey.

Given these results, several one-way ANOVA Tukey post hoc tests – specifically, Tukey's Honest Significant Difference (HSD) test – were performed in order to identify which factor levels are significantly impacting the self-reported ratings of design thinking journeys. The following tables (Table 9 - Table 12) show the p-values for all of the Tukey HSD tests. Factor levels with highlighted p-values are significant.

		All	**Female**	**Male**	**Noneng.**	**Engin.**	**Research**	**Analyze**	**Ideate**	**Build**	**Comm.**
First - Final	**Ind. Exp.**	0.030	0.065	0.126	0.017	0.569	0.074	0.372	0.669	0.267	0.254
	Ind. Perf.	0.790	0.440	0.005	0.496	0.580	0.868	0.613	0.372	0.798	0.879
	Team Exp.	0.018	0.091	0.040	0.143	0.066	0.169	0.198	0.859	0.188	0.194
	Team Perf.	0.067	0.138	0.634	0.667	0.014	0.142	0.246	0.375	1.000	0.426

Table 9: Tukey HSD test results (p-values) for Iteration using one-way ANOVA with each factor level

		All	**Noneng.**	**Engin.**	**Research**	**Analyze**	**Ideate**	**Build**	**Comm.**	**First**	**Final**
Male - Female	**Ind. Exp.**	0.680	0.739	0.504	0.364	0.339	0.800	0.724	0.818	0.650	0.435
	Ind. Perf.	0.317	0.949	0.166	0.195	0.458	0.898	0.939	0.801	0.464	0.001
	Team Exp.	0.107	0.218	0.627	0.435	0.516	0.437	0.383	0.576	0.164	0.780
	Team Perf.	0.002	0.008	0.518	0.036	0.365	0.149	0.256	0.254	0.055	0.032

Table 10: Tukey HSD test results (p-values) for Gender using one-way ANOVA with each factor level

		All	**Female**	**Male**	**Research**	**Analyze**	**Ideate**	**Build**	**Comm.**	**First**	**Final**
Non-Eng. - Engin.	**Ind. Exp.**	0.045	0.043	0.914	0.863	0.043	0.528	0.269	0.389	0.490	0.033
	Ind. Perf.	0.034	0.030	0.978	0.838	0.132	0.154	0.354	0.565	0.321	0.035
	Team Exp.	0.165	0.411	0.236	0.066	0.850	0.839	0.687	0.290	0.322	0.369
	Team Perf.	0.151	0.736	0.009	0.382	0.266	0.846	0.631	0.479	0.778	0.078

Table 11: Tukey HSD test results (p-values) for Academic Discipline using one-way ANOVA with each factor level

		All	Female	Male	Noneng.	Engin.	First	Final
Build - Analyze	**Ind. Exp.**	0.147	0.481	0.148	0.369	0.633	0.175	0.715
	Ind. Perf.	0.999	1.000	0.991	0.997	1.000	0.982	0.999
	Team Exp.	0.309	0.521	0.522	0.628	0.686	0.484	0.758
	Team Perf.	0.818	0.939	0.578	0.981	0.817	0.995	0.759
Communicate - Analyze	**Ind. Exp.**	0.180	0.519	0.185	0.354	0.728	0.175	0.803
	Ind. Perf.	0.995	0.999	0.996	0.980	0.999	0.976	1.000
	Team Exp.	0.778	0.861	0.927	0.702	0.999	0.823	0.975
	Team Perf.	0.771	0.917	0.481	0.948	0.875	0.896	0.947
Ideate - Analyze	**Ind. Exp.**	0.332	0.712	0.230	0.440	0.912	0.536	0.746
	Ind. Perf.	1.000	0.998	0.991	1.000	1.000	0.976	0.940
	Team Exp.	0.681	0.812	0.822	0.896	0.872	0.988	0.649
	Team Perf.	0.999	1.000	0.769	1.000	0.979	1.000	1.000
Research - Analyze	**Ind. Exp.**	0.533	0.658	0.918	1.000	0.094	0.861	0.746
	Ind. Perf.	0.837	0.921	0.974	1.000	0.220	0.976	0.903
	Team Exp.	0.533	0.632	0.927	0.623	0.954	0.868	0.732
	Team Perf.	0.996	0.968	0.851	0.999	0.999	1.000	0.991
Communicate-Build	**Ind. Exp.**	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Ind. Perf.	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Team Exp.	0.934	0.976	0.927	1.000	0.826	0.977	0.975
	Team Perf.	1.000	1.000	1.000	1.000	1.000	0.988	0.991
Ideate -Build	**Ind. Exp.**	0.991	0.995	0.999	1.000	0.982	0.947	1.000
	Ind. Perf.	0.998	0.997	1.000	0.998	1.000	1.000	0.984
	Team Exp.	0.971	0.988	0.983	0.984	0.997	0.776	1.000
	Team Perf.	0.913	0.927	0.997	0.957	0.986	1.000	0.819
Research - Build	**Ind. Exp.**	0.002	0.031	0.033	0.269	0.002	0.017	0.115
	Ind. Perf.	0.693	0.908	0.834	0.992	0.296	0.791	0.967
	Team Exp.	0.995	1.000	0.927	1.000	0.974	0.960	1.000
	Team Perf.	0.597	0.629	0.986	0.921	0.673	0.988	0.481
Ideate - Communicate	**Ind. Exp.**	0.997	0.998	1.000	1.000	0.995	0.955	1.000
	Ind. Perf.	0.993	0.985	1.000	0.985	1.000	1.000	0.967
	Team Exp.	1.000	1.000	0.999	0.995	0.954	0.977	0.936
	Team Perf.	0.881	0.903	0.986	0.907	0.995	0.956	0.971
Research - Communicate	**Ind. Exp.**	0.002	0.034	0.043	0.255	0.003	0.016	0.159
	Ind. Perf.	0.615	0.833	0.867	0.967	0.339	0.760	0.940
	Team Exp.	0.995	0.994	1.000	1.000	0.991	1.000	0.968
	Team Perf.	0.538	0.578	0.961	0.851	0.749	0.854	0.759
Research - Ideate	**Ind. Exp.**	0.007	0.075	0.056	0.327	0.011	0.097	0.129
	Ind. Perf.	0.855	0.985	0.834	1.000	0.296	0.760	1.000
	Team Exp.	0.999	0.998	0.999	0.986	0.999	0.988	1.000
	Team Perf.	0.975	0.975	1.000	1.000	0.922	0.998	0.979

Table 12: Tukey HSD test results (p-values) for Phase using one-way ANOVA with each factor level

Based on these results, additional tests were performed to validate assumptions of the one-way ANOVA tests. That is, performing the Shapiro-Wilks test to confirm a normal distribution of the data and performing Levene's test to confirm that the population variances are equal. Table 13 provides the results from all of these tests. The response "TRUE" indicates that the test was passed while "FALSE" indicates that the test was not passed.

	Factor	Factor Level	Shapiro-Wilk test	Levene Test
Ind. Exp.	Iteration	All	FALSE	FALSE
	Iteration	nonengineering	TRUE	FALSE
	Discipline	All	FALSE	TRUE
	Discipline	female	FALSE	TRUE
	Discipline	analyze	TRUE	TRUE
	Discipline	final	TRUE	TRUE
	Phase	All	FALSE	TRUE
	Phase	female	FALSE	TRUE
	Phase	male	TRUE	TRUE
	Phase	engineering	TRUE	TRUE
	Phase	first	FALSE	TRUE
Ind. Perf.	Iteration	male	TRUE	TRUE
	Gender	final	TRUE	TRUE
	Discipline	All	FALSE	FALSE
	Discipline	female	FALSE	FALSE
	Discipline	final	TRUE	FALSE
Team. Exp.	Iteration	All	FALSE	TRUE
	Iteration	male	TRUE	TRUE
Team. Perf.	Iteration	engineering	FALSE	TRUE
	Gender	All	FALSE	FALSE
	Gender	nonengineering	FALSE	FALSE
	Gender	research	TRUE	TRUE
	Gender	final	TRUE	FALSE
	Discipline	male	TRUE	TRUE

Table 13: Results for the Shapiro-Wilks test and Levene's test for all factors

The following plots (Fig. 9 through Fig. 17) provide a closer look at how the significant factors and factors levels from Table 13 impact the trajectories of self-reported ratings for students' design thinking journeys.

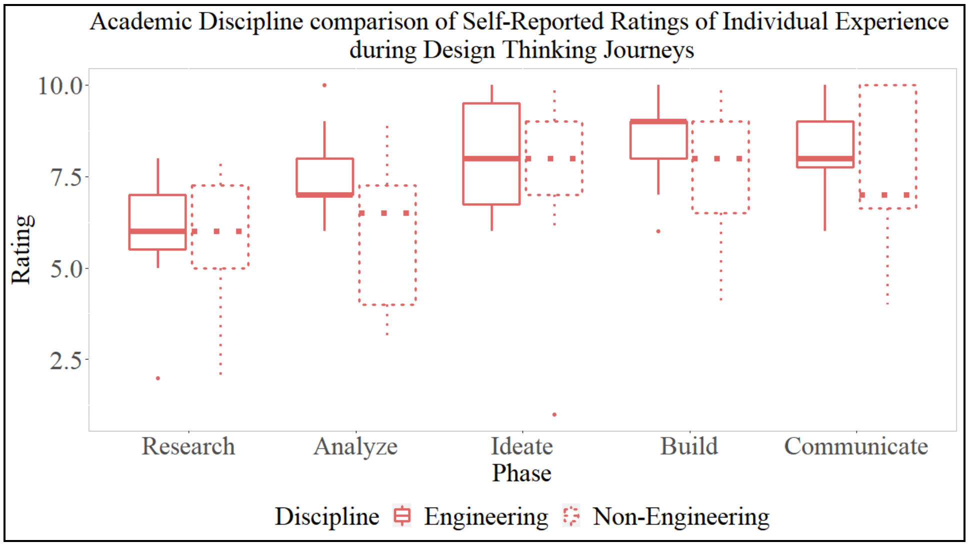


Figure 9: Plot demonstrating the significant impact of Academic Discipline on the Analyze Phase of Individual Experience Self-Reported Ratings

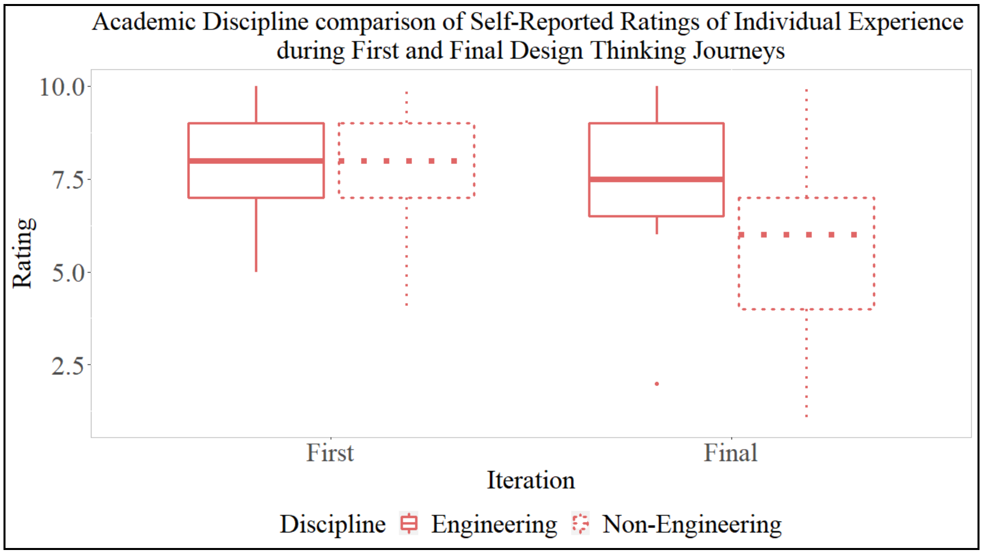


Figure 10: Plot demonstrating the significant impact of Academic Discipline on the Final Design Thinking Journey for Individual Experience Self-Reported Ratings

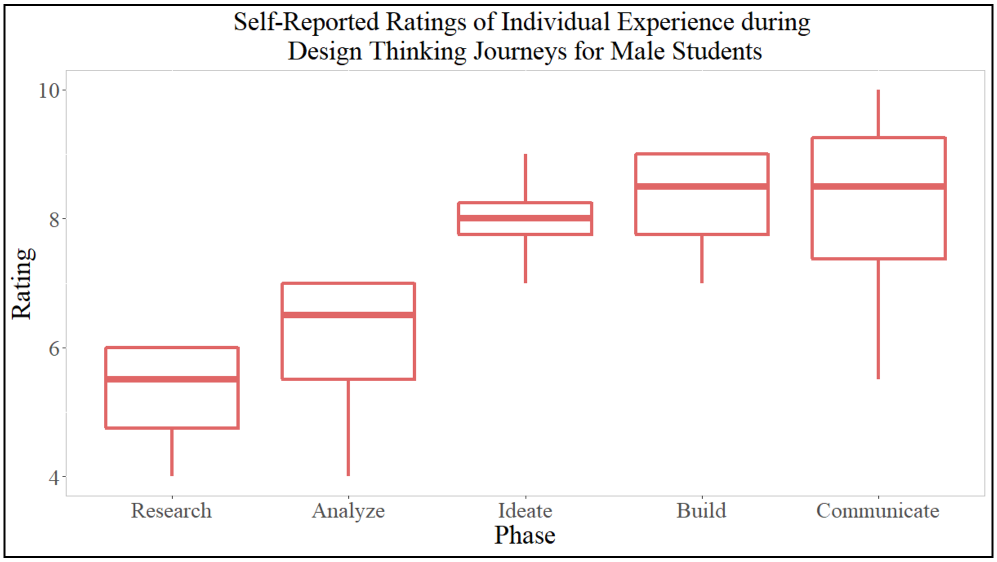


Figure 11: Plot demonstrating the significant impact of Design Thinking Phase on Male Students for Individual Experience Self-Reported Ratings

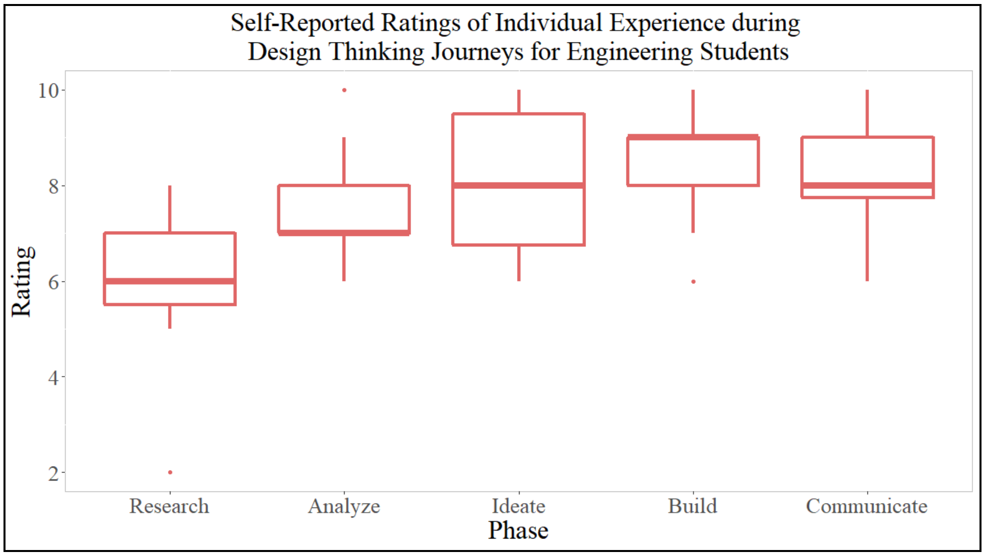


Figure 12: Plot demonstrating the significant impact of Design Thinking Phase on Engineering Students for Individual Experience Self-Reported Ratings

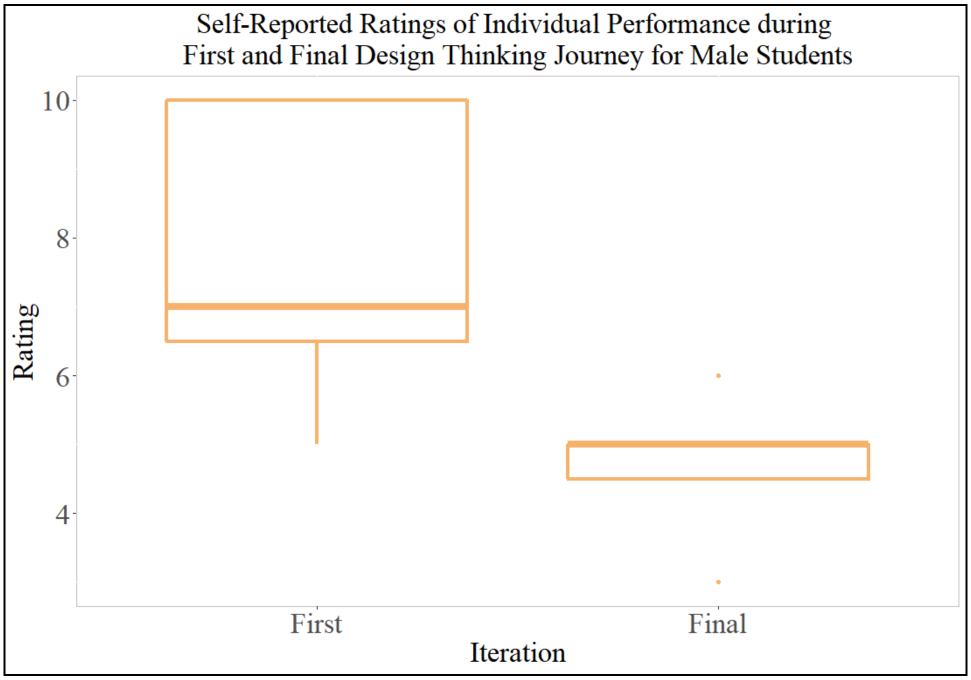


Figure 13: Plot demonstrating the significant impact of Journey Map Iteration on Male Students for Individual Performance Self-Reported Ratings

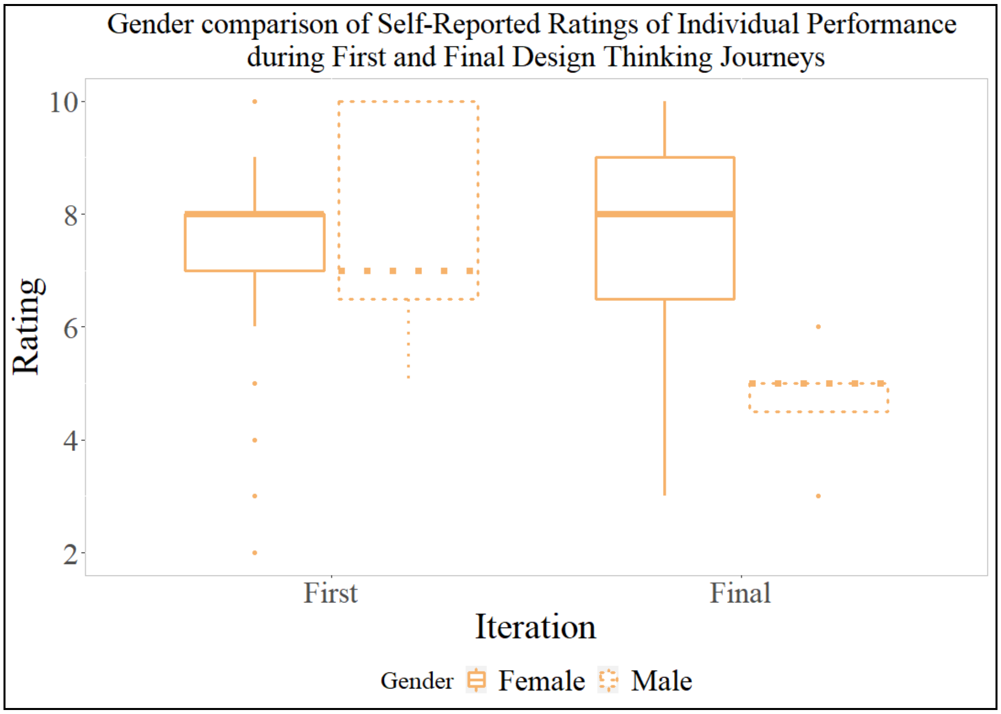


Figure 14: Plot demonstrating the significant impact of Gender on the Final Iteration of Individual Performance Self-Reported Ratings

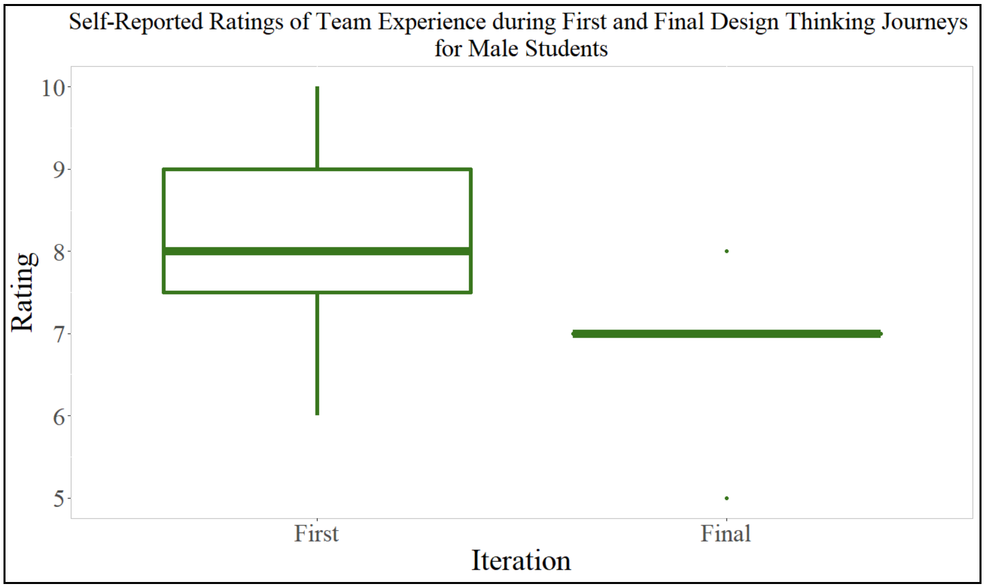


Figure 15: Plot demonstrating the significant impact of Journey Map Iteration on Male Students for Team Experience Self-Reported Ratings

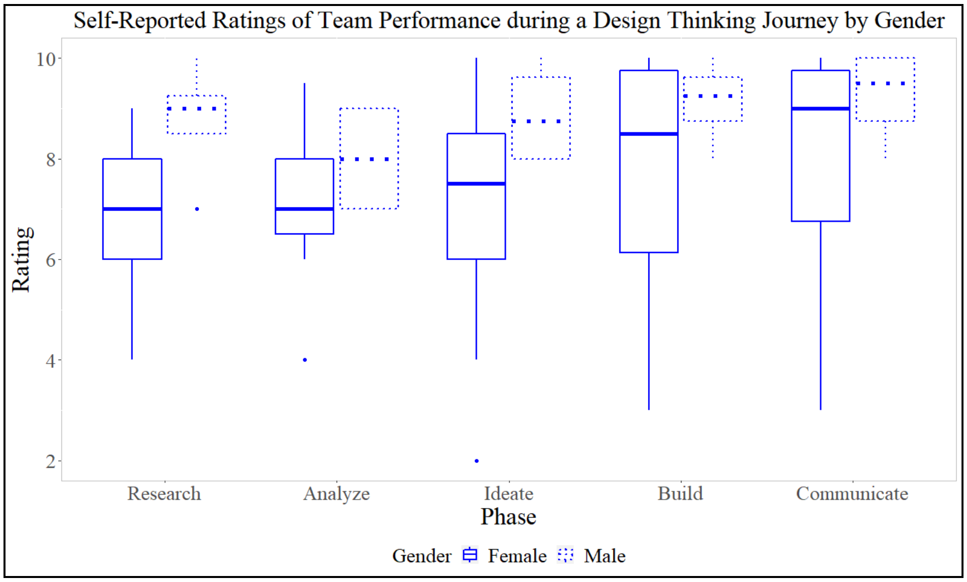


Figure 16: Plot demonstrating the significant impact of Gender on the Research Phase for Team Performance Self-Reported Ratings

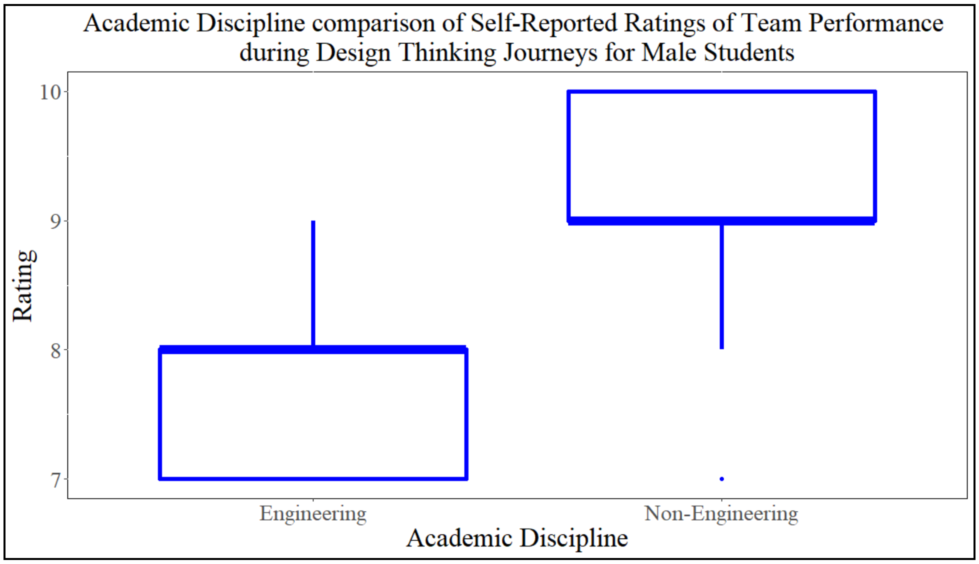


Figure 17: Plot demonstrating the significant impact of Academic Discipline on Male Students for Team Performance Self-Reported Ratings

2.4.2.1 Key Insights from Significant Factors and Factors Levels

The independent variables for this study included four factors and 11 factor levels as expressed in Table 2. The Type III ANOVA tests were performed to determine the significance that the four factors have on self-reported ratings, while the one-way ANOVA Tukey post hoc tests helped identify which specific factor levels had an impact on self-reported ratings.

Ultimately, self-reported ratings for the individual experience of design thinking journeys expressed the most significant impact from these factors and factor levels. Specifically, the beginning of the design thinking journey seemed to be a significantly worse experience than the later half of the journey for male students and engineering students in particular.

Non-engineering students expressed a significant difference in their self-reported ratings during their first journey map vs their final journey map. On the other hand, there was no significant difference for engineering students between their first and final self-reported rating of individual experience. This result may hint at the difference in value or big picture perspective that non-engineering students have towards the design thinking process. As a design thinking instructor, guide, or practitioner it may be important to understand further if this result has anything to do with the current implicit value system of the design thinking process. In other words, do current indicators of success in the design thinking process appeal more to engineering vs non-engineering students?

Finally, another key result shows a significant difference male and female self-reported ratings of team performance during the research phase of the design thinking process. This result might suggest that expectations for rigorous research are not aligned between male and female students.

2.4.3 Qualitative Themes Associated with Self-Reported Journey Map Ratings

The beginning of the qualitative analysis process started with documenting all comments in the Mural platform for convenience of sorting. Below, Fig. 18 illustrates the format of gathering all of the qualitative comments in the Mural platform.

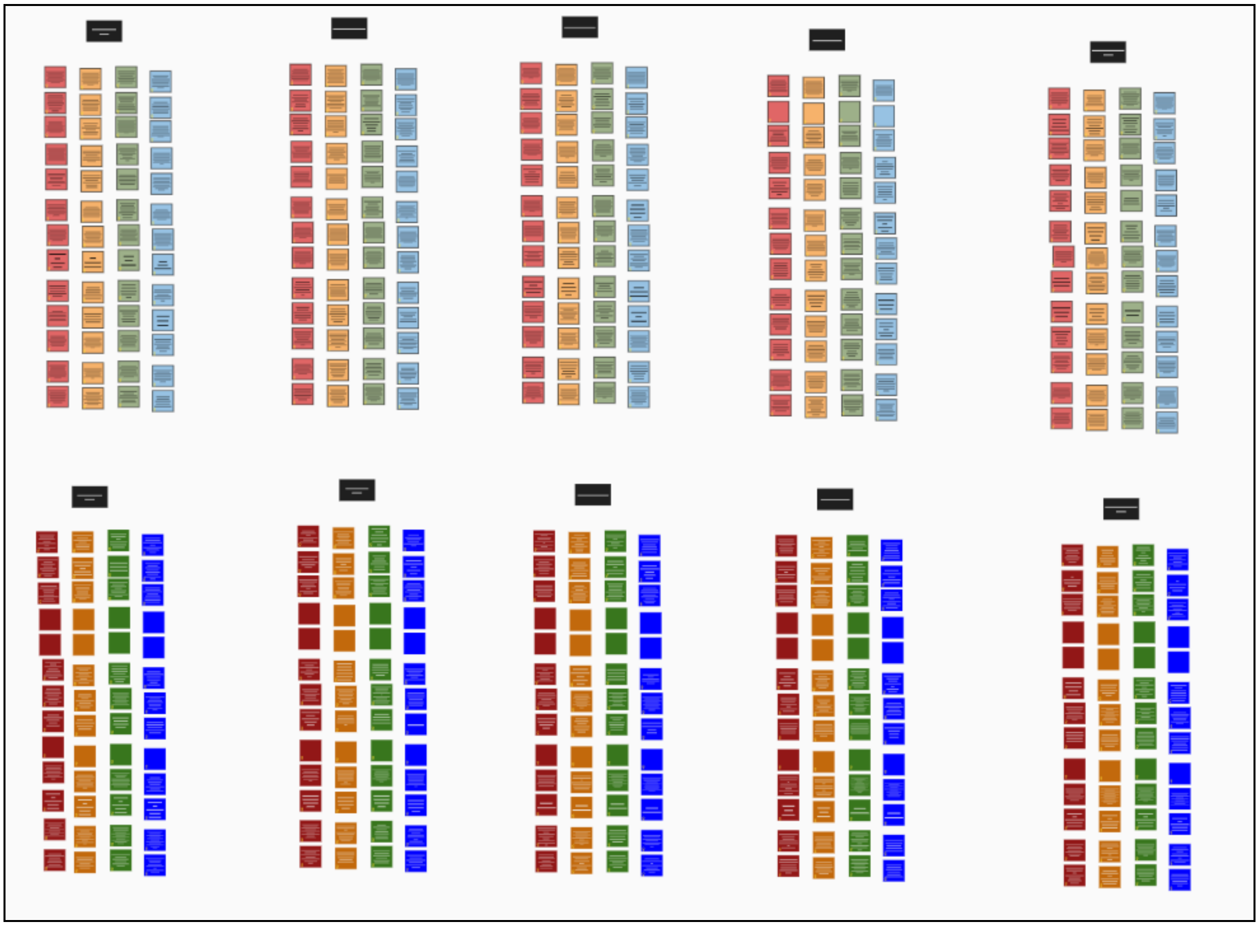


Figure 18: Unsorted qualitative comments from design thinking journeys provided in Mural

Next, Table 14 provides high level themes extracted from qualitative feedback about individual experience during the design thinking journey.

	Themes	# of comments	Avg. rating
Research	Indifference	3	7
	Vague, unclear, and confusing	5	5
	Overwhelming and stressful	9	5.1
	Virtual team engagement is a challenge	1	8
	Learning new things	5	7.5
Analyze	Intriguing motivation for next steps	4	8
	Confusing and frustrating virtual experience	3	5.6
	Gaining clarity and sense making is enjoyable	7	7.4
	Overwhelming amount of work	2	7
	This was a challenge and I can do better	6	5.5
Ideate	Enjoyable push to be creative	8	8
	Lots of effort, little time, still worth it	7	8
	Clarity and organization fueled my success	1	8
	policy, culture, support for niche themes	1	8
	Not enough structure. Limitless.	2	5.5
	I could have done better	3	7.5
Build	Critical thinking. Learning by doing	3	9
	Seeing it all come together	7	8.3
	team skill building. a learning curve that's worth it	4	7
	more time would be nice	4	6.8
	engaging and useful team activities	3	9
Communicate	A creative challenge that is worth it	8	7.2
	clarity and creative freedom	3	9
	relief of being at the finish line	2	7.8
	effectively communicating your ideas feels rewarding	8	8.8
	Not my favorite	2	6

Table 14: Major themes from qualitative comments about the individual experience during the design thinking journey

For the research phase in Table 14, there is a general trend of themes ranging from exploratory excitement to discomfort with lack of structure. Some of that is due to class logistics -- such as lots of assignments upfront and many different virtual platforms to gain familiarity with. On the other hand, some discomfort is due to the nature of what the design thinking process requires of its participants. Cycles of convergence and divergence are notable topics in themes that have come from qualitative feedback about the individual experience through the research phases (and other phases for that matter).

The converging aspect of the analyze phase contributed to the major themes of this phase. In addition, there seemed to be more optimism about diverging in future steps. There were also mentionings of logistical struggles with the virtual format of this experience. Moreover, the overwhelming nature of how demanding the design thinking process can be when done in such a short time frame is apparent through these themes as well.

The individual experience for the ideate phase centered around an appreciation for the nudge to be creative and the pressure to diverge and converge with so little time. There was an interesting polarity around the feeling of structure as some students reported indulging in the variety of solutions that comes with this phase vs others feeling unsupported by the limitless boundaries.

Feedback about the build phase largely leaned toward the excitement of finally bringing an idea to life. If the design thinking process were a story, this phase would likely fall somewhere between the rising action and the climax. The process of getting to a moment of achievement (in this case a prototype being completed) seems to be a rewarding enough experience to elicit a lot of positive recounts of this phase experience.

For the individual experience, the communication phase was dominated by feelings of satisfaction and relief. There were notes about how much effort it took to complete the phase -- which seemed to be par for the course compared to feedback from the other phases concerning "not enough time" being a consistent trend.

Next, Table 15 provides high level themes extracted from qualitative feedback about individual performance during the design thinking journey.

	Themes	# of related comments	Avg. rating
Research	Second guessing my performance. It was a struggle	9	6.2
	I was active and engaged	2	8.5
	The pace was tough. Still figuring out my approach	4	6.3
	Satisfied with room to improve	7	7.6
	Insightful user feedback	1	6
Analyze	Clarity. How to identify and focus on what is important	5	7.4
	Personal obstacles	1	2
	Satisfied with room to improve	12	7.8
	Active and engaged team member	2	9
	Activities make or break the experience	3	6.5
Ideate	Coming up with great ideas is tougher than I thought	4	7.4
	Struggle understanding some tasks	1	7
	Generating ideas is fun	1	5
	Time struggle	3	5
	Class structure & activities helped me create ideas I am proud of	4	9
	Satisfied with room to improve	4	7.5
	Commitment to team engagement is key	6	7.9
Build	Critical thinking and thought provoking	2	7
	Confidence and competence to realize prototype	5	9.1
	Lots of room to improve	5	5.6
	Motivating the team. stepping into leadership	2	8
	I met expectations	6	7.8
	Skill expertise vs skill development	2	8
Communicate	Pride in effective communication through tools & media	8	7.8
	Crafting a thoughtful narrative	2	7.5
	Time struggle	1	9
	Room for improvement	3	4.5
	Teamwork	8	8.3

Table 15: Major themes from qualitative comments about the individual performance during the design thinking journey

This research phase involved lots of initial struggles related to expectations of a very fast paced design thinking process. This sentiment of an initial struggle balanced pretty well with an optimistic outlook about making a satisfactory first step into the design thinking process. Overall, a general theme seems to be something around individuals gauging what is required of them to be successful moving forward -- which makes sense with this phase being the first.

The analyze phase was even more dominated by a feeling of achieving expectations with room for growth. Specifically, many comments relate to completing tasks and assignments and feeling like they could have been better executed. The adjustment period seems to have lingered from what was shared in the research phase about gauging what it takes to be successful. Other key themes related to identifying what is important. It's interesting that comments from the first self-reported comments were generally lower and spoke about lack of clarity, while comments in the final self-reported feedback stated how this phase provided lots of insight and clarity.

The ideate phase was comparatively more wide ranging in the type of feedback that was gathered. A commitment to team engagement was a common theme -- lots of comments noted how students focused on being a great team member by facilitating discussions, activities, and completing assignments in a timely manner. On the other hand, there were a spectrum of reactions about how the difficulty, enjoyment, and experience through facilitation either made this phase easier to perform well or eye-opening to how the creative task required of this phase can be as challenging as it is enjoyable. There were also continuing themes of time restraints and satisfactory effort with "room to improve" as traits of student performance.

For the build phase, themes concerning the need for improvement and to meet expectations were leading the feedback about this phase; however, there were also points about the confidence that several individuals had towards their prototype's success. One of the more niche feedback themes discussed how existing or developing skill sets play a critical role in individual performance.

Qualitative feedback about the communicate phase for individual performance centered around the effort and pride that students took in crafting the most effective tools and media for communicating their final prototype. While a video was one of the main deliverables required of this phase, there were lots of feedback referencing supporting tools as just as important to individual performance in the communication phase. Finally, teamwork, both from the perspective of an individual stepping up to do more work for their team and others relying on help from their teammates, was also a common theme in feedback.

Next, Table 16 provides high level themes extracted from qualitative feedback about individual performance during the design thinking journey.

	Themes	# of comments	Avg. rating
Research	Communication struggles: time zones & busy schedules	5	6.8
	Breaking the ice	1	8
	stepping up for other team members	2	8
	disengaged team members	4	6
	workload	3	7.7
	satisfied: so far, so good	6	8
	conflict between team members	1	7
Analyze	teammates aiding in understanding	6	6.8
	team members helping others in need	2	3.5
	shared passion for the work	1	9
	inconsistent expectations	3	5.7
	communication / virtual collaboration struggles	3	7
	team members that show up and contribute	5	8.2
	conflict between team members	2	3.5
Ideate	Poor communication	5	3.4
	Intentional and structured feedback	2	8
	Punctuality concerning team commitments	1	7
	Team expectations beginning to settle	3	8.7
	Engagement with team members	6	7.6
	Building upon each other	5	8.6
Build	Safe space for sharing	8	8.6
	stabilized team chemistry	3	9.7
	coordination struggles & mediocre progress	4	4.5
	persevering through exhaustion as a team	5	8.1
	discussion with little collaboration	1	8
Communicate	Frustrations with the team & unhealthy communication	5	3.2
	helpful team mates makes for an enjoyable experience	7	8.9
	benefits of sticking with it: a team experience that got better over time	6	8.5
	satisfied but could do better	2	6.3
	guilt from not contributing enough	2	7
	tough workload	1	6

Table 16: Major themes from qualitative comments about the team experience during the design thinking journey

In the research phase of the team experience journey, one of the major themes of feedback centered around the learning curve of communicating virtually with each other while living in different time zones and having busy schedules that may not always align. Another popular theme included disengaged team members, in which the virtual setting seemed to enable these kinds of behaviors by allowing students to be present without being interactive (i.e. logging into the virtual platform for meeting without turning on a camera or microphone to engage in collaborative work). Another popular theme for this phase included a general satisfaction with how team members showed up and contributed right away. Other more specific themes dealt with the initial workload and conflict between team members making the beginning of the design thinking journey a bit of a struggle at the start.

Qualitative feedback for the analyze phase involved themes expressing agreeable team chemistry. One of the major themes focuses on an appreciation for team members coaching each other to gain a shared understanding. Another emphasizes the value of team members that show up and contribute consistently. Some of the less populated themes related to continuing communication struggles working exclusively in a virtual environment, conflicts between teammates, and inconsistent expectations.

The ideate phase led with themes around poor communication, engagement with team members, and an emphasis on building upon the ideas of others. The poor communication can be traced back to earlier phases based on other qualitative feedback themes. On the other hand, some comments mentioned a positive shift in the sentiment of the team experience -- such as those related to the theme about team expectations beginning to settle.

The build phase was headlined by qualitative data about the importance of having a safe space for sharing how each team member navigated supporting the construction of their team prototypes. Complementary to this is a theme about achieving a stabilized team chemistry -- where team members finally feel like they are on the same page. There were still mentions of coordination struggles by some participants that ultimately had a lot to do with not achieving a particular desired outcome in time or not seeing eye to eye on what ideas should be realized in the final prototype. Finally, there was a theme that acknowledged how teams persevered through the collective burn out of being near the end of an intense design thinking journey.

Qualitative feedback from the communicate phase highlighted themes that seemingly translate directly from what was explained in the previous phase: a maturing team chemistry. This was supported with examples of teammates picking up the slack where others were having a hard time and the acknowledgement of an established workload balance between team members. This was not the case for all of the feedback. There were also other extremes where frustrations amongst teammates due to poor communication and an unbalanced workload. Relative to the other phases, the communication phase seems to reflect polarized team experiences for students.

Next, Table 17 provides high level themes extracted from qualitative feedback about individual performance during the design thinking journey.

	Themes	# of comments	Avg. rating
Research	Establishing team expectations	4	8.6
	Feeling limited by broad topics	2	7.5
	Equal participation from team members is key	6	6.4
	External factors compromising team performance	2	7.8
	Confusion caused by poor communication & collaboration	4	6
	Meeting expectations on a tight schedule	4	6.8
Analyze	Great effort with room to grow	3	7.7
	Group work vs individual work	2	6.5
	Process of converging as a team	2	7.5
	Lots of room for improvement	3	6.7
	External factors limiting performance	2	7.5
	Optimism about team collaboration habits	7	8.9
	Finding success despite team obstacles	2	7
Ideate	Picking up the slack for other teammates	3	8.7
	Felt rushed and in a hurry	3	7.7
	A fresh start for team chemistry	4	8
	Indifferent	1	6
	Team engagement inhibiting collaboration	2	3
	Collaboration fueled team success	7	8.3
	Time to pivot	1	5
Build	Feeling inspired by teammates' work	1	9
	Converging to a final idea	2	8.5
	Follow through & balanced workload	2	8.5
	Success within time constraints	1	10
	Teammates doing their part	6	8
	Praise for the team	4	8.8
	Idea vs reality of prototype	4	7.8
	Indifferent	1	6
	More work to be done	1	3

Communicate	Unhealthy communication & lack of effort	3	3.7
	Collaboration and timely work fueling success	4	9.1
	Proactive requests for help	1	9
	Live feedback from peers (audience)	1	10
	Everyone did their best	2	8.8
	Improvement relative to other phases	4	9
	Unbalanced workload	2	7.5
	Success relative to time	3	7.3
	Pride in final outcomes	3	9.7

Table 17: Major themes from qualitative comments about the team performance during the design thinking journey

Qualitative feedback about team performance in the research phase emphasized the importance of engagement from each team member. Many other themes in fact serve as examples of common experiences when team members fail to show up (such as confusion caused by poor communication and collaboration or external factors compromising team performance). An interesting and less popular theme was about the limitations of pursuing broad research topics. Based on one of the specific comments of feedback, it is implied that having a broad topic to research requires much more time to grasp that what was allotted in this design thinking journey.

Qualitative feedback about the analyze phase for team performance showed how much teams were thinking about their current practices as signs for either better days or difficult times to come. For example, many themes related to either optimism or satisfaction with current efforts by teammates to do their best given all sorts of factors that given time are supposed to get easier to manage. On the other hand, there were also a few themes that expressed a growing concern about communication and engagement by individual team members and how that impacts the overall team performance.

Theme from the ideate phase mostly dealt with how collaboration or lack thereof supported a teams success or really spelled a recipe for disaster. Some teams noted continued struggles to virtually collaborate with teammates in other time zones. In a few cases, team members were able to step in and pick up the slack for those that were not available for whatever reason.

The qualitative feedback about team performance during the build phase included major themes related to teammates following through in their roles, general praise for the success of the team, and the struggle or success of going from a great idea to a tangible prototype. Some other themes touched on the process of converging to a final idea to prototype as a team, time constraints as a barrier to achieving success during this phase, and feelings of indifference about this phase altogether.

Qualitative feedback about team performance in the communicate phase had many different themes. Unhealthy communication, unbalanced workloads, and success relative to time were themes with the lowest average ratings. On the other hand, many other themes exemplified nearly opposite feelings about this phase by mentioning how the collaborative nature of the team fueled their success in this last phase. In fact, one of the themes implies that this was the best phase for a few students regarding team performance. Ultimately, there seemed to be pretty stark differences in the qualitative feedback for this phase compared to others -- there were no signs of indifference.

2.4.3.1 Key Insights from Qualitative Themes

Many themes emerged from the qualitative comments about the four types of feedback (individual experience, individual performance, team experience, and team performance) that were documented in this study. Exploring these qualitative themes proved to be valuable by providing additional context to significant factors that were identified (section 2.4.2) and revealing insights that were not readily apparent from how the self-reported ratings were analyzed.

For comments about individual experience in the design thinking process, there seemed to be polarizing sentiments about activities requiring divergence. For example, some students really enjoyed the ideate phase while others were really frustrated by it because of its limitless boundaries. Another key theme about the individual experience in the design thinking process includes a general shared excitement for prototyping. Here students mentioned the appreciation for making their ideas tangible.

For comments about individual performance in the design thinking process, the most notable theme expressed an initial struggle to meet expectations of the research phase in the design thinking process.

For comments about team experience in the design thinking process, a key theme emerged during the ideate and build phase. Here comments expressed polarizing sentiments regarding their team experience. Some mentioned the formation of team chemistry while other noted the unraveling of poor communication.

Finally, for comments about the team performance in the design thinking process, a notable theme suggested that divergent phases in the design thinking process (such as the research phase) presented feelings of limitation. While this may seem counterintuitive, students mentioned a struggle to grasp a clear understanding of their problem as reasons for feeling limited.

2.4.4 Limitations

Limitations of this study are related to sample size, unbalanced data, and contextual factors related to exclusively remote collaboration. For example, the proportion of female to male students was not balanced. There were only three male students included in this study. Concerning unbalanced data, one student did not submit a response for one of their first Journey Map phases while several male students did not submit data for the final Journey Map phases.

In relation to the unbalanced data, many statistical tests were used to declare significance of several factors and factor levels acting on the students' self-reported ratings. Using so many statistical comparisons with this unbalanced data set and a small sample size of participants makes this work vulnerable to the multiple comparisons problem. Future work would benefit from clarifying these vulnerabilities by using methods that address this conflict – such as the Bonferroni correction.

The distinction between academic disciplines was drawn at engineering vs. non-engineering. Taking into account the specific disciplines of the participants would likely lead to other ways to consider how different academic paths might impact a participant's journey through the design thinking process.

In order to improve the accuracy and value of studies like this in the future, it would be valuable to consider many strategies for eliciting honest and thoughtful feedback (both through self-reported ratings and qualitative feedback) throughout the entirety of the process. Here is a question to keep in mind: what motivators are effective in sustainably gathering this data, such that all steps in the design thinking phase are accurate in telling the story about the participants' experience?

Concerning the qualitative feedback, there was a wide range in depth of the responses. From this, one suggestion is to take a critical approach to minimizing and filtering trivial, and potentially disingenuous, feedback in future studies so that the most accurate themes surface through qualitative analysis. On a similar note, it may also be useful to explore additional qualitative analysis methods, such as computer aided methods, that may serve as complementary (or, equally valuable, contradicting) to the human-led qualitative analysis methods used in this study.

While there are quantitative methods that can help identify unreliable data, detecting misrepresentative results in qualitative data may be more difficult when using computational methods for qualitative analysis. The analysis for this data was done manually, so it may be helpful to adapt a systemic approach that identifies and corrects misrepresentative qualitative data in future work. For example, this particular study did not include a strong incentive to gain a depth of qualitative responses from students since they were told that these submissions would be graded for completion and not quality of content. One alternative, grading the journey map assignments for "quality content," may make students feel biased towards positive assessments of the course or their peers in an effort to get a better grade. Essentially, it is important to be strategic in designing ethical incentives to collect qualitative data.

Finally, with the setting for this study being exclusively virtual, it is likely that a fully in-person or hybrid version of this study would yield different results.

2.4.5 Future work

With a comfortable understanding of valued design thinking mindsets & capabilities, outcomes, and participant experience, a significant contribution to the field would involve assessing how factors related to mindsets & capabilities, outcomes, and participant experience interact with each other. Identifying factors that have the most significant impact on what it takes to design think effectively enables academic, professional, and organizational efforts toward scouting and developing design thinking mindsets, cultivating ideal environments for design thinking experiences, and producing optimal results from design thinking work.

One of the expected results of this study included finding some kind of symmetry between the first and final design thinking journeys. Or perhaps more interesting, to find a significant difference in the one of the factor level's impact on the iterations of self-reported ratings of the first vs final design thinking journeys. In other words, this means discovering if the perspectives of design thinking participants change after they have had a moment to reflect on the experience in its entirety. In retrospective, it may have been helpful to actually inquire about the hypothesized perspective shift through a procedural step in this study. Instead, adding this layer of inviting the participant to acknowledge a perspective shift (or consistency) may provide more insight than. After all, some change may be due to poor memory or recency bias.

Takeaways from the qualitative feedback suggest that some design thinking phases invite more polarizing experiences than others. Based on the qualitative feedback it seems to be the research phase and the communication phase (or the beginning and the end of the design thinking journey). It may be helpful to invest in understanding strategies to both diagnose and help teams that are having an extreme experience on the negative end in these phases.

2.5 Conclusion

The guiding research questions for this study are all rooted in better understanding participants' perspectives of the design thinking process. The following results were the most notable findings from this work.

First, self-reported ratings of individual experience during the analyze phase were significantly different for engineering and non-engineering students. Also, this study found that first and final self-reported ratings of the design thinking experience are significantly different for non-engineering students. This may be due to varying expectations of the value of the design thinking experience by non-engineering students. Finally, the pace of typical design thinking experiences can be a lot to digest and as a result, the individual experiences of design thinking participants at the beginning phases (research) are significantly worse than individual experiences at the later phases (ideate, build, and communicate).

2.5.1 Acknowledgements

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3 Journey Mapping the Virtual Prototyping Experience

3.1 Introduction

The “maker movement” has empowered individuals to design and build [39]. It has also inspired universities to found and support on-campus makerspaces across the globe [40]. Makerspaces have become a key resource to students taking courses that require the creation of tangible prototypes [41,42].

Layers of excitement surrounding the maker movement include equitable making practices, better known as the “democratization of design”, and environmentally sustainable making practices. Unfortunately, there is some evidence that makerspaces can be more inviting to men than women. For example, Vossoughi et. al point out the historical foundations of making as being systematically biased regarding gender and class [23]. With the creation of more equitable prototyping experiences in mind, researchers have noted the need to understand the physical and emotional needs of users [43]. This work has taken a specific focus in measuring the emotions of users that engage in virtual prototyping by collecting self-reported emotional levels for users at different stages in their prototyping journey. A direct application of this work includes empowering design educators, facilitators, and students to strategically create and modify pedagogical techniques to improve this experience.

Research on makerspaces in engineering design education has largely focused on characterizing the in-person making experience and have done so at a large-scale level using metrics like engineering design self-efficacy (see Section 3.2.2). Similarly, research on prototyping in engineering design education has focused extensively on *how* and *why* students prototype, and less on the makerspace experience (see Section 3.2.1). Little is known about the student virtual prototyping experience when leveraging exclusively remote makerspaces. Also, techniques to evaluate complex interactions, such as virtual collaborations in design, are still being pioneered. As remote learning becomes ever more commonplace, and uncertainty over the COVID-19 pandemic persists, understanding remote engagement with makerspaces, its role in prototyping, and techniques to evaluate it, will become crucial for engineering design education.

The goal of this study is to identify patterns in students’ virtual prototyping experience while leveraging a remote makerspace, with intentions of informing university instructors, makerspace facilitators, and even students of where to anticipate struggles and frustration with the virtual prototyping experience. Accordingly, we explore two research questions in this work:

R1: How do students’ self-reported emotional levels change across the process of developing functional and experiential prototypes?

R2: How does a student’s gender identity or academic discipline shape the trajectory of their self-reported emotional level during prototyping?

In this work, we begin with a description of related work exploring students’ prototyping and makerspace experiences (Section 3.2). Then, we cover our research methods (Section 3.3), present results from our study (Section 3.4) and discuss their implications (Section 3.5).

3.2 Related Work

3.2.1 Novice Designers' and Students Prototyping Experiences

Prototyping is widely acknowledged to be an essential stage of the engineering design process [44,45], and has accordingly been studied from a variety of perspectives in the context of engineering design education. Many studies have examined *how* students and practitioners prototype. In terms of *how* prototyping activities occur for students in the design process, Menold et al.'s work on exploring how novice designers articulate prototyping decisions highlighted a strong favoritism towards familiar tools and methods, and a willingness to compromise, or 'satisfice,' during the prototyping process due to constraints on the designer's familiarity or knowledge [46]. Grounded in insights like this, numerous approaches have been developed to structure and formalize *how* designers engage with prototyping in a design project, including the Prototyping Canvas [47] and the Design Principle Cards [48] among other interventions. Broadly, these approaches seek to guide designers in the prototyping design decisions that they make.

Another set of studies has examined *why* designers prototype. Lauff's work on prototyping in academic and professional environments shows significant differences in why practitioners engage with prototypes, versus why students engage with them: while students expected prototypes to perform *narrow* technical functions, professionals intended prototypes to serve *broad* purposes, such as communication and decision-making [49–51]. Interventions to help guide designers in better understanding why they prototype include Menold et al.'s Prototyping for X framework (PFX) [52]. Broadly, approaches like PFX seek to guide designers in aligning their intentionality behind prototypes with clear goals and well-established frameworks for successful prototyping.

Most notably for this study is work that explores *how* students prototype, with a focus on the discrete steps and accompanying rationale taken. In their longitudinal study of student use of prototypes across an entire design project, Deininger et al. discovered that while students acknowledged the importance of prototypes, their effective use of best prototyping practices varied substantially between students and lacked intentionality [53].

In this work, we take a preliminary step to expand on Deininger et al.'s work by understanding the emotional journey that defines students' experiences with prototyping, in the context of a discrete prototype development task using a remote makerspace. Insights about the emotional journey augment existing knowledge about the prototyping process by examining discrete points in the prototyping via makerspace process that elicit positive and negative emotions, which in turn can help explain observed prototyping behaviors and outcomes, and support more effective interventions to support students.

3.2.2 Novice Designers' and Students' Makerspace and Prototyping Experiences

Over the past twenty years, makerspaces have proliferated in academic environments and are formative elements of design education today [41,54–56]. Central to the study of the role and nature of makerspaces on university campuses is research exploring how individual students participate in and engage with makerspaces.

A commonly-used instrument to describe this is engineering design self-efficacy (EDSE), based on Bandura's principle of self-efficacy [57], which describes an individual's belief in their ability to complete a task. High levels of student EDSE have been shown to correlate with increased engagement in engineering education and persistence in the engineering course of study [58–60]. EDSE is described as consisting of measures of confidence, motivation, expectation of success, and anxiety. In Morocz et al.'s study of makerspace users and non-users, the research team found that users participating in makerspaces more often exhibited more confidence and less anxiety than those who participated less [61]. Hilton et al.'s recent study of three university makerspaces established that higher (voluntary) participation in makerspaces correlates with higher EDSE scores, particularly in confidence, motivation, and expectation of success [42]. Hilton et al. also found that women at two of the studied universities participated less in makerspaces than men, and in all three universities, women reported lower levels of EDSE.

Much of the literature on makerspaces describes in-person makerspace experiences. A recent study describes the effectiveness of efforts to create 'remote' makerspace-like experiences, largely driven by the COVID-19 pandemic, in which making activity is facilitated remotely in a variety of ways. Leung and Chiu demonstrated a successful pivot to delivering makerspace-like experiences via mailed prototyping kits [62]. Liu et al. described a reframing of a prototype-centric curriculum to one anchored in virtual making tours and prototype simulations [63]. Benabdallah et al.'s survey of six fabrication-centric design courses forced to teach remotely illustrated a range of strategies to recreate the makerspace experience, from sending making equipment to students to mailing fabricated parts to them; the researchers highlight that across all strategies, important learning about fabrication was realized, but iteration was important and inequities between students were exacerbated [64].

While prior work like that of Morocz et al. and Hilton et al. seek to understand *large-scale* impacts of makerspaces and their influence on EDSE less is known about how students traverse the use of a makerspace at an *individual* level. Furthermore, such studies have focused on in-person makerspaces. Similarly, work like Benabdallah et al.'s set a rich foundation of remote makerspace experiences from the *instructors'* and *curricular* perspectives; however, an understanding of the student experience from the *students' perspective* remains unexplored.

In this work, we extend on both bodies of findings to understand (1) participants' journeys at individual task-level of the makerspace and (2) how such journeys occur with a remote makerspace experience. To do so, we take a preliminary step to understanding the emotional journey that defines students' experiences with prototyping, at a level more abstract than the traditional EDSE framework.

3.2.3 Discipline, Gender, and Equity in Engineering and Design Education

It has been acknowledged that design education did not begin with strong foundations in equity and inclusion [9,23]. Moreover, a look at the current landscape of design education does not indicate that these important values have successfully been implemented in the design education pedagogy. In fact, Jennifer Rittner provides a detailed look at the current playing field of design education by noting several examples of recent design solutions that are not acceptable and – given a community of designers with higher standards for inclusion, representation and equity – could have been avoided [65].

Academic discipline and gender are a few contextual factors known to influence the impact of design education. Through an examination of design thinking practices, Lake et. al observed 44 obstacles that were created and perpetuated by design education blindspots due to disciplinary bias on behalf of the facilitators (faculty in this case) [66]. Some researchers have shown the impact of gendered tendencies, such as ownership bias being more present in male students, on collaborative design decisions [67]. Meanwhile, other researchers have demonstrated no significant differences between male and female students regarding self-assessment of beauty and creativity in their prototypes [68]. While these studies about gender were not directly opposed, they do invite a conversation about the differences in design education needs regarding collaborative and individual work.

Taking these studies into account, our research aims to contribute to this conversation by investigating the emotional level of students from different genders and academic disciplines as they navigate prototype journeys

3.3 Methods

3.3.1 Course Description

This study was conducted in a course at a major public research university in the United States. The course had a pool of 22 students, with half of students identifying as male and half identifying as female. The majority of students were from the United States (95% United States-based / 5% non-United States-based). Although the course was listed in a department within the College of Engineering, a large number of student majors were represented. The largest single discipline represented was engineering (six students) with other students representing business, chemistry, design, and other majors. All course activities were conducted remotely, via synchronous videoconference and collaborative activities facilitated by the Mural platform.

The course examined in this study was a project-based learning course focusing on using Human-Centered Design to address challenges in the field of cybersecurity. Project areas were developed by course faculty and six student teams were formed around the project areas based on individual voting. These project areas offered students a large amount of flexibility to explore the problem domain and ranged from exploring responses to artificial intelligence-enabled social engineering attacks to building trust and security into COVID-19 contact tracing applications.

The course guided students through five design phases of the HCD process (Research, Analyze, Ideate, Build, and Communicate), and required several final project deliverables: a digital prototype, a physical prototype, a video illustrating the value of the prototype, and a project presentation. The prototypes were a key focus of the design work in the class. In a partnership with a university-operated makerspace, students were required to submit a physical part design corresponding to the team's functional prototype to be fabricated via laser cutting, 3D-printing or vinyl cutting. Parts were then mailed to students. Specifics of the prototype assignments are outlined in Section 2.2 below.

3.3.2 Data Collection

In order to study the student virtual prototyping experience, this work leverages elements of the Critical Incident Technique (CIT) and Journey Mapping. The CIT is a procedure that helps researchers obtain important behavioral information from defined situations. The following core steps are highlighted as critical to the CIT: (1) Identifying the objective, (2) Creating a plan and setting specifications, (3) Collecting data, (4) Analyzing data, and (5) Interpreting and reporting the data [69]. The CIT has been noted as a valuable method for identifying and translating important information from practicing engineers to engineering students [70]. Journey Mapping (also known as experience mapping) is a method that is used to visually document the experience of a target user. This visual document typically includes a chronological order of events, needs that are significant to the user, and some might include a metric corresponding to the user's satisfaction at stages of the journey [71]. These techniques are popular tools for investigating complex services. For example, Westbrook et. al used a combination of these methods to better understand the strengths and weaknesses of an online data retrieval system used to support clinicians in their clinical work [72]. In most examples of the CIT, the critical incidents are predetermined by the researchers. In this case, we have adapted the method to give the participants more agency over which and how many critical incidents they determine to be important.

The scope of this study focuses on two user journeys that students navigate during the ideate, build, and communication phases of the course: (1) creating a functional prototype and (2) creating an experiential prototype.

Each project team of students was required to submit part files to have a functional prototype fabricated at the university's makerspace. Some functional prototypes could be used to directly express tangible value for a team's project challenge. In cases where the project team's ideas were virtually based, the functional prototype operated as a conversation starter –communicating concepts tangibly to gain feedback from target users. Initially, each student was to explore individually creating their own prototype before deciding as a team which prototype to have fabricated. While one prototype design was ultimately selected for each project team, each student was to receive the fabricated parts for their functional prototype in the mail.

Experiential prototypes were defined by the journey that each project team navigated through to create their final prototype and communicate its value in a two minute video. This prototype journey included more collaborative work and emphasized the need to communicate the value of the final prototype. Functional prototypes may have been included in the two minute videos, but it was not a requirement.

An interactive form (created in Google Slides) was used to collect the student's journeys through the functional and experiential prototype processes. The following instructions were provided to students at the beginning of the feedback form:

"The purpose of this exercise is to create two Journey Maps that illustrate your experiences prototyping. The Journey Maps should reflect your (1) functional prototype experience . . . and your (2) experiential prototype experience . . .

For each step in your journey map, please associate an emotional level that corresponds to how you felt during that stage. For this exercise, feelings above the x-axis represent positive emotions that make you want to keep going. Feelings below the x-axis represent negative emotions that make you less motivated to continue."

The term "emotional level" was used in the feedback form to encourage students to acknowledge a broad range of emotions that might have contributed to their excited states (any emotional states other than neutral) throughout their prototype journeys. Also, the form includes two primary sources of feedback for each prototype journey. The first source of feedback includes an interactive plot (illustrated in Fig. 19) where students were to document their emotional state at different steps in their journey. The plot illustrated in Fig. 19 is a screenshot of what students were presented with. They were instructed to define a minimum of 5 steps.

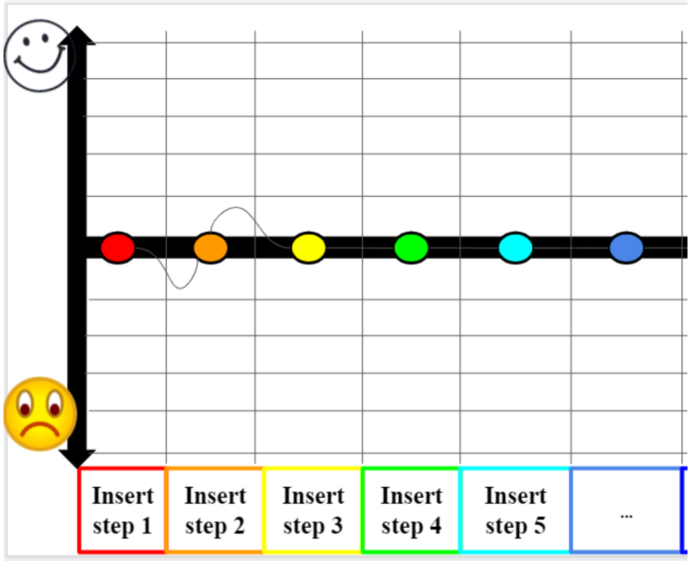

Figure 19: Interactive plot used to document student journey maps

The second source of feedback includes a space to provide written feedback for each step that the student has identified as critical.

A total of 31 journeys were collected from 16 students (1 student only provided an experiential prototype journey). Of these students, 8 identified as female and 7 male. Also, 4 students were studying engineering while 12 were from non-engineering disciplines.

Specifically, 15 journeys were collected for the experiential prototype and 16 journeys were collected for the functional prototype. After collecting all of the students' journey maps for the functional and experiential prototypes, one researcher interpreted quantitative values for each student's journey map to use for analysis (see Table 18).

	Step 1	Step 2	Step 3	Step 4	Step 5
Student #1	-1.5	0	1	2	-0.5
Student #2	0	1	-1.5	1	2
Student #3	-3	4	2	5.5	3.5

Table 18: Journey Map Quantitative Interpolation Example

Several key assumptions were made during data collection. First, it was assumed that all students began their experience, for both prototype journeys, at a neutral emotional level (an emotional level equal to zero). Second, it was assumed that the researcher's numeric assignment of the emotional level at each step was representative of the students' qualitative response. This is important because there were not any numbers on the vertical axis of the journey map plot as illustrated in Fig. 19. The change in emotional level from step to step was assumed to be linear. Third, the distance (in time) from step to step for each individual journey, was assumed to be uniform. For example, for two students submitting journeys with five steps each, the time represented by each step was assumed to be the same. However, it is acknowledged that the students may have had different time periods that they intended to represent with the separation of steps. Finally, the concept of *emotional level* was left to student interpretation, and it was assumed that while specific interpretations may have differed between students, students are describing broadly similar things when they determine self-evaluated emotional level.

3.3.3 Data Analysis

The aggregate journeys for the experiential and functional prototypes were computed by linearly interpolating the emotional level at each step from start to finish for each user journey. Before linear interpolation between each step of each journey, all of the journeys were normalized to a common number of steps. For the functional prototype, journeys included 5, 6, 7, 8, and 9 steps. For the experiential prototype, journeys included 5, 6, 7, and 9 steps. Using the least common multiple for these step variations, the experiential prototype journeys assumed a total number of 630 steps, while the functional prototype journeys assumed a total number of 2,520 steps.

While a positive emotional level value indicates motivation to move forward and a negative emotional level value indicates a barrier to progress, an emotional level value close to zero might communicate less motivation to navigate through a particular step, or the prototype journey overall. This understanding is supported by the instructions given to students before constructing their journey maps. This attention to how "volatile" the emotional levels are across the prototype journeys formed the basis for a new metric, *emotional volatility*, defined as the absolute value of the emotional level at each step during a student's journey. The average emotional volatility per step was computed for each student's journey.

To more clearly compare different journeys consisting of a different number of steps, beginning, middle, and end phases were created to bucket stages of student journeys. The *beginning* phase was defined as the average of emotional levels in steps 1 and 2, and the *end* phase as the average of emotional levels in steps *n* and *n-1* (where *n* represents the total number of steps defined by the student). The *middle* phase represents the average of all steps from step 3 to *n-2*. These phases allow us to compare characteristic phases of student experience in the prototyping process across any number of steps defined by the students. Lastly, students identified the title of each step in their journey with a short phrase. Researchers used this written feedback to identify common themes across the prototype journeys.

3.4 Results and Discussion

In this section, the following key results are described from this work: comparing student's emotional levels during the functional and experiential prototype journey (Section 3.4.1), comparing the emotional volatility of all students during the functional and experiential prototype journey (Section 3.4.2), comparing student's emotional levels based on gender and academic discipline (Section 3.4.3 and Section 3.4.4), and comparing general themes observed from written feedback as associated with phase of the student's journeys (beginning, middle, end), extreme steps identified in student journeys (maximum & minimum emotional level reported for each student journey), and type of journey (functional vs experiential prototype) (Section 3.4.5).

	Experiential Journey Map	Functional Journey Map
# of Steps (Mean)	6.67	6.88
# of Steps (Standard Deviation)	1.50	1.67
Emotional Level (Mean)	1.11	1.24
Emotional Level (Standard Deviation)	2.09	2.26
# of Distinct "Highest" Categories	6	6
# of Distinct "Lowest" Categories	3	6

Table 19: Journey map characteristics

3.4.1 Aggregate Trends in Experiential and Functional Prototype Journeys

Journey maps completed by students exhibited a wide range of characteristics (Table 18). Experiential prototype journey maps had an average of 6.67 steps (sd = 1.50), while functional prototype journey maps had an average of 6.88 steps (sd = 1.67). The average emotional level reported by students during the experiential prototype journey was 1.11 (sd = 2.09) while the average emotional level reported by students during the functional prototype journey was 1.24 (sd = 2.26). The steps corresponding with the highest and lowest emotional levels during the experiential prototype journey exhibited 6 and and 3 distinct categories, respectively. The steps corresponding with the highest and lowest emotional levels during the functional prototype journey both exhibited 6 distinct categories.

Fig. 20 and Fig. 21 illustrate the aggregate journey of all students for the experiential and functional prototype, respectively. The aggregate journeys were computed by linearly interpolating the emotional level across all students' journeys.

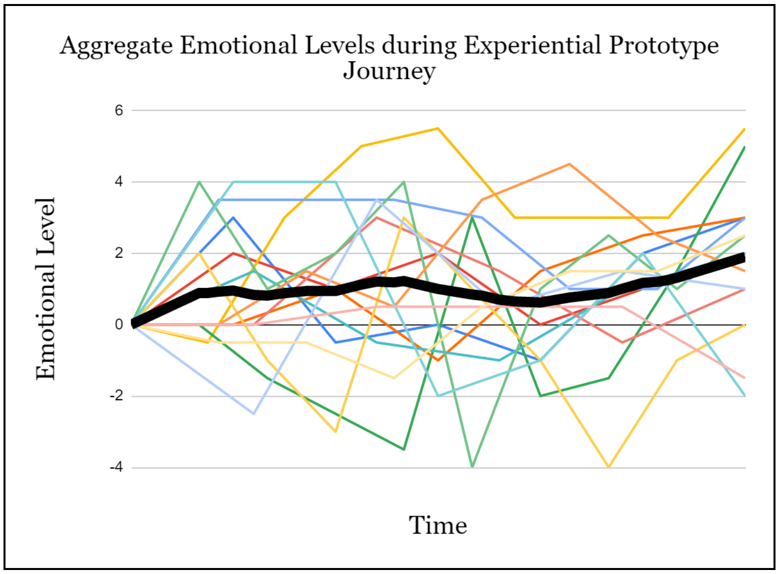

Figure 20: Aggregate Journey of Experiential Prototypes for All Students

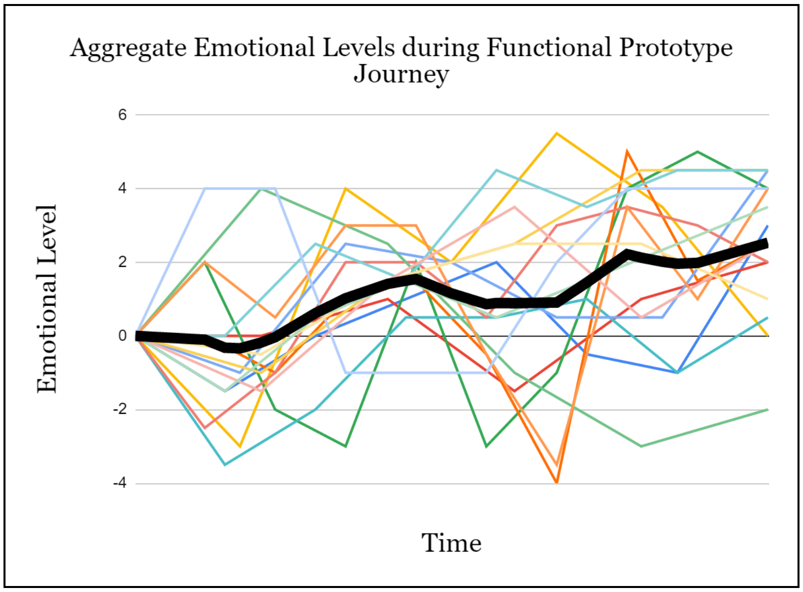

Figure 21: Aggregate Journey of Functional Prototypes for All Students

The aggregate journey for the experiential prototypes, Fig. 20, communicates an upward trend with 1 point of inflection. The aggregate journey for the functional prototypes, as illustrated in Fig. 21, has more changes. There are 2 relative maximums and 3 relative minimums observed in the emotional level of this aggregate journey.

Comparing the journeys surrounding the experiential and functional prototypes, several insights are notable. The experiential prototype journey (Fig. 20) suggests an initial spike of positive emotional stimuli followed by some emotional damper just before concluding with another positive surge in emotional level. The initial trend for the functional prototype journey shows a decrease in emotional level; however, both journeys end at a similarly positive emotional level (2). Overall, the functional prototype journey exhibits more points of inflection than the experiential prototype journey, which could suggest a need for more instructor support or a stronger emotional investment in the journey.

These findings have several implications for design education. First, assuming that a decrease in emotional level indicates a need for support and an increase in emotional level indicates confidence in moving forward with the prototype journey, these results could help design instructors identify the best opportunities to provide more facilitation as well as when to be more hands off. Second, understanding the differences between the context of the experiential and functional prototype journeys could empower both design instructors and students to better prepare for the lulls in emotional level such as implementing motivational design interventions and activities.

3.4.2 Aggregate Emotional Volatility Exhibited in Experiential and Functional Prototype Journeys

Using the emotional volatility metric as defined in the methods section, the average emotional volatility per step for each student was measured. The results are illustrated using a histogram in Fig. 22 and Fig. 23.

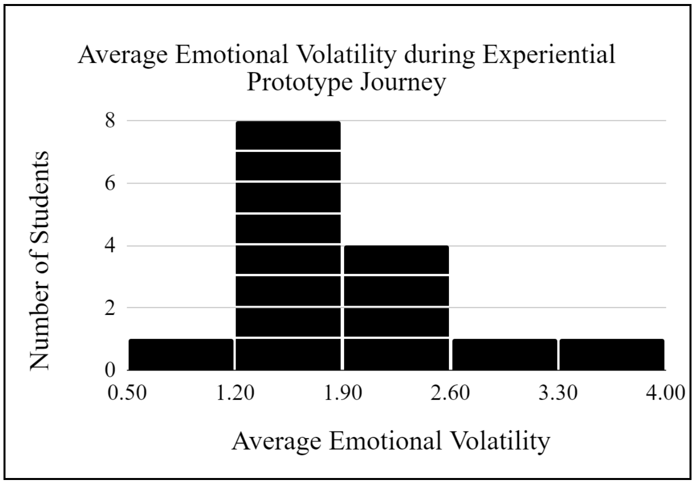

Figure 22: Distribution of Average Emotional Volatility for All Students During the Experiential Prototype Journey

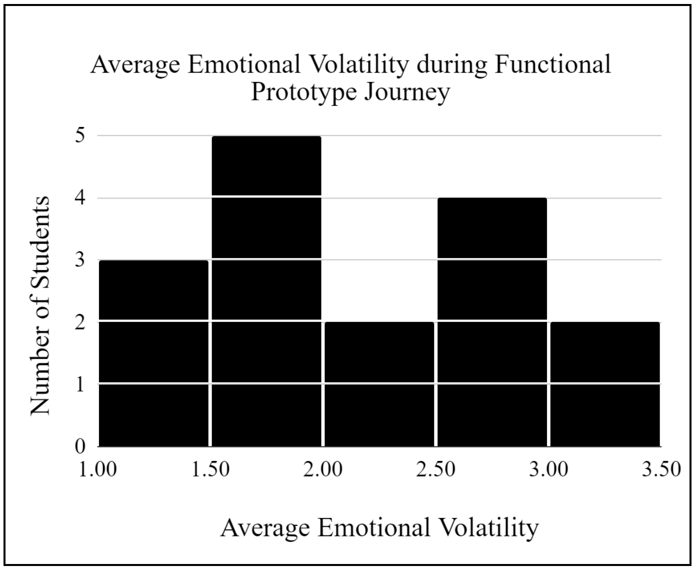

Figure 23: Distribution of Average Emotional Volatility for All Students During the Functional Prototype Journey

Fig. 22 illustrates that, for most students, the average emotional volatility was below 1.9. In contrast, for the functional prototype journey (Fig. 23), the majority of students expressed an average emotional volatility greater than or equal to 2.

These results offer several possible insights. Regarding the emotional volatility in the experiential prototype journeys (Fig. 22), our findings suggest that students are exposed to similar amounts of emotional stimuli. Regarding the emotional volatility of journey maps for functional prototypes (Fig. 23), our findings suggest that students' exposure to emotional stimuli is more variable.

Taken together, there are several potential implications for design education from these results. First, this might suggest that the experiential prototype journey included less strenuous activities for the students involved as opposed to the functional prototype journey. The most notable differences between the two journeys were the need to collaborate on a final prototype concept and pitch video (a requirement of the experiential prototype journey) and the need to individually design a prototype before collectively choosing one to have fabricated as a team.

3.4.3 Emotional Level of Prototype Journeys based on Gender

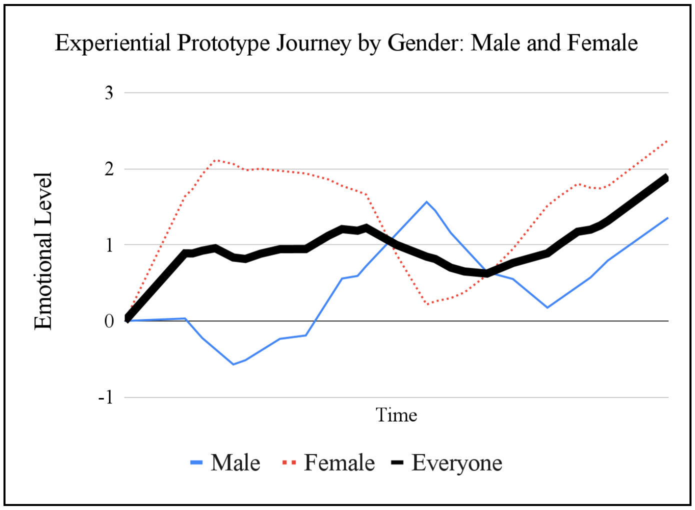

Figure 24: Comparison of the experiential prototype journey for female and male students

Comparing the aggregate journey of the experiential prototypes for male and female students suggests relatively polarized experiences. Female students seem to generally show higher emotional levels at the beginning and end of the journey than male students (Fig. 24).

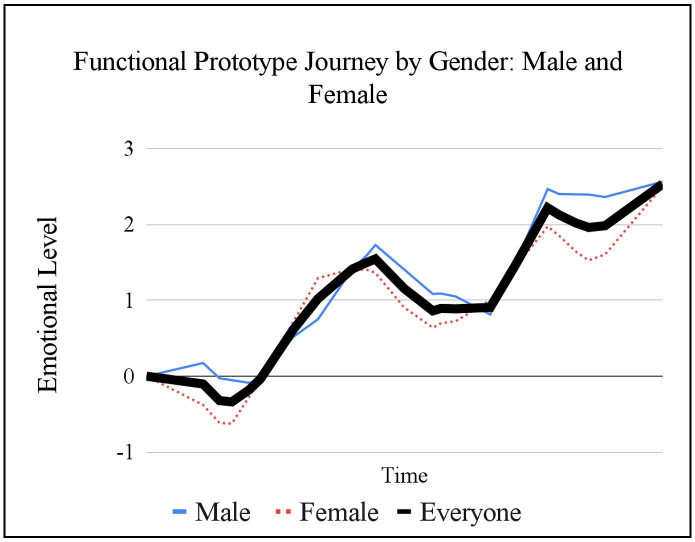

Figure 25: Comparison of the functional prototype journey for female and male students

The aggregate journey of the functional prototypes for male and female students suggests relatively similar experiences (Fig. 25). This relationship is in contrast to what was observed in (Fig. 24).

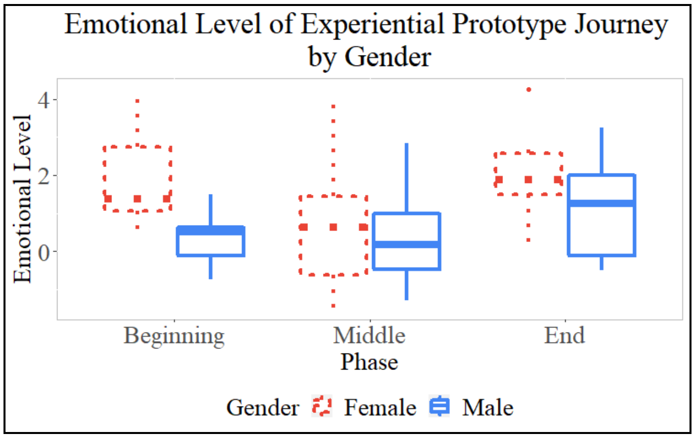

Figure 26: Comparison of the experiential prototype journey for female and male students

Phase	**Significance of Difference between Male and Female Emotional Level** (pairwise t-test p-value)
Beginning	0.016
Middle	0.682
End	0.873

Table 20: t-test comparing experiential prototype journey for female and male students

Fig. 24 and Table 20 suggest differing emotional experiences between female and male students at the beginning and end phases of the experiential prototype journey. A pairwise t-test indicated a significant difference ($p < 0.05$) between Female and Male student's emotional levels at the beginning phases of the experiential prototype journey, but not in the later stages (Table 20).

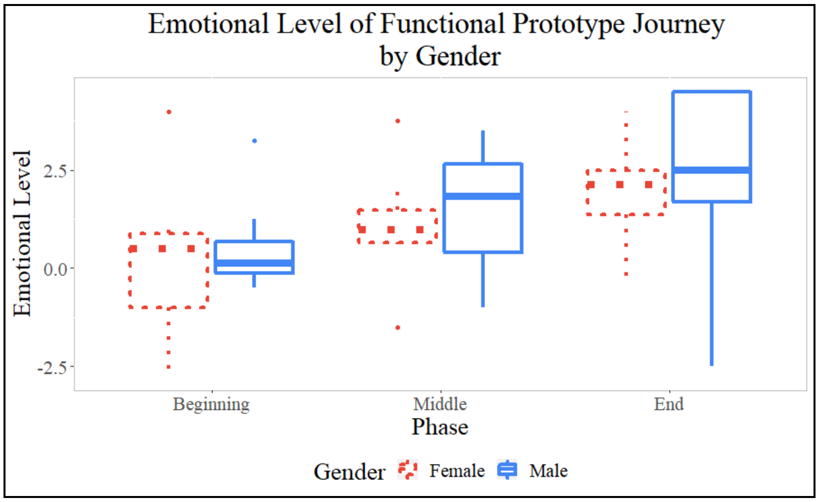

Figure 27: Comparison of the functional prototype journey for female and male students

Phase	**Significance of Difference between Male and Female Emotional Level** (pairwise t-test p-value)
Beginning	0.719
Middle	0.604
End	0.631

Table 21: t-test comparing functional prototype journey for female and male students

There were no statistical significance detected (Fig. 25 and Table 21) between Female and Male students at any phases of the functional prototype journey.

	p-value		
Gender	Beg - Mid	Beg - End	Mid - End
Female	0.207	1.000	0.080
Male	0.870	0.105	0.113

Table 22: Two factor ANOVA test comparing beginning, middle, and end phases of experiential prototype journey for female and male students

	p-value		
Gender	Beg - Mid	Beg - End	Mid - End
Female	0.375	0.006	0.244
Male	0.271	0.152	0.296

Table 23: Two factor ANOVA test comparing beginning, middle, and end phases of functional prototype journey for

female and male students

These findings suggest several insights about the prototyping process for students. For example, the p-values in Table 20 and Table 21 suggest that, for the beginning phases, there is likely to be more differentiation in female and male students' experiential prototype journeys than the functional prototype journeys. Also, it is notable that Table 23 suggests statistically significant differences between the beginning and end phases for Female students during the functional prototype journey while no phases show statistically significant differences for the experiential prototype journey.

One plausible explanation for these trends is that expectations of the experiential prototype journey might be causing an initial polarized experience based on gender. Also, the differing emotional levels observed at the end of the functional prototype journey could be due to the format of submitting the final prototype or differing satisfaction with the prototype that was ultimately created. Last, these results invite a discussion about how removing barriers to the individual prototyping experience may not translate to the collaborative prototyping experience.

3.4.4 Emotional Level of Prototype Journeys based on Academic Discipline

Comparing the experiential journey maps of non-engineering and engineering students (Fig. 28) suggests that the experience for engineers involves more changes in emotional level than for non-engineering students. For the functional prototype experience, however, the engineering and non-engineering student experience appears less different (Fig. 29).

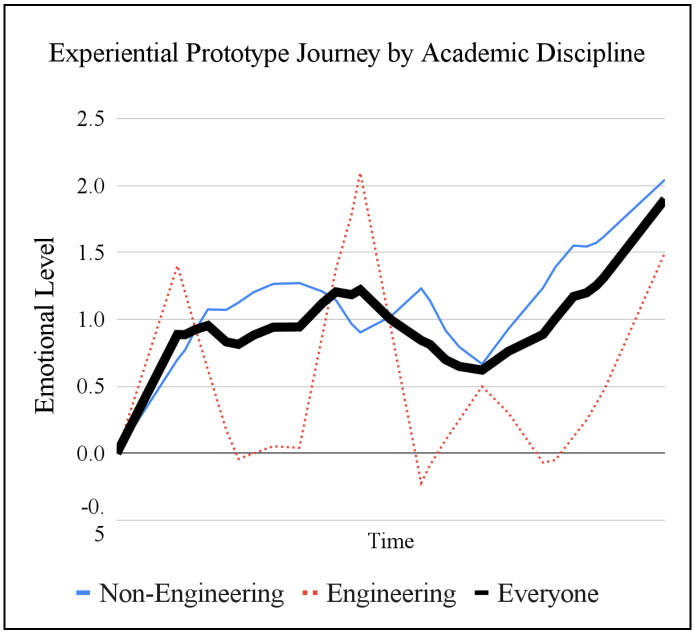

Figure 28: Comparison of the experiential prototype journey for the non-engineering and engineering students

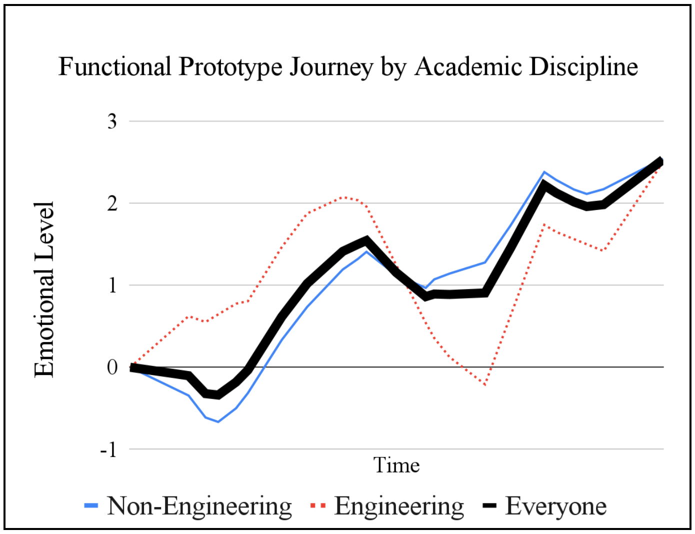

Figure 29: Comparison of the functional prototype journey for the non-engineering and engineering students

Examining journey phases, the engineering and non-engineering student experiential prototype journeys appear consistent. Non-engineering students tend to have higher emotional levels during the end phase, but there was no statistically significant ($p > 0.05$) difference found (Fig. 30). While these results represent a small sample size of engineering students, it draws attention to potential differences in prototype expectations between engineering and non-engineering students.

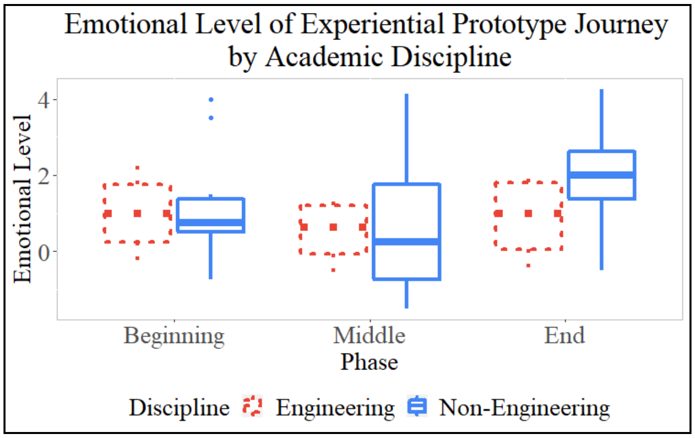

Figure 30: Comparison of the experiential prototype journey for the engineering and non-engineering students

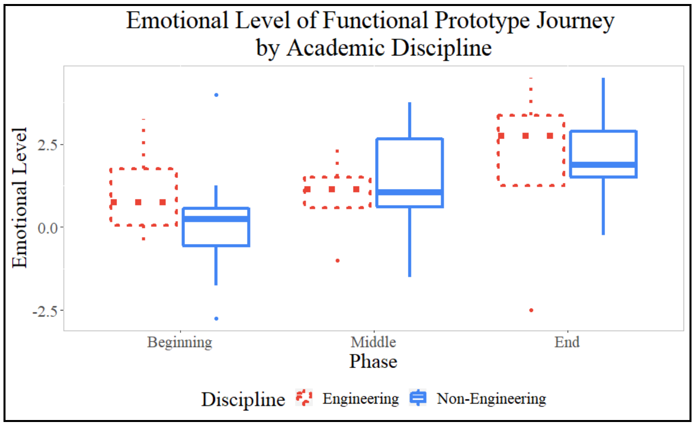

Figure 31: Comparison of the functional prototype journey for the engineering and non-engineering students

3.4.5 Patterns in Journey Map Steps with Highest and Lowest Emotional Levels

Table 24 and Table 25 present the themes that were observed for the steps in the prototype journeys that corresponded with the highest and lowest emotion level values.

Step with **highest** Emotional Levels	User research, diverging into ideas, converging on key ideas, high fidelity prototype work, converging on what story to tell, finishing/receiving the final product
Step with **lowest** Emotional Levels	User research & feedback, Group decision-making, Prototyping tasks

Table 24: Categories observed at the highest and lowest emotional level for experiential prototype journeys

Step with **highest** Emotional Levels	Converging upon an idea, Diverging into ideas, Team planning, diverging on prototype tasks, submitting the final design, converging on prototype decisions
Step with **lowest** Emotional Levels	Material selection, technical training, conducting user research, diverging into ideas, converging upon an idea, prototype decision-making

Table 25: Categories observed at the highest and lowest emotional level for functional prototype journeys

Brainstorming, user research, and prototype decision-making seem to be among the most recurring categories for both experiential and functional prototype journeys. Also, most categories observed in Table 24 and Table 25 are related to some form of step in the design process that involves convergence or divergence of thought. In other words, either a very explorative and creative activity is at hand (for example, brainstorming or building the prototype) or a critical decision is being made (such as converging on an idea or submitting the final design). A better understanding of these steps in the prototyping journey, that trigger the highest and lowest emotional levels from students, could be used to validate or debunk the critical steps in the prototyping journey as identified by design facilitators and instructors. Acknowledging where there might be a disagreement in perspective between students, instructors, and facilitators could lead to better support for the prototyping experience in design education.

3.4.6 Implications for Design Education

Key insights from this work relevant to design education research relate to the assignment (experiential versus functional prototypes), gender, and the identification of categories associated with important steps in student's prototype journeys. Specifically, results comparing the experiential and functional prototype journey suggest that future work investigating where needs associated with collaborative versus individual group prototyping diverge is necessary.

Concerning gender, this work contributes to the ongoing dialogue about opportunities for design education researchers to highlight where gender bias is having the most impact in the design process; here, specifically the prototyping process was examined. The finding that functional prototyping appears to exhibit a less positive experience for female students at its onset suggests that there is opportunity to improve this experience, enhance EDSE, and ultimately contribute to more equitable learning and professional outcomes. Future work could identify strategic interventions that are proven to mitigate this.

Finally, steps in the prototype journeys that corresponded with the highest and lowest emotional levels were primarily centered around brainstorming and decision-making. Further research will aim to refine these categories to identify more discrete steps in the prototype journey that impose excited emotional levels from students.

3.4.7 Limitations and Future Work

Future work should investigate ways to reduce assumptions associated with the data set, by (1) requesting student feedback at consistent intervals throughout the prototyping process and (2) replacing the qualitative emotional level feedback tool with a Likert scale to enhance the consistency of the interactive journey mapping tool between participants (Fig. 19). The former suggestion to reduce assumptions would strengthen the integrity of the linear interpolation approach used in the current study to approximate each participant's emotional level at stages in between the discrete steps identified in journey maps.

Tangentially, this research provides implications for similar studies that aim to demystify the barriers to prototyping. One implication might direct researchers to prioritize gaining the perspective of facilitators in addition to students (for example, comparing a journey map of the prototyping experience created by instructors and other design facilitators with personally constructed journey maps of students). Another implication might lead to gaining user feedback in real-time as opposed to collecting this data after the prototyping experience.

3.5 Conclusion

Motivations for this work are grounded in understanding the virtual prototyping experience of university students with the purpose of informing instructors, makerspace practitioners, and other prototype facilitators. Journey Mapping and the Critical Incident Technique were used to collect data about students' journeys through two virtual prototyping experiences. Notable results from this work include a statistically significant difference in emotional levels of Female and Male students during the beginning phase of the experiential prototype journey (Table 20); a statistically significant difference between the beginning and end phases of the functional prototype journey of Female students (Table 23); and more emotional volatility observed in functional prototype journeys than experiential prototype journeys (Fig. 22 and Fig. 23).

3.5.1 Acknowledgements

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4 Life Cycles of Making in Small Scale Making Environments

4.1 Introduction

Reducing the environmental impacts of the global supply chain is an increasingly important conversation. While transparency around the environmental impact of our global supply chains still has lots of room for improvement [73], an opportunity to reduce a community's dependency on global supply chains involves bolstering their local supply chains in industries such as manufacturing and fabrication. In fact, Tomas Diez describes an initiative to facilitate this retreat from global supply chain dependency in a white paper associated with the Fab City Foundation[1] [74]. This particular initiative relates to building resilience in local manufacturing and fabrication supply chains. Initiatives like these exemplify why prioritizing sustainable behaviors in small scale fabrication spaces is critical to supporting environmental impact goals as these spaces grow in their roles of supporting local supply chains.

While some researchers have found little evidence to consider small scale fabrication spaces as significant actors in local supply chains [75], there are a few example scenarios regarding how makerspaces and fab labs stepped in to support local communities during the onset of the COVID-19 pandemic that suggest otherwise [76,77]. Moreover, Kohtala and Hyysalo concluded that while the making and prototyping community is still evolving quite rapidly, it is worthwhile to continue these studies in hopes of raising the standard for sustainable practices in these spaces [78].

In an attempt to craft a pathway towards sustainable practices in small scale fabrication spaces that are aligned with what is needed to avoid climate catastrophe, this research seeks to do the following: (1) learn from actors within small scale fabrication spaces about the current state of sustainable practices, (2) propose opportunities to introduce sustainable interventions, and (3) identify key obstacles to achieving sustainable practices that are in alignment with environmental impact goals. This research is inspired by a vision to inform the following guiding questions:

Q1: Where are the greatest opportunities to reduce environmental impacts in the Life Cycle of small scale fabrication spaces?

Q2: How do the Life Cycle stages of small scale fabrication spaces differ in their environmental impact contributions?

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[1] https://fab.city/

Q3: Which processes in the Life Cycles of small scale fabrication spaces contribute most toward environmental impact?

The following research questions offer a specific starting point for investigating the guiding questions:

R1: What do influential actors in small scale fabrication spaces predict as best opportunities to reduce environmental impacts within the life cycle of small scale fabrication spaces

R2: Which actors within small scale fabrication spaces are most knowledgeable about each life cycle stage? Which actors have the most influence over the decision making and/or sustainable practices at each stage?

R3: Where are the best opportunities to gather reliable data about processes within the life cycles of small scale fabrication spaces?

4.2 Related Work

Pathways towards sustainable practices in prototyping and making regressed with the onset of planned obsolescence [79]. The financial return that resulted from this strategic marketing approach proliferated throughout many markets with tangible consumables. More recently, researchers have begun to acknowledge the need to educate prototyping and making communities about sustainability in hopes that more sustainable behaviors and practices begin to surface [79].

4.2.1 Product Life Cycles of Prototyping and Small Scale Making Spaces

Few studies have taken advantage of the life cycle analysis framework to investigate entire small scale fabrication spaces. For those that have used life cycle analysis as a tool to investigate sustainability, the focus was typically on evaluating specific tools and equipment within these spaces, such as 3d printers, laser cutters, and CNC mills. Minimizing idle time and machine tool paths serve as some of the suggestions for reducing environmental impact with these tools [80–82]. Other researchers have used the product life cycle to assess how individuals, as opposed to the entire space, engage in prototyping and making. For example, Klemichen et al. surveyed a large group of fab lab members across Germany and concluded a gap between the declarations of sustainability as important and the products and projects that precipitate from their experiences [83]. Similarly, Vasquez et al. introduced the sustainable prototyping life cycle for digital fabrication as an analysis framework to evaluate the sustainability of digital fabrication with bio-based materials. Their adaptation of the product life cycle included four stages: raw material acquisition, manufacturing and distribution, use, and end of life. Ultimately, reducing transportation distances, reducing energy consumption, and ensuring efficient use of machines were identified as opportunities to improve sustainability.

4.3 Methods

4.3.1 Scope

The scope of this study included adult actors that self identify as involved in small scale fabrication spaces within the US. Ages included those 18 and older. All genders, races, ethnicities, languages, and literacies were welcome to participate. A total of 18 subjects chose to be involved in this study as semi-structured interview participants.

4.3.2 Data Collection

Prospective semi-structured interview subjects were be contacted by email, word of mouth, and phone -- specifically, phone calls were be made based on Makerspaces, Fablabs, Techshops, Hackerspaces and other small scale fabrication spaces that showed contact information publicly online via google search. The target number of semi-structured interviews was influenced by studies from Guest et. al. (2006) and Ray Galvin (2015). Specifically, Galvin shares that given a random sample of interview participants for a particular topic of interest, approximately 12 semi structured interviews were enough to capture 93% themes that are present in at least 20% of the population. Guest et. al. arrived at a similar conclusion, stating that saturation of the meta themes that are relevant to the focus of the interviews occurs after 12 semi structured interviews [84,85].

Prospective subjects for semi structured interviews were selected based on mutual availability for interviews between the researcher and the subject.

Recruitment materials included a flyer (see Appendix A), a recruitment Letter written via email, script for verbal recruitment, interest form & survey via Google Form (see Appendix B), and semi structured interview guide (see Appendix C). The “interest form” was the intake form for all potential participants. Within the interest form, prospective participants had the option to book a semi structured interview session, sign up to participate in the virtual focus group, or navigate to the survey form section.

Through the interest form, prospective interview participants were prompted to share contextual background information regarding their affiliation with the life cycles of making in small scale fabrication spaces. Roles within the life cycles of making, organizational affiliation, population of community, years of experience, and familiarity with tools and equipment.

Finally, after sharing this information, participants were directed to book an interview appointment via Google Calendar.

4.3.3 Data Analysis

Transcriptions for all semi structured interviews were simultaneously created during each interview using a feature in the Zoom video conference platform. After all interviews were complete, a research team of interview coders were recruited to support coding the interviews. The coding approach for this study draws on work from DeCuir-Gunby et al. (2011) and Saldaña (2013) [86,87]. DeCuir-Gunby et al. provide a documentation scheme that was adapted for this study while Saldaña (2013) inspired the iterative nature of the research team debriefing after each round of coding.

The following steps outline the coding process that was established for the research team. First, each team member was instructed to download a copy of the interview that they intend to code. Next, team members were reminded of the product life cycle stages and research themes that have been selected as coding categories (see Table 26).

Life Cycle Stages	**Research Themes**
Raw Materials	Ideas for Sustainable Behaviors
Manufacturing	Reliable Data & Information
Distribution	Decision Making Factors
Use	Social Awareness*
Disposal	Other*

Table 26: Codes used to transcribe interviews based on product life cycle stages and themes related to research questions

For this study the “product” of focus for the life cycle stages refers to the actual making experience in small scale fabrication spaces. Based on that definition, the “Use” life cycle stage refers to the engagement of an individual in a small scale fabrication setting, while raw materials, manufacturing, and distribution refer to inputs and logistics needed to create this experience. Finally, the disposal stage refers to products and waste streams that come from these making experiences.

Research themes displayed in Table 26 initially included ideas for sustainable behaviors, reliable data and information, and decision making factors. After the first cycle of coding, the research team debriefed and decided to add social awareness as a code. The “other” category in the research themes column signifies that codes outside of the predefined categories are encouraged. On the other hand, the life cycle stages were fixed categories.

Each code that was documented included these four components: (1) life cycle stage, (2) research theme, (3) quote from the interview transcript, and (4) a note describing why this quote is important. The research team uploaded all codes to a Google Form where they were soon transferred to a Mural board for further analysis. Using the affinity mapping technique, all codes were then sorted according to life cycle stage and research themes. Ultimately, sub themes were interpreted based on the notes and quotes affiliated with each research theme and life cycle stage.

4.4 Results and Discussion

In total, 18 semi structured interviews were conducted. In this chapter the following results are shared regarding these interviews: contextual background of the interview participants (see Section 4.4.1), quantitative results of codes (see section 4.4.2), and insights from affinity mapping (see Section 4.4.3).

4.4.1 Contextual Background of Interviewees

The following figures, (Fig. 32 - Fig. 36) reflect the participants’ responses to questions about their contextual background in small scale fabrication spaces.

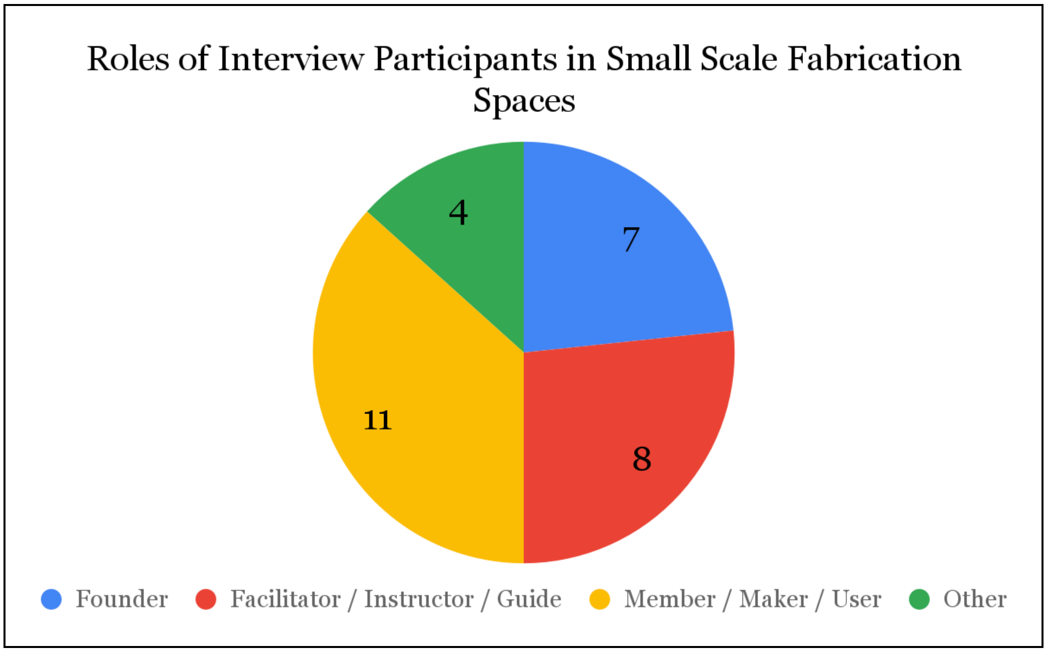

Figure 32: Roles of interview participants in small scale fabrication spaces

In total, 7 participants identified as a Founder, 8 participants identified as a Facilitator / Instructor / or Guide, 11 participants identified as a Member / Maker / or User, and 4 participants as “other” roles. The other categories included Board Member, Board Chair, Equipment Purchasing, and Manager. Also, 8 participants identified as having multiple roles. Next, Fig. 33 illustrates the organizational affiliations of interview participants.

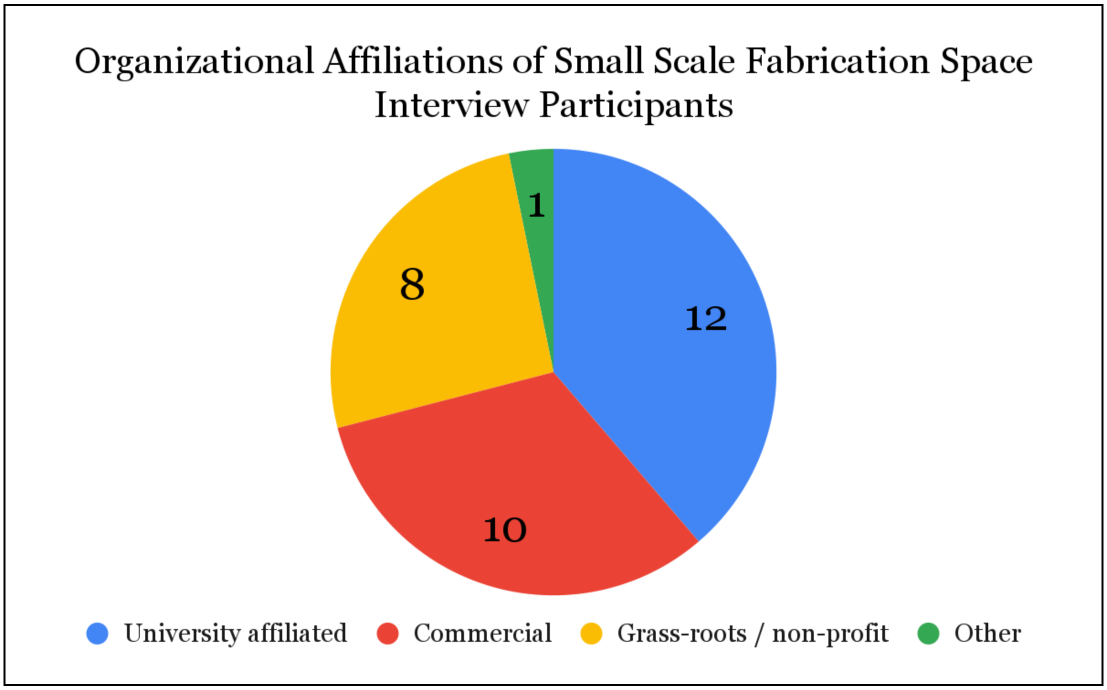

Figure 33: Organizational affiliations of small scale fabrication space interview participants

In total, 12 participants reported working in University Affiliated spaces, 10 participants reported working Commercial spaces, 8 participants reported working in Grass-roots / non-profit spaces, and 1 participant reported working in "other" spaces – in this case a library. Also, 10 participants reported working in multiple kinds of organizational spaces. Next, Fig. 34 illustrates the community population that each participant has experience working with.

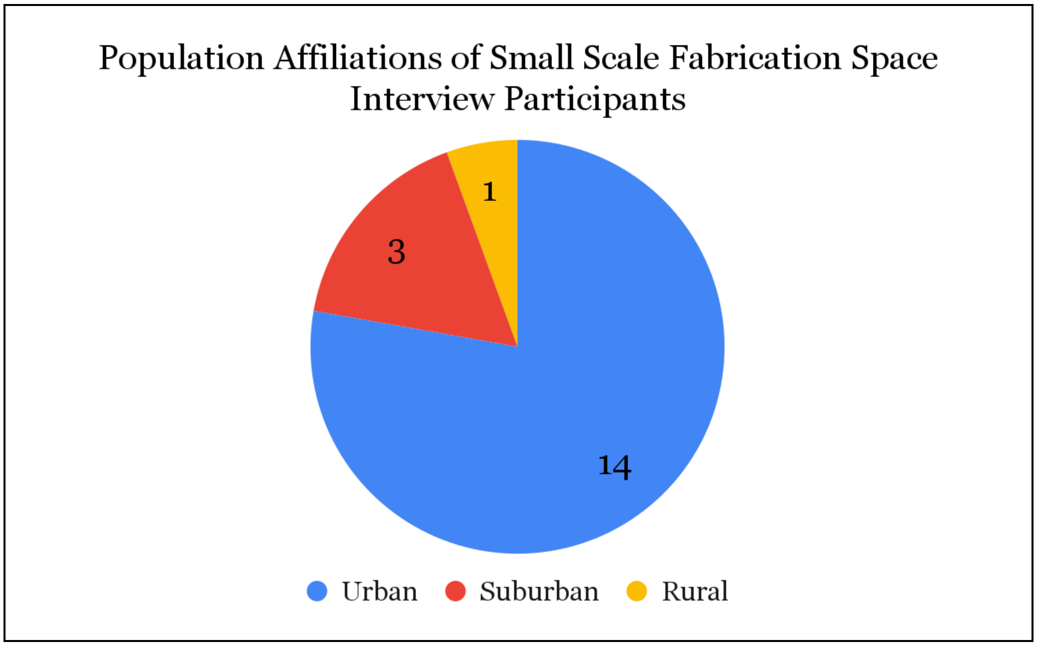

Figure 34: Population affiliations of small scale fabrication space interview participants

In total, 14 participants reported working in urban areas, 3 participants reported working in suburban areas, and 1 participant reported working in rural areas. Also, 1 participant reported working in multiple kinds of community population areas. Next, Fig. 35 illustrates the variations of interview participant's years of experience in small scale fabrication spaces.

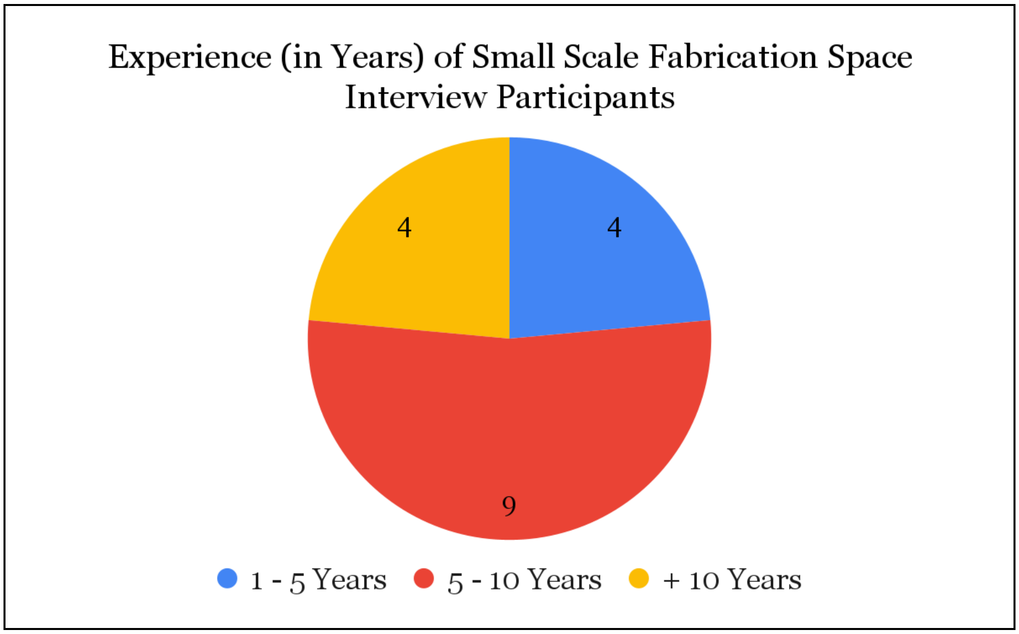

Figure 35: Experience (in years) of small scale fabrication space interview participants

In total, 9 participants reported 5 -10 years of experience, 4 participants reported 1-5 years of experience, and, also, 4 participants reported more than 10 years of experience. Finally, Fig. 36 illustrates the familiarity that interview participants have with the following tools and equipment that are commonly used in small scale fabrication spaces.

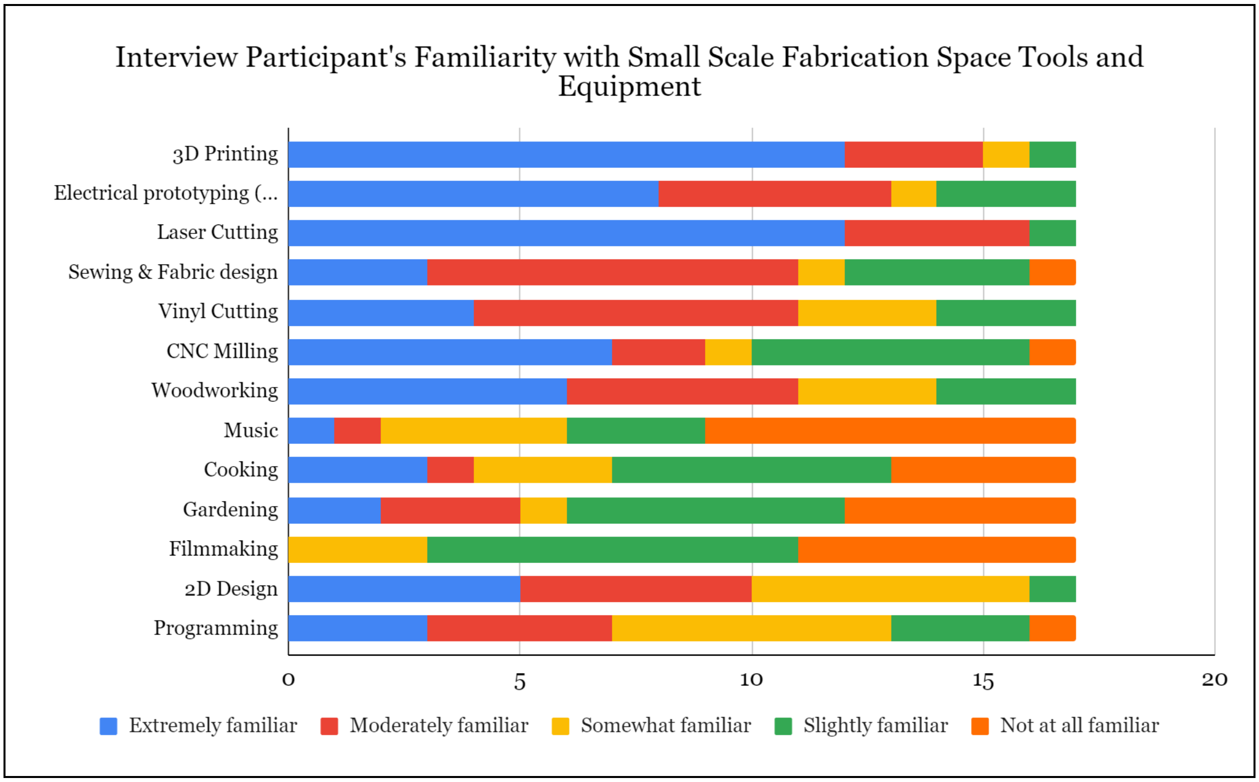

Figure 36: Interview participant's familiarity with small scale fabrication space tools and equipment

4.4.2 Quantitative Results

A total of 374 codes were documented for all interviews. Between the life cycle stages, 59 codes are related to raw materials, 32 codes are related to manufacturing and processing, 23 codes are related to transportation and distribution, 204 codes are related to use, and 55 codes are related to disposal.

Life Cycle Stage	# of codes
Raw Materials	59
Manufacturing and Processing	32
Transportation and Distribution	23
Use	204
Disposal	55
Total	374

Table 27: Number of codes produced based on life cycle stage

Regarding the research themes, 130 codes are related to ideas for sustainable behaviors, 55 codes are related to reliable data and information, 97 codes are related to decision making factors, 46 codes are related to social awareness, and 46 codes are related to other research themes.

Research Theme	# of codes
Ideas for Sustainable Behaviors	130
Reliable Data and Information	55
Decision Making Factors	97
Social Awareness	46
Other	46
Total	374

Table 28: Number of codes produced based on research theme

4.4.3 Insights from Affinity Mapping

This section highlights all of the sub themes that were produced from sorting and interpreting quotes and notes that were documented as codes. The sub themes are presented in relation to the product life cycle stages that they represent.

4.4.3.1 Raw Material Insights

Table 29 shares the 11 sub themes that were identified for the raw materials life cycle stage.

	Research Theme	Sub Theme
Raw Materials	Ideas for Sustainable Behaviors	Outsourcing logistical services & products that reinforce sustainable (and efficient) practices
	Ideas for Sustainable Behaviors	Emphasizing reusable and recyclable materials
	Ideas for Sustainable Behaviors	Establishing clear goals in material (or equipment) choice
	Reliable Data & Information	Material Broker: Someone who moderates the conversation between potential suppliers (or funders) and the space
	Reliable Data & Information	Company specific information about material or equipment quality
	Reliable Data & Information	Technical experts within the community of the space
	Decision Making Factors	Government policies have the power to dictate availability and affordability of materials -- often directly impacting viability of local vs global material purchases
	Decision Making Factors	Quality and reliability of the supplier
	Decision Making Factors	Maintaining financial sustainability of the space
	Decision Making Factors	Consideration of compatibility with culture of the space
	Obstacles to a Sustainable World	Lack of clearly defined goals for space material and equipment needs

Table 29: Sub themes identified for the raw materials life cycle stage

Concerning the research themes about ideas for sustainable behaviors, decision making factors, and obstacles to a sustainable world there is a sub theme related to incorporating a selective approach to material and equipment purchases or donations that are accepted by the space. When material and equipment selection has minimal restrictions, this causes the space to fall into pitfalls that not only cause problems for the space itself – such as clutter from excess materials that no one needs or rarely used equipment taking up space – but also, it provides the misleading notion to the donating entity that they have greatly supported a reduction in environmental impact. Instead, the burden of guilt for contributing to environmental impact through waste is passed along to the receiving entity. While this particular dilemma seems relatively simple, it gets more complicated for organizations that rely on donations due to their financial constraints. In some cases, taking on the potential burden of wasting materials may be the tacit “catch” that makes the exchange worthwhile to the donating organization.

Opportunities to minimize environmental impact due to donated materials that are not useful are mostly related to establishing firm selection criteria for accepting donations. This may seem difficult for organizations that have a broad range of activities or a loose definition of what goes on in their space. Still, a few of these tips might help in creating a foundation of selection criteria. One suggestion is to prioritize materials that are in ready-to-use condition based on the equipment that exists within the space. There was a specific example of a makerspace that had been receiving donated pieces of plywood that were not worthwhile for the donating company to keep around. These pieces of plywood were suitable for use on laser cutters and CNC mills. Another suggestion is to consider the capacity of the space's individual expertise with various materials. While this may be a less common scenario, donations may be available from all sorts of organizations that are looking to get rid of their junk. In a case where materials come with safety hazards or special handling practices, they may not be worthwhile to accept and it's important that the receiving entity turns down these offerings. Finally, inquiring with the individuals that frequent the space is a great way to practically ensure that donated materials are actually desired by the space. This suggestion actually leads into another sub theme that has many contributing codes: the consideration of compatibility with the culture of the space – in regards to raw material decision making factors.

Many reasons were provided that reinforce the need to consider the culture of the space with material and equipment selection. For example, academic spaces that largely serve collegiate students typically have requests for materials that support high fidelity capstone projects. In fact, some go to great lengths to make sure that the material is in ready to use form. However, there were examples of academic spaces that stock minimal materials (only providing ink for printers and resin for 3d printers). In this case, the founders of the space see their roles as providing specialized equipment and not materials. There were comments about factoring social causes into the decision to purchase or not purchase from specific suppliers. However, it was also mentioned that aligning social causes with the suppliers of needed materials and equipment is not a top priority – such as cost, quality, and availability.

With that being said, quality and reliability of suppliers adds layers of factors to consider. Many interview participants mentioned a desire to source their materials from local rather than international manufacturers. However, for some types of materials, the price point, availability, and quality make local suppliers less fitted to meet the needs of the space. This is particularly the case for most electronics where some of the interview participants directly mention that purchasing local electronics is not even considered most of the time.

Material brokers have been described as the individuals that engage with material and equipment suppliers on behalf of the space. This broker may work for the space or may be a friend of someone associated with the space. Executing their job effectively sometimes involves navigating personal relationships with other individuals or organizations to achieve deals that supply readily available materials and equipment to a space at an affordable price point. Because these personal relationships are often key to workarounds, this broker usually has lots of previous experience within the tangible making and fabrication industry.

4.4.3.2 Manufacturing and Processing Insights

Table 30 shares the 6 sub themes that were identified for the manufacturing and processing life cycle stage.

	Research Theme	Sub Theme
Manufacturing and Processing	Ideas for Sustainable Behaviors	Improving source transparency about material quality, expected lifetime, and other necessary information
	Reliable Data & Information	Incentives for most factories / suppliers to align with sustainable objectives are mostly related to efficiency
	Decision Making Factors	Awareness of material toxicity and other limiting factors of prospective materials
	Decision Making Factors	Cost, material quality, and availability play a big role in deciding between international vs domestic manufacturers to purchase from
	Obstacles to a Sustainable World	Competition, financial return, and other revenue based goals limit the flexibility of sustainable practices for sourcing manufactured materials for small scale making
	Obstacles to a Sustainable World	Attention to policies that significantly influence profitability reduce a manufacturing company's capacity to consider the most sustainable option

Table 30: Sub themes identified for the manufacturing and processing life cycle stage

Ideas for more sustainable manufacturing and processing behaviors in making include improving source transparency about the quality, expected lifetime, and repairability of equipment and materials. This comes as no surprise as expected machine lifetime about digital fabrication tools has been reported as unreliable in other research studies [80]. On a similar note, one participant mentions an initiative that they have encountered where manufacturers are required to provide a rating repairability. Ideas like these have the potential to encourage higher equipment and tool transparency standards. Still, there is a lot of room for improvement here.

Concerning recycling pure vs recycled materials, some participants mention how it is sometimes cheaper to go with the unsustainable option. While this may be true, it was also mentioned that the purchase price for sourcing and manufacturing materials and equipment does not properly represent the labor and material cost that went into it. This lack of transparency contributes to decision making that neglects accounting for sustainable processes mostly because the effort to truly make an informed decision is so high compared to other factors like price, quality, and availability.

Competition and financial return often make manufacturers advocate for policies that inhibit sustainable behaviors – such as suppressing or limiting the right to repair consumer products. For example, a few stories from participants spoke about policies of manufacturers that require purchasing entire new units or large components for small equipment fixes on the consumer end or even servicing policing that require the entire piece of equipment to be shipped for servicing as opposed to offering the consumer agency by simply delivering the needed part. While, of course, manufacturers have their own rationale for creating these policies, they act as deterrents to extending the life times of fabrication tools and equipment which leads to greater environmental impact from purchasing new equipment.

4.4.3.3 Transportation and Distribution Insights

Table 31 shares the 7 sub themes that were identified for the transportation and distribution life cycle stage.

	Research Theme	Sub Theme
Transportation and Distribution	Ideas for Sustainable Behaviors	Robust documentation of physical supply/inventory supports efficient logistics for restocking materials
	Ideas for Sustainable Behaviors	Packaging that uses sustainable materials
	Ideas for Sustainable Behaviors	Networks and social initiatives that encourage local exchange of needed resources
	Reliable Data & Information	Missing of misleading information about a material's cost for labor and distribution limit a making environment's ability to make informed choices
	Decision Making Factors	Degree of transparency between the supplier and purchasing entity
	Decision Making Factors	Reliability supplier's distribution system often impacts local vs global purchasing habits
	Decision Making Factors	Justifications for additional steps in the distribution phase are dependent upon the making environment's priorities (i.e. accessibility, material quality, minimizing inhouse processing, etc.)

Table 31: Sub themes identified for the transportation and distribution life cycle stage

Tempting decision making factors that are hard to work around include purchasing from international suppliers that have really affordable prices and high quality products. Participants have mentioned that sometimes all of the labor, manufacturing, and distribution costs are not accurately represented in the purchase prices. Evenmoreso, the environmental impact compared to purchasing local or regional products is similarly not represented. A few ideas that combat this obstacle to more sustainable behaviors includes developing and embracing a local network within manufacturing spaces so that the barrier to find local suppliers is minimized for small scale fabrication spaces. A key factor in enabling this kind of network would be the material broker (see section 4.4.3.1) and similar actors that have personal relationships with individuals and organizations in local manufacturing industries.

Packaging of products, incoming and outgoing, from small scale fabrication spaces was noted as an area for improving sustainable behaviors. One participant mentions how much excess packaging (specifically for electronics) goes directly to landfill. One idea that was mentioned involves reusable shipping storage for fabrication materials and components. Particularly with this idea, the participant elaborated on what it might take to gain traction by saying that if these storage containers were designed so that the consumer obviously knew that they were durable and designed for longevity, then maybe they would become relevant in the distribution space.

Finally, robust documentation of material supply enabling efficient restocking practices is another sub theme to address. A few participants mentioned a system that they use to stock foundational materials for their equipment and a common decision making factor was reliability and availability of the supplier to restock the needed materials. Robust documentation supports efficient material flow to the small scale fabrication space and, potentially, could make it easier to incorporate using local suppliers for some materials and components.

4.4.3.4 Use Insights

Table 32 and Table 33 share the 28 sub themes that were identified for the use life cycle stage.

	Research Theme	Sub Theme
Use	Ideas for Sustainable Practices	Establishing community expectations and agreements related to sustainable practices
	Ideas for Sustainable Practices	Accessible and understandable guidelines for using sustainable prototyping strategies and techniques
	Ideas for Sustainable Practices	Compiling universal practices that help local communities develop sustainable foundations
	Ideas for Sustainable Practices	Feedback systems that offer checks and balances for upholding community expectations and equipment quality
	Ideas for Sustainable Practices	Supporting local community's understanding of recycling, remanufacturing, and reusing materials
	Ideas for Sustainable Practices	Localizing making, repair, and other necessary operations for the surrounding community as a means of strengthening community resilience
	Ideas for Sustainable Practices	Offering support for product repair reinforces sustainable mindsets within making environments
	Ideas for Sustainable Practices	Financial structure and revenue streams that are compatible with goals to be more sustainable
	Reliable Data & Information	Structured and informal leadership that offer key relationships to community and knowledge that informs best practices in making environments
	Reliable Data & Information	Empirical knowledge gained from material interaction: learning by doing
	Reliable Data & Information	Perceived value and purpose of maker environments from outsiders
	Reliable Data & Information	Community expertise as available resources to members of the space
	Reliable Data & Information	Material policy imposed by the space often supports sustainable behaviors with materials
	Reliable Data & Information	Conducting necessary market research informs knowledge of repurposing recycled products and intended use of the created product
	Decision Making Factors	Optimizing the efficiency of production logistics, which may include considering lead times, pace of restocking materials, and frequency of customer requests
	Decision Making Factors	Realizing efficiency through longevity in tools and equipment, and material conservation
	Decision Making Factors	Personal values of leadership and membership inform sustainable (or unsustainable) decision making
	Decision Making Factors	External policies related to rights to repair and safety standards
	Decision Making Factors	Intended use of the product created in the space

Table 32: Sub themes identified for the use life cycle stage

	Research Theme	Sub Theme
Use	Social Awareness	Equipping the community with knowledge and agency to make reasonably sustainable decisions
	Social Awareness	Awareness and preparation to cater to needs of the members -- which may vary by demographic and other contextual factors
	Obstacles to a Sustainable World	Maximizing financial return over social impact and sustainable practices
	Obstacles to a Sustainable World	Struggle to balance investment in base operations, achieving sustainable practices, access for community, or improving quality of making experience
	Obstacles to a Sustainable World	Vulnerabilities of operations that rely on volunteer labor
	Purpose of the Space	Enabling high quality execution of personal group projects
	Purpose of the Space	Cultivating a safe space for making with community
	Purpose of the Space	Cultivating a safe space for exchanging skills, knowledge, and other resources with community
	Purpose of the Space	Accessibility to specialized equipment and tools

Table 33: Additional sub themes identified for the use life cycle stage

The diversity of motivation and purpose for using a small scale fabrication space was broad. A few popular themes from this collection of interviews included executing individual and group projects, community building with other makers and fabricators, and sharing skills with other makers and fabricators. These motivators for being in any space warrant a stark difference in many behaviors during the use life cycle stage – any many other stages for that matter. For example, the purpose that most members attend any small scale fabrication space informs the kinds of equipment that they may use (related to raw materials and manufacturing and processing stages).

Ideas for sustainable behaviors during the use of small scale fabrication spaces included localizing making, repair, and other necessary operations for the surrounding community. In fact, one participant shared their personal anecdote of establishing themselves as a localized lite manufacturing space saying, “the whole thinking of a makerspace is that we’re really more of a prototyping place, but I’ve started to actually go into light manufacturing here.”

Other ideas for sustainable behaviors are related to establishing best practices both for use of equipment and upkeep of the space. One participant shared how failure to do this can lead to poor practices around sharing space and minimizing clutter saying, “We have learned that if people take advantage of you, you never get it back. If they take an inch, they take a mile, and then you’re not getting it back. And that’s a real problem. So [on the] space side of things, it’s that people [will] expand if you don’t.” Ultimately, there were many notes that echoed the need to establish shared expectations and standards for the space regarding cleanliness as it relates to storage and clutter, proper use and maintenance of equipment, and even sleeping.

Noted as reliable sources of information were technical experts and leaders of small scale fabrication spaces. Technical experts both provide value to other members that enjoy sharing and learning from each other as well as for the managers of the space in case the technical expert has capacity to support training other members or consulting with management about material and equipment upgrades. Leaders of small scale fabrication spaces are wide ranging in their duties. Particularly because most small scale fabrication spaces evolve in their nature over time (acquiring new tools and expanding membership), the leaders often become well acquainted with other local fabrication spaces and at times serve as a conduit to connect community members to these resources when they are in need. For example, one participant shared how they were able to support a couple of members at their space during a time of crisis: “We were able to use our nonprofit status and our connections to the larger corporate world and community to sort of say ‘ hey here’s some specific things that we — we as in our community, as in this specific very small portion of our community – need.’ And I think that there’s so much more power in ‘We’.”

Finally, although many spaces thrive on volunteer organizational structures in an effort to reduce barriers to access, a few participants noted the vulnerabilities of this style. Volunteer burnout and inconsistent capacity are the primary sources of issues here. For example, the following quote from a participant details how their tendency to volunteer more led to volunteer burnout: “I’ve always been community oriented, so I just started volunteering for everything. You need shop clean up days? You need tool storage builds? I do that. Whatever [it is], I’ll kind of do whatever… And, as I’m sure you know, if you’ve been involved in these spaces, the more you give the more they’ll take.”

4.4.3.5 Disposal Insights

Table 34 shares the 11 sub themes that were identified for the disposal life cycle stage.

	Research Theme	Sub Theme
Disposal	Ideas for Sustainable Behaviors	Tangible strategies for reducing the waste stream
	Ideas for Sustainable Behaviors	Repurposing non-disposal materials and equipment
	Ideas for Sustainable Behaviors	Allocating resources towards the promotion of recycling
	Reliable Data & Information	Recycled materials as sources of inspiration
	Decision Making Factors	Individual knowledge and support for disposal decision making from the space itself impact proper disposal behaviors
	Decision Making Factors	Anticipated quality and cost of recycled materials
	Social Awareness	Mindsets for reducing the waste stream
	Obstacles to a Sustainable World	Unclear options for reuse and recycling of scrap materials
	Obstacles to a Sustainable World	Minimal incentives and competing interests are barriers to properly recycling or repurposing products from a making environment the space
	Obstacles to a Sustainable World	Misleading efforts that place guilt of waste on others in the life cycle of making
	Obstacles to a Sustainable World	Dealing with material scraps that are not recyclable or involve high costs to recycle

Table 34: Sub themes identified for the disposal life cycle stage

Obstacles to sustainable behaviors regarding disposal are related to lack of knowledge and minimal incentives. In most cases, actors feel unsure about how to properly dispose of material. The extra effort that it takes to properly dispose or repurpose materials combined with minimal incentives to figure it out perpetuate unsustainable disposal practices.

For small scale fabrication spaces that emphasize prototyping and making, it may seem intuitive that recycling and repurposing used materials is common. However, many participants mentioned how the quality of recycled materials is a deterrent to using recycled instead of new materials. This was particularly the case for folks that intend to use the space for making high fidelity prototypes.

4.4.4 Limitations

The scope of this study could have been more clearly defined regarding what qualifies as a small scale making space. Initially, this term “small scale making space” was used with the intent of inviting all perspectives from tangible making environments that contribute to their communities at a predominantly local level as opposed to those that operate more nationally and globally. Moving forward, similar studies may find more actionable results from studying a more niche subset of these small scale making spaces.

4.4.5 Future Work

Niche research that investigates small scale fabrication spaces based on their minimum viable product. In this case, executing individual and group projects, community building with other makers and fabricators, and sharing skills with other makers and fabricators would serve as three categorical places to begin. In particular, it would be interesting to specifically focus on individuals, groups, or organizations that have made the transition from making and prototyping to lite manufacturing (as expressed in section 4.4.3.4)

4.5 Conclusion

The purpose of this research study was to explore the state of sustainable practices in the life cycles of small scale fabrication spaces. Through 18 semi structured interviews and a rigorous coding approach, the following results were obtained.

Cost, quality, and availability are factors that lead the decision making process for sourcing raw materials and manufactured components. Including social alignment and embracing local suppliers in decision making seems to be considered on a conditional basis.

On a similar note, transparency is a common obstacle regarding making sustainable decisions in sourcing raw materials and manufactured components. The often cheap price points of global suppliers are attractive to decision makers in these spaces; however, this may not be the case if there were more transparency about the environmental impact contributions from purchasing these materials and components.

Material brokers, technical experts, and leaders within small scale fabrication spaces serve as key resources in establishing internal and external operations – such as equipment maintenance and coordinating supplier relationships. They are also important towards creating a community that embraces skill sharing.

Motivation for attending and interacting with small scale fabrication spaces vary broadly. Executing individual and group projects, community building with other makers and fabricators, and sharing skills with other makers and fabricators were noted as common drivers for attending small scale fabrication spaces. These motivators seem to influence decision making and sustainable behaviors throughout all the life cycle stages.

Finally, organizational structures that rely on volunteer support from their community often suffer from volunteer burnout. However, their savings from having less paid staff contribute to making the space more accessible.

5 Conclusion

5.1 Dissertation Summary

This dissertation introduces design thinking as an approach to address wicked problems. Traits of the design thinking process – such as collaboration, empathy, iteration, risk taking – seem to match characteristics of wicked problems – problems that are perceived differently by each individual, that require its solver to acknowledge accountability, and that never stop.

With intentions to support more inclusive design thinking practices, Chapters 2 and 3 reinforce our understanding of the participant experience during the design thinking process. Both focus on how gender and academic discipline may serve as significant factors in design thinking experiences.

Chapter 4 examines the life cycles of making, which relates to sustainable design thinking practices as tangible making and prototyping are key components of the design thinking process. Through speaking with several actors that have experience in small scale fabrication spaces, this study framed insights about the state of sustainable practices throughout the life cycle stages of making, prototyping, and other small scale fabrication spaces.

Major takeaways from this dissertation include participants having significant struggles at the beginning of the design thinking experiences compared to the end of design thinking experiences (see Chapter 2 and Chapter 3) and hints that non-engineering students may perceive value in their design thinking experiences differently than those from engineering disciplines (see Chapter 2). Concerning sustainable behaviors in prototyping and making, the most notable takeaways involve how the lack of transparency in the manufacturing and distribution of needed materials and equipment make it difficult for decision makers to prioritize sustainable, and even social, factors.. Instead cost, availability, and quality remain driving factors for decision making. In addition, the driving purpose for fabrication spaces (such as community, project execution, or skill building) was revealed as an influential factor in sustainable behaviors throughout all stages of the life cycles of prototyping and making.

5.2 Future work

Results from this dissertation serve as a launch pad into deeper understanding of design thinking experiences and how they may be improved. Generally, future work that aims to reinforce sustainable and inclusive practices in design thinking would benefit from investigating how demographic context and motivation influence perceived value of, and observed behaviors in, design thinking processes.

For more inclusive design thinking experiences, there would be value in future work that explores “extreme” design thinking experiences to understand if there is a significant polarity between participant experiences as they move further along in the design thinking process. A complimentary study might propose strategies for simultaneously assessing and intervening in the participant experience. In this regard, outputs of the work might better equip design thinking guides, in addition to participants, with a suite of interventions to remedy participant experiences that are below the norm.

Also, connecting the engagement between design thinking and wicked problem solving would benefit from further development of metrics and evaluation techniques for inclusive design thinking. For example, proving the relationship between more populated solution spaces and participants that report significantly better design thinking experiences is one place to start.

In future studies about life cycles of small scale fabrication spaces, it may be useful to evaluate sustainable practices based on a classification system of an entity’s motivation or purpose. Distinguishing observed sustainable behaviors based on how small scale fabrication spaces define their minimum viable product to their members may help researchers identify trends associated with decision making factors, sustainable behaviors, and specific actors that are key to how these niche spaces pursue success. One example of next steps that further the understanding of sustainable design thinking – in its relation to small scale fabrication spaces – includes a combination of systems thinking and life cycle analysis frameworks that directly connects sustainable design thinking practice to reduction in environmental impact. Systems thinking tools offer an approach for collecting and sorting through factors that influence sustainable behaviors – ideally resulting in a collection of patterns that empower design thinking practitioners to identify successful behaviors. The life cycle analysis framework provides a quantitative methodology for communicating statistical significance of reducing harm to the environment through sustainable design thinking practice.

Overall, the sense of urgency to improve practices that address the wicked problems of the world will likely continue to grow – and along with it rises the value of future work that embraces the advantages of design thinking.

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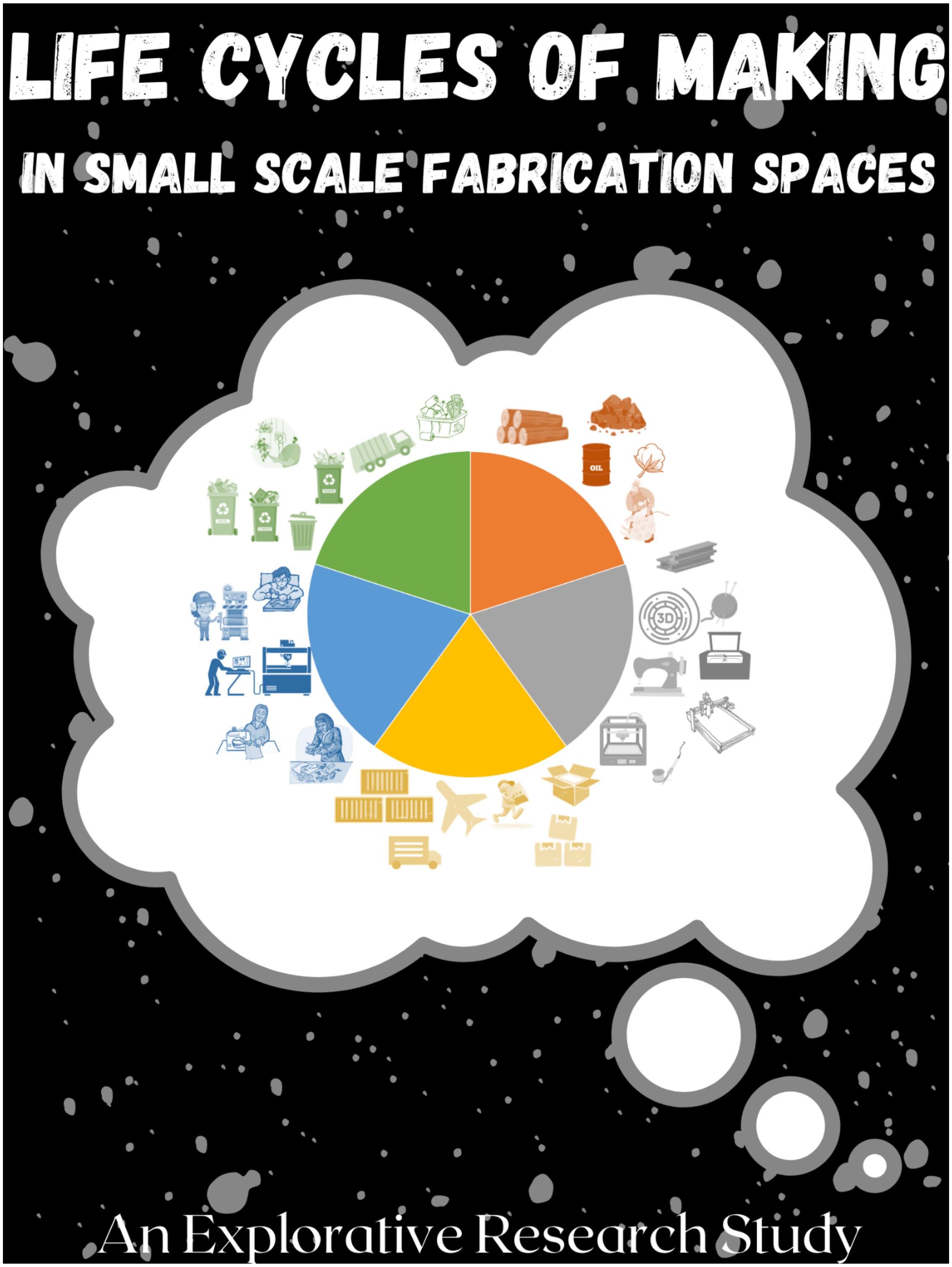
7 Appendix A


LIFE CYCLES OF MAKING
IN SMALL SCALE FABRICATION SPACES
OIL
3D
An Explorative Research Study

What is this study about?

Our goal is to understand the life cycle of small scale fabrication spaces, which includes (but is not limited to) makerspaces, FabLabs, wood shops, and hackerspaces. By "life cycle" we mean the following 5 stages: (1) Raw Materials & Inputs, (2) Processing & Manufacturing, (3) Transportation & Distribution, (4) Use, and (5) Disposal. While we anticipate a lot of familiarity with the "Use" and "Disposal" stages, we welcome perspectives from all five life cycle stages in this study.

Who gets to be involved?

We encourage participation from anyone located within the US that considers themselves involved in any stage of the small scale fabrication life cycle (i.e. makers, hackers, facilitators, lab/shop managers, directors, digital fabrication tool experts, manufacturers, etc.) Also, we will be providing compensation to participants via gift cards.

How do I participate?

There are three opportunities to participate:

- Survey Form: (15 - 30 min) [$20 gift card]
- Virtual 1-on-1 Interview (30 - 45 min) [$40 gift card]
- Virtual Focus Group Session (45 min - 1 hour) [$30 gift card]

Use the following link to share your interest in participating in the study: **https://forms.gle/jwTF7b7Csd1gLG2m7**

This work is being led by George Moore, Mechanical Engineering PhD candidate at UC Berkeley. Your are welcome to contact him at george_moore@berkeley.edu with any questions about this study.

8 Appendix B

2/4/22, 2:17 PM Interest Form: Life Cycles of Making in Small Scale Fabrication Spaces

1. I would like to complete this interest form based on the description provided above *

Mark only one oval.

○ Yes
○ No

Background

First are a few questions to help us understand your affiliation with small scale fabrication spaces

2. What types of tools & equipment are you most familiar with in small scale fabrication spaces? *

Mark only one oval per row.

	Not at all familiar	Slightly familiar	Somewhat familiar	Moderately familiar	Extremely familiar
3D Printing	○	○	○	○	○
Electrical prototyping (Soldering, etc.)	○	○	○	○	○
Laser Cutting	○	○	○	○	○
Sewing & Fabric design	○	○	○	○	○
Vinyl Cutting	○	○	○	○	○
CNC Milling	○	○	○	○	○
Woodworking	○	○	○	○	○
Music	○	○	○	○	○
Cooking	○	○	○	○	○
Gardening	○	○	○	○	○
Filmmaking	○	○	○	○	○
2D Design	○	○	○	○	○
Programming	○	○	○	○	○

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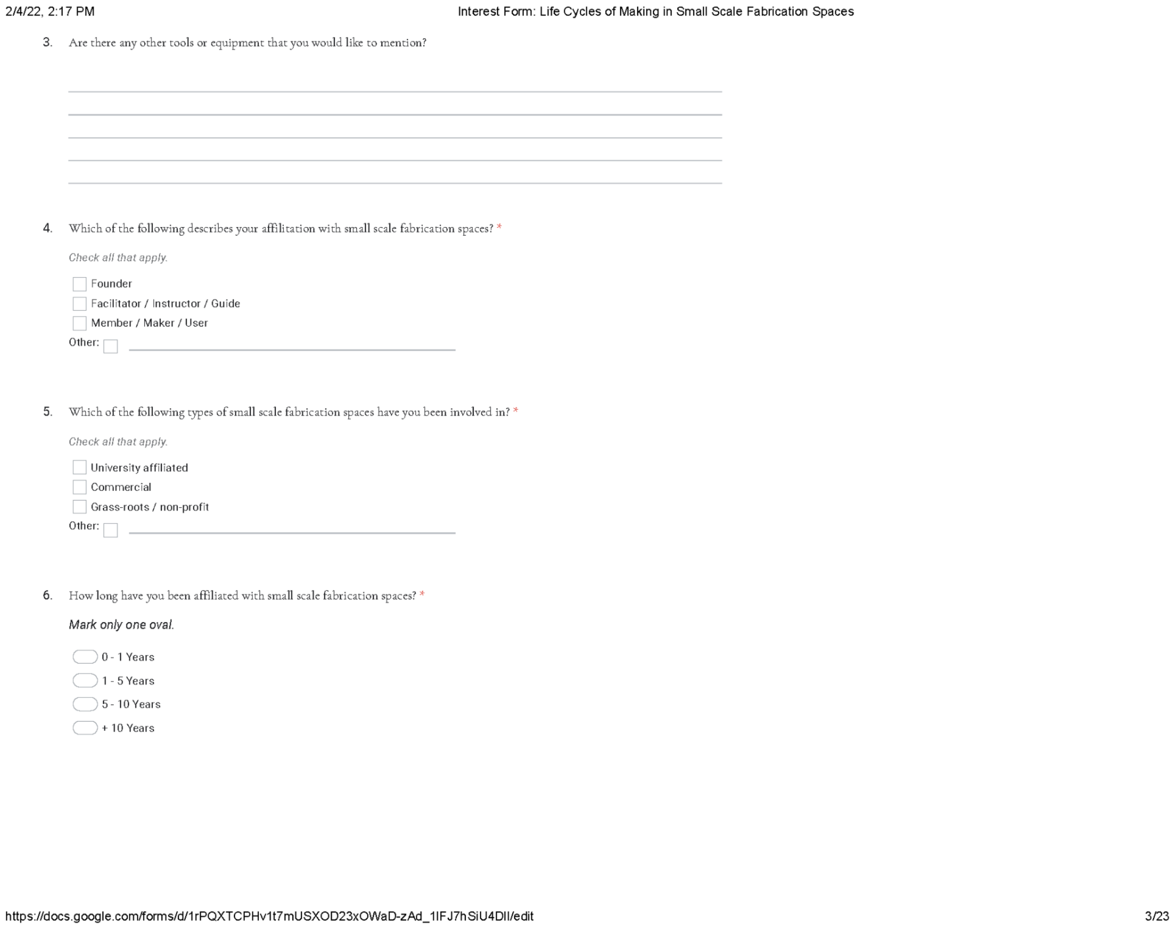

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3. Are there any other tools or equipment that you would like to mention?

4. Which of the following describes your affiliation with small scale fabrication spaces? *

Check all that apply.

☐ Founder
☐ Facilitator / Instructor / Guide
☐ Member / Maker / User
Other: ☐

5. Which of the following types of small scale fabrication spaces have you been involved in? *

Check all that apply.

☐ University affiliated
☐ Commercial
☐ Grass-roots / non-profit
Other: ☐

6. How long have you been affiliated with small scale fabrication spaces? *

Mark only one oval.

○ 0 - 1 Years
○ 1 - 5 Years
○ 5 - 10 Years
○ + 10 Years

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7. What kind of community best represents the context of the small scale fabrication spaces that you are familiar with? *

Mark only one oval.

○ Rural
○ Suburban
○ Urban
○ Other: ______________________

8. Which research activity would you like to participate in? *

Mark only one oval.

○ Semi Structrured Interview (30 - 45 min) *Skip to question 9*
○ Virtual Focus Group (45 min - 1 hour) *Skip to question 13*
○ Survey Form (15 - 30 min) *Skip to section 5 (Survey)*

Semi Structured Interview Booking

Use this link to reserve a semi structured interview slot:

https://calendar.google.com/calendar/u/0/selfsched?sstoken=UVBTMXhTUzBad3R6fGRlZmF1bHR8NjY0MTUxZWYzNTNlMGI5NWJmZTExMjBkYjA5NzgxOGQ

Available dates are recurring on Monday, Tuesday, and Wednesday from 3pm to 5pm. Starting Feb 14th and ending March 16th.

9. First Name or Forename (Personal Name) *

____

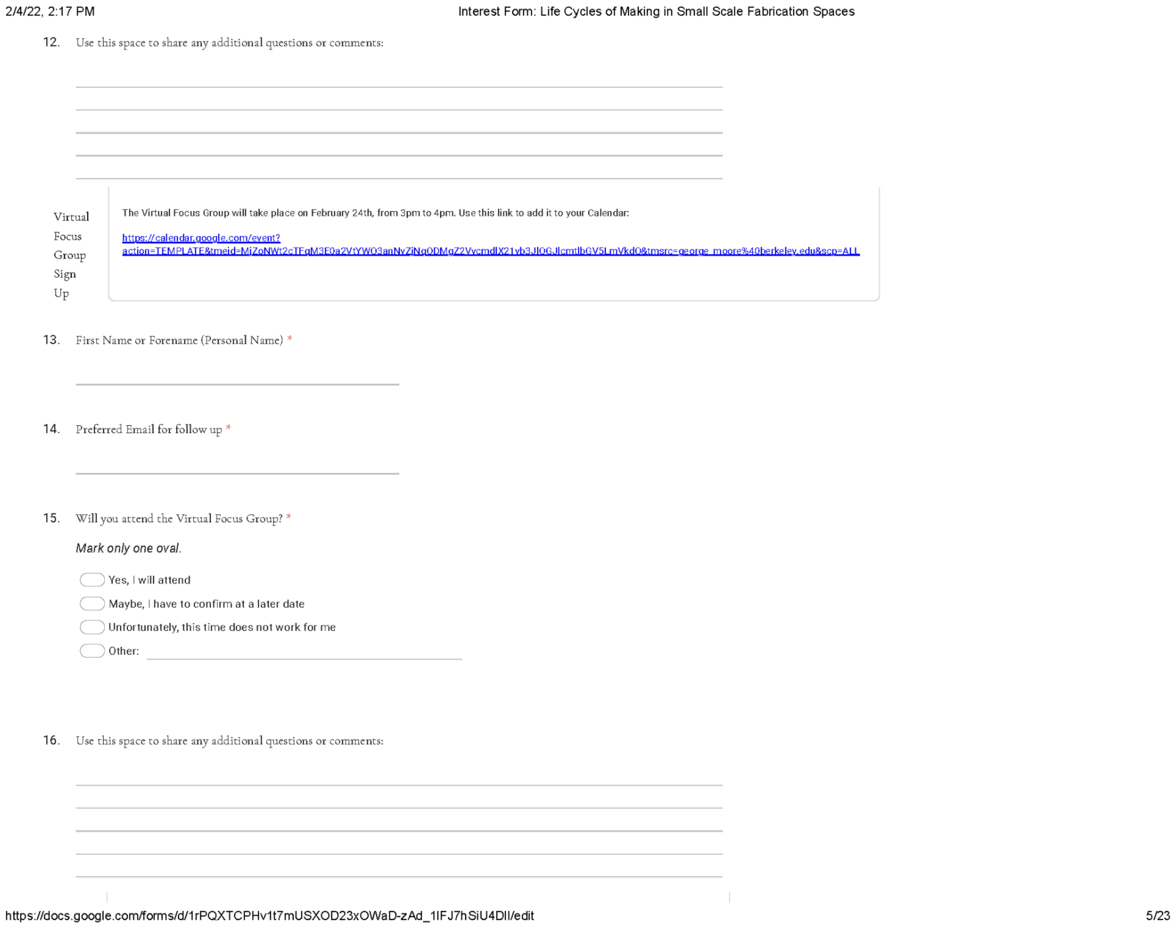
10. Preferred Email for follow up *

____

11. Have you booked your Semi Structured Interview? *

Mark only one oval.

○ Yes
○ No, these dates do not work for me.
○ No, but I will soon



12. Use this space to share any additional questions or comments:

Virtual Focus Group Sign Up

The Virtual Focus Group will take place on February 24th, from 3pm to 4pm. Use this link to add it to your Calendar:

https://calendar.google.com/event?action=TEMPLATE&tmeid=MjZoNWt2cTFqM3E0a2VtYWO3anNvZjNqODMgZ2VycmdlX21vb3JlOGJlcmtlbGV5LmVkdQ&tmsrc=george_moore%40berkeley.edu&scp=ALL

13. First Name or Forename (Personal Name) *

14. Preferred Email for follow up *

15. Will you attend the Virtual Focus Group? *

Mark only one oval.

○ Yes, I will attend
○ Maybe, I have to confirm at a later date
○ Unfortunately, this time does not work for me
○ Other:

16. Use this space to share any additional questions or comments:

Survey

The following survey questions were curated with the intention of learning more about the life cycles of making within small scale fabrication spaces – such as makerspaces, FabLabs, wood shops, hackerspaces, etc.

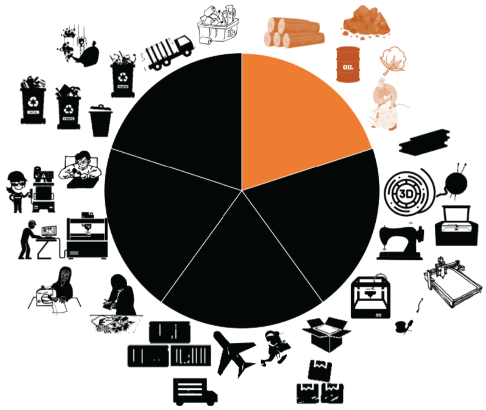
This survey is divided into sections based on the 5 life cycle stages: (1) Raw Materials & Inputs, (2) Processing & Manufacturing, (3) Transportation & Distribution, (4) Use, and (5) Disposal. It is not expected that you are an expert in each life cycle stage. Hence, we encourage you to share your thoughts, ideas, and opinions openly.

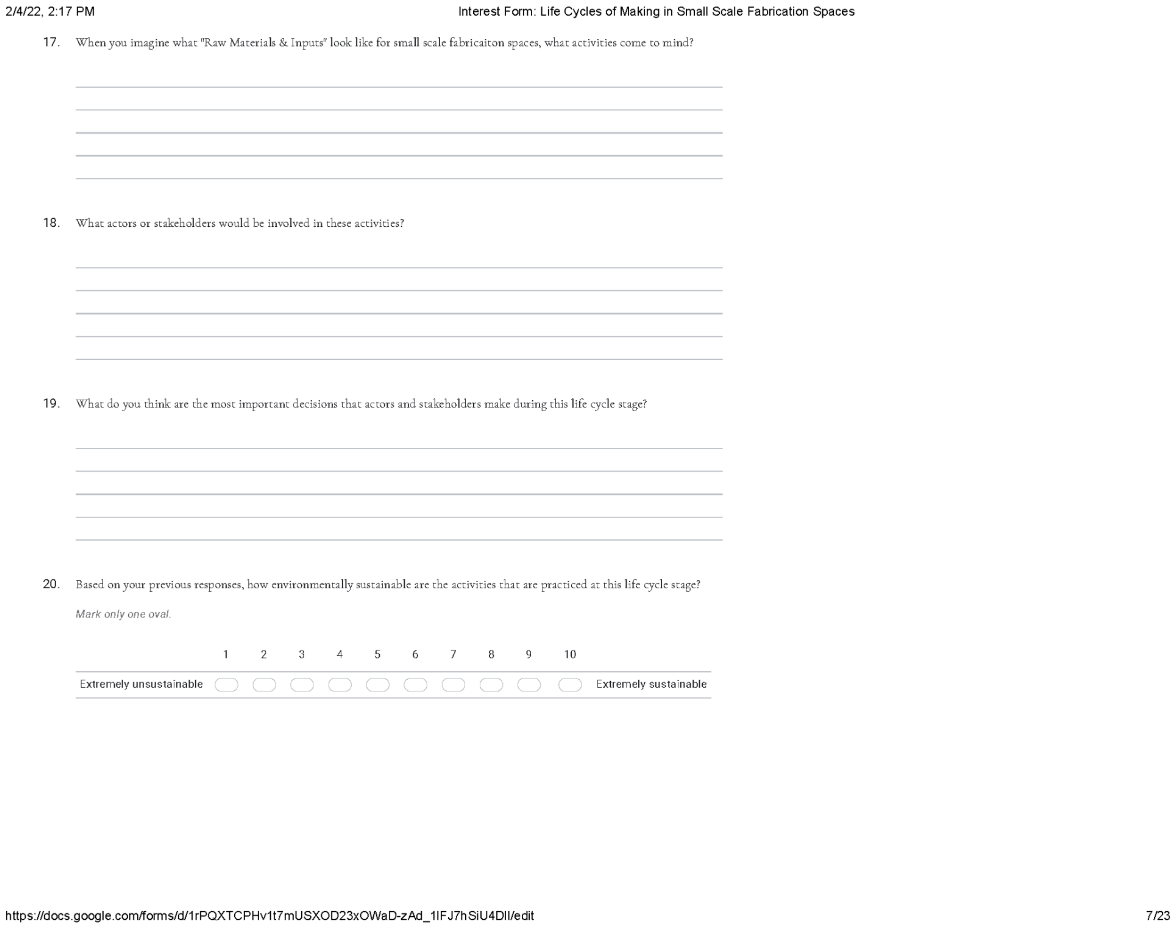
We appreciate your interest in contributing to this work and are to excited to share the results with you at the conclusion of this study.

Raw Materials & Inputs

This stage in the life cycle of small scale fabrication spaces is about the origin of the materials and other inputs that are needed to realize the desired function of small scale fabricaiton spaces.

Stage 1: Raw Materials & Inputs





2/4/22, 2:17 PM Interest Form: Life Cycles of Making in Small Scale Fabrication Spaces

17. When you imagine what "Raw Materials & Inputs" look like for small scale fabricaiton spaces, what activities come to mind?

18. What actors or stakeholders would be involved in these activities?

19. What do you think are the most important decisions that actors and stakeholders make during this life cycle stage?

20. Based on your previous responses, how environmentally sustainable are the activities that are practiced at this life cycle stage?

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Extremely unsustainable	○	○	○	○	○	○	○	○	○	○	Extremely sustainable

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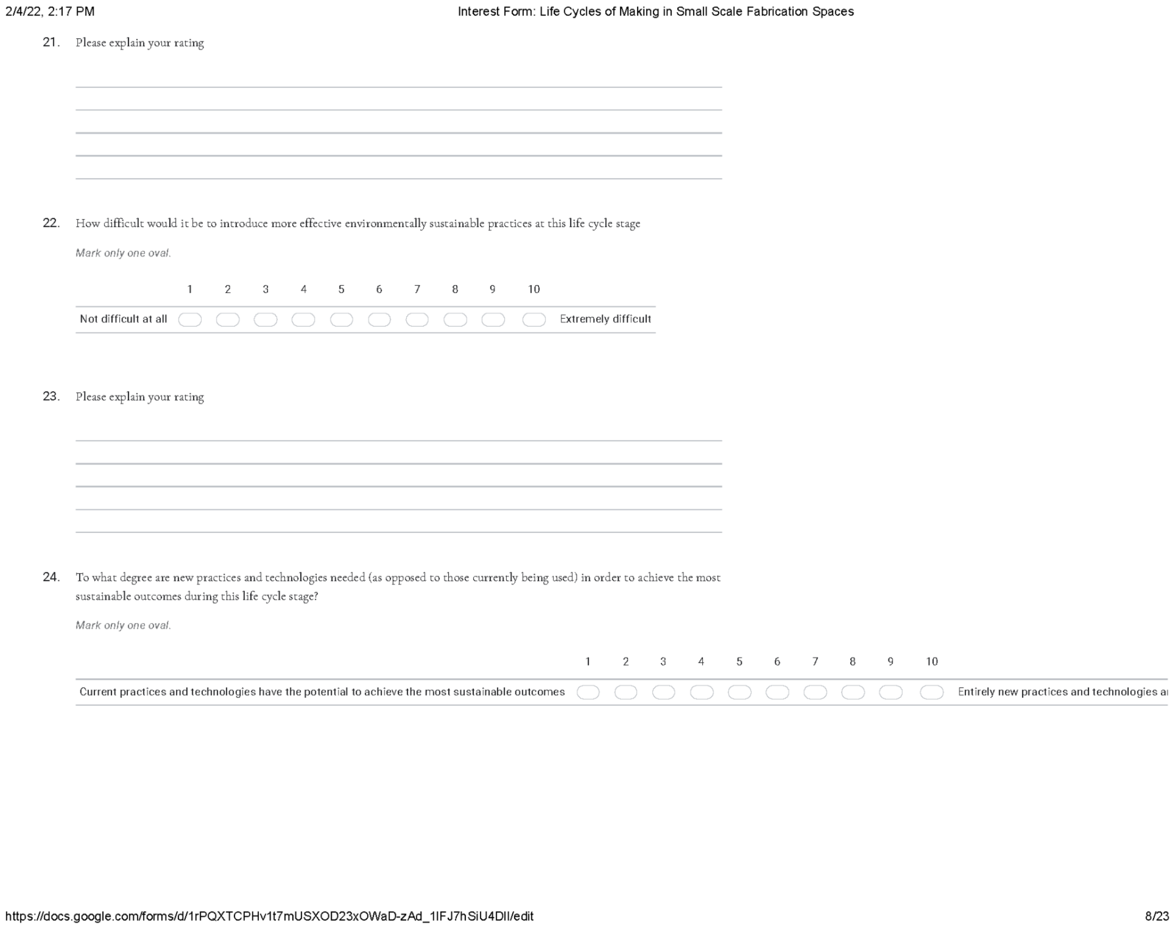


21. Please explain your rating

____
____
____
____
____

22. How difficult would it be to introduce more effective environmentally sustainable practices at this life cycle stage

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not difficult at all	○	○	○	○	○	○	○	○	○	○	Extremely difficult

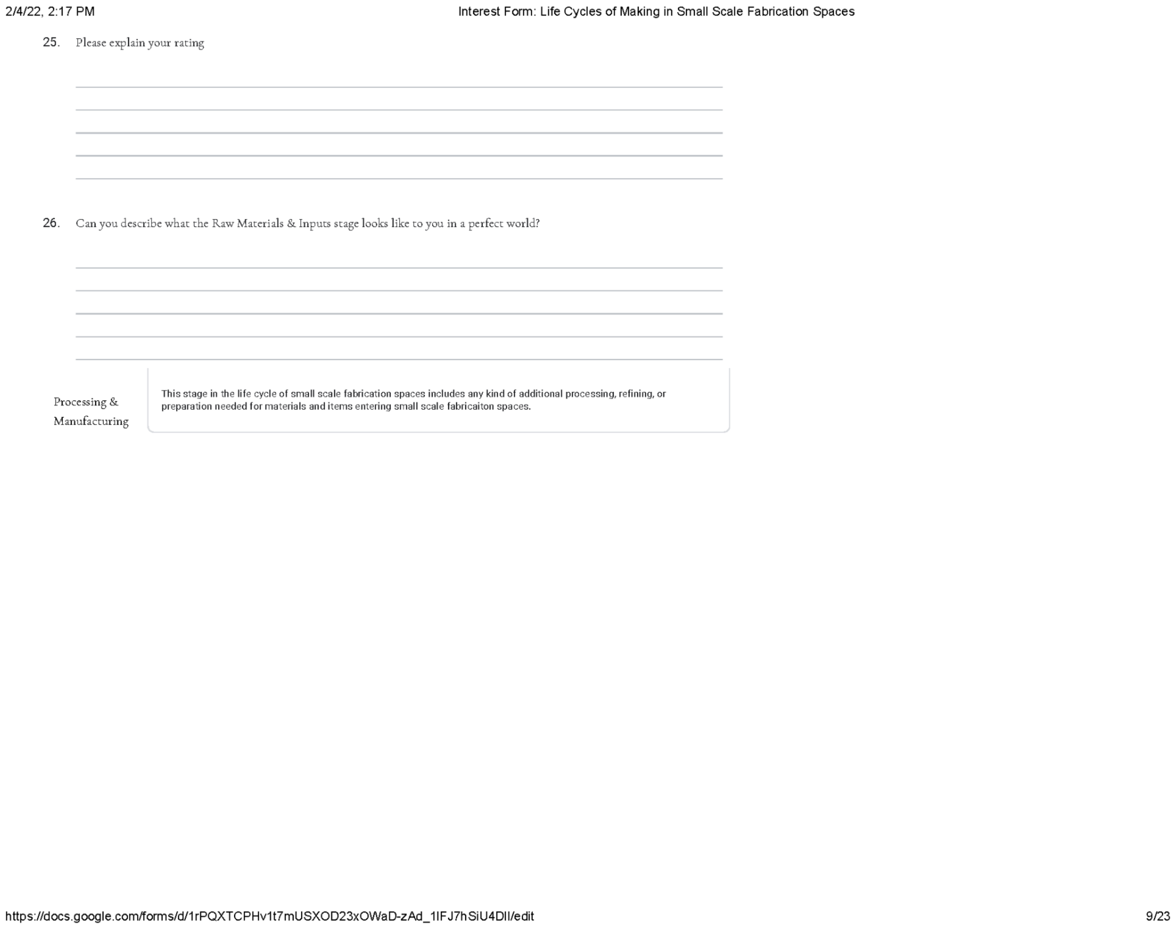
23. Please explain your rating

____
____
____
____
____

24. To what degree are new practices and technologies needed (as opposed to those currently being used) in order to achieve the most sustainable outcomes during this life cycle stage?

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Current practices and technologies have the potential to achieve the most sustainable outcomes	○	○	○	○	○	○	○	○	○	○	Entirely new practices and technologies ar



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25. Please explain your rating

26. Can you describe what the Raw Materials & Inputs stage looks like to you in a perfect world?

Processing & Manufacturing	This stage in the life cycle of small scale fabrication spaces includes any kind of additional processing, refining, or preparation needed for materials and items entering small scale fabricaiton spaces.

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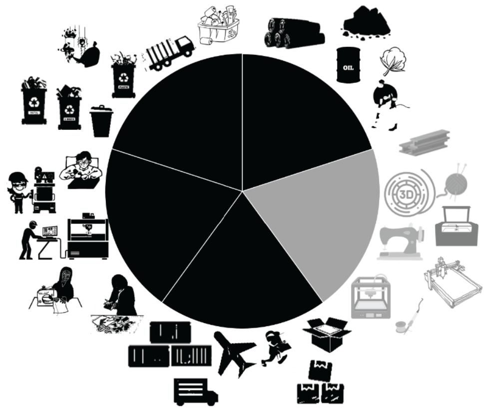
Stage 2: Processing and Manufacturing



27. When you imagine what "Processing & Manufacturing" looks like for small scale fabricaiton spaces, what activities come to mind?

28. What actors or stakeholders would be involved in these activities?

2/4/22, 2:17 PM Interest Form: Life Cycles of Making in Small Scale Fabrication Spaces

29. What do you think are the most important decisions that actors and stakeholders make during this life cycle stage?

30. Based on your previous responses, how environmentally sustainable are the activities that are practiced at this life cycle stage?

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Extremely unsustainable	○	○	○	○	○	○	○	○	○	○	Extremely sustainable

31. Please explain your rating

32. How difficult would it be to introduce more effective environmentally sustainable practices at this life cycle stage

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not difficult at all	○	○	○	○	○	○	○	○	○	○	Extremely difficult

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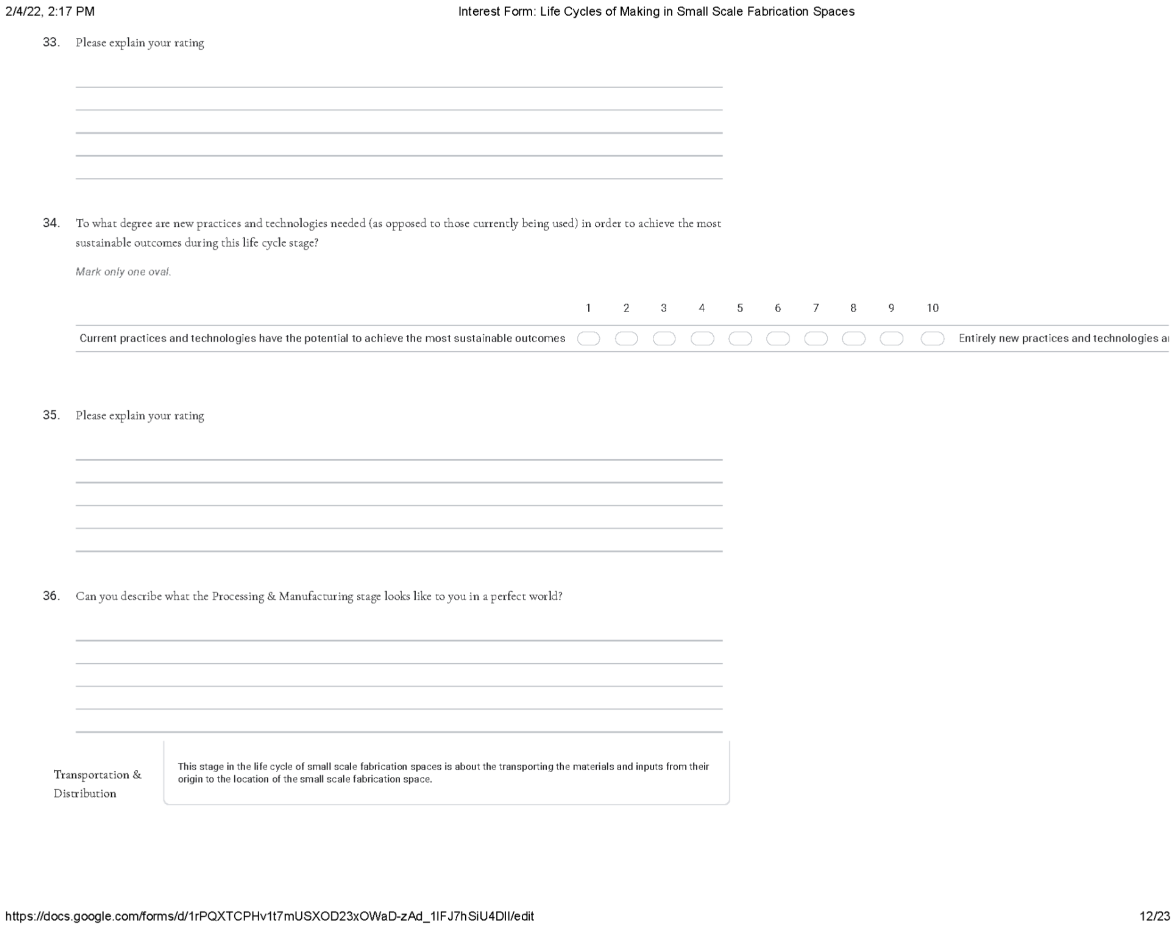


33. Please explain your rating

34. To what degree are new practices and technologies needed (as opposed to those currently being used) in order to achieve the most sustainable outcomes during this life cycle stage?

Mark only one oval.

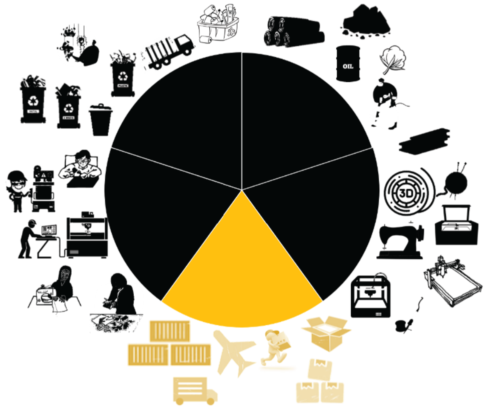
	1	2	3	4	5	6	7	8	9	10	
Current practices and technologies have the potential to achieve the most sustainable outcomes	○	○	○	○	○	○	○	○	○	○	Entirely new practices and technologies a

35. Please explain your rating

36. Can you describe what the Processing & Manufacturing stage looks like to you in a perfect world?

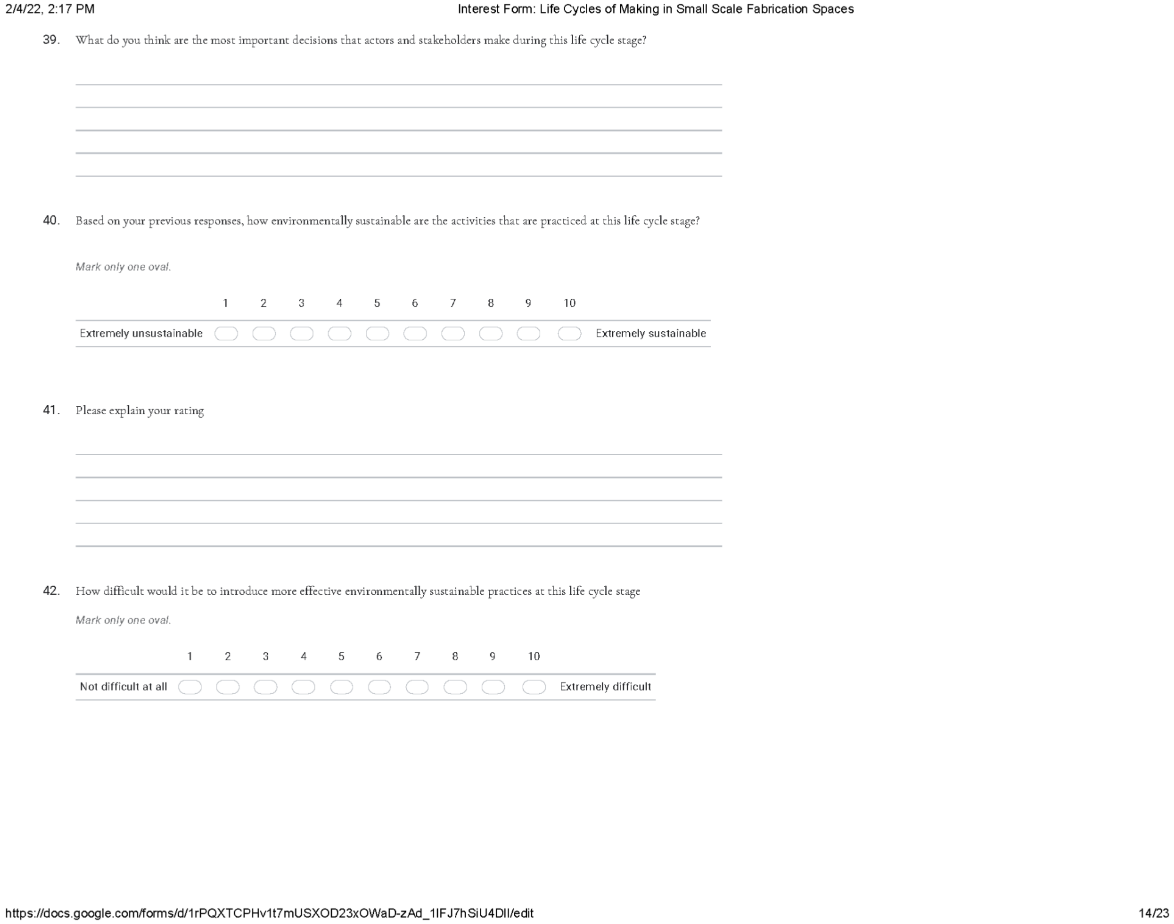
Transportation & Distribution	This stage in the life cycle of small scale fabrication spaces is about the transporting the materials and inputs from their origin to the location of the small scale fabrication space.

Stage 3: Transportation & Distribution



37. When you imagine what "Transportation & Distribution" looks like for small scale fabricaiton spaces, what activities come to mind?

38. What actors or stakeholders would be involved in these activities?



39. What do you think are the most important decisions that actors and stakeholders make during this life cycle stage?

40. Based on your previous responses, how environmentally sustainable are the activities that are practiced at this life cycle stage?

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Extremely unsustainable	○	○	○	○	○	○	○	○	○	○	Extremely sustainable

41. Please explain your rating

42. How difficult would it be to introduce more effective environmentally sustainable practices at this life cycle stage

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not difficult at all	○	○	○	○	○	○	○	○	○	○	Extremely difficult

43. Please explain your rating

44. To what degree are new practices and technologies needed (as opposed to those currently being used) in order to achieve the most sustainable outcomes during this life cycle stage?

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Current practices and technologies have the potential to achieve the most sustainable outcomes	○	○	○	○	○	○	○	○	○	○	Entirely new practices and technologies a

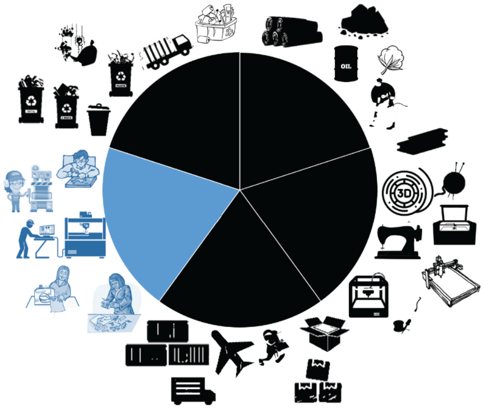
45. Please explain your rating

46. Can you describe what the Transportation & Distribution stage looks like to you in a perfect world?

Use

This stage in the life cycle of small scale fabrication spaces is about the experiences and practices of makers and other actors when using small scale fabrication spaces.

Stage 4: Use



47. When you imagine what the "Use" stage looks like for small scale fabricaiton spaces, what activities come to mind?

48. What actors or stakeholders would be involved in these activities?

49. What do you think are the most important decisions that actors and stakeholders make during this life cycle stage?

50. Based on your previous responses, how environmentally sustainable are the activities that are practiced at this life cycle stage?

Mark only one oval.

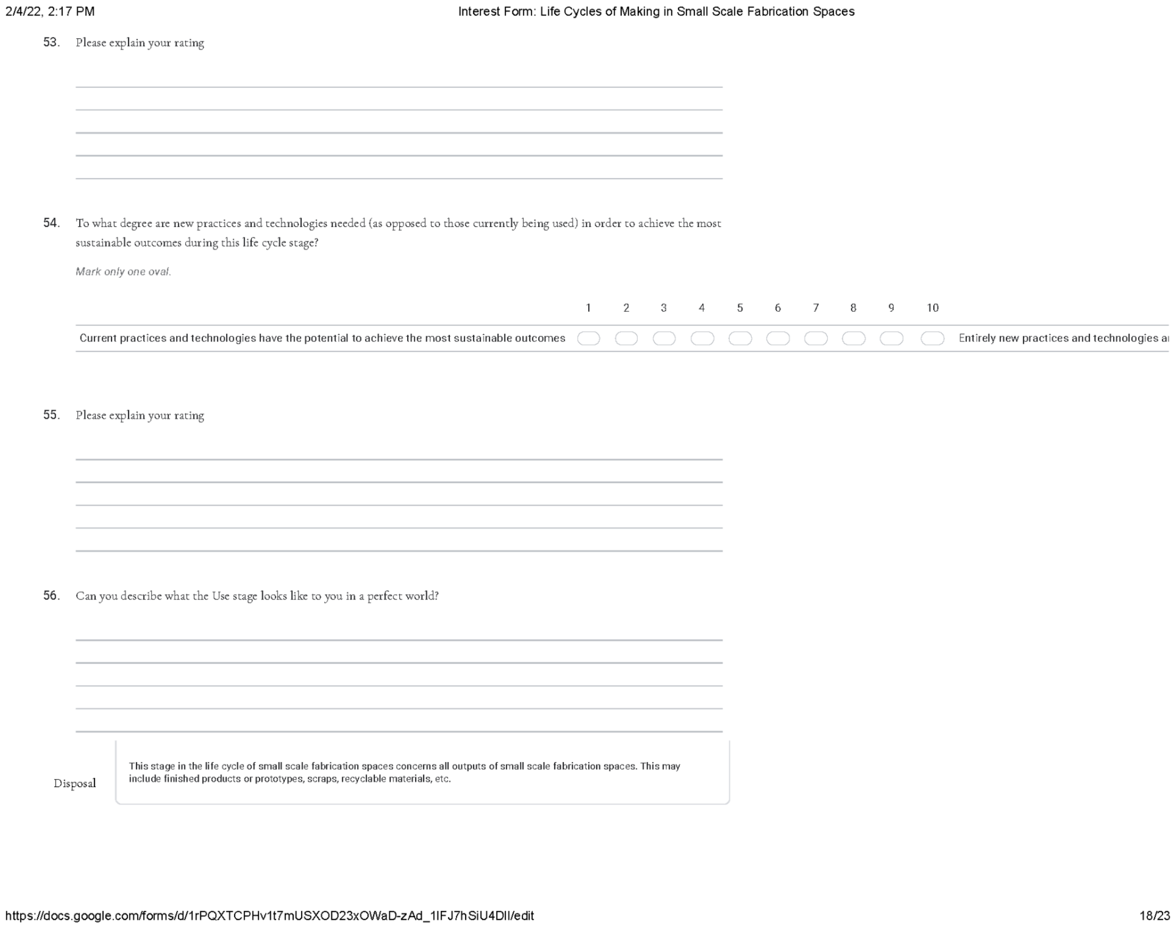
	1	2	3	4	5	6	7	8	9	10	
Extremely unsustainable	○	○	○	○	○	○	○	○	○	○	Extremely sustainable

51. Please explain your rating

52. How difficult would it be to introduce more effective environmentally sustainable practices at this life cycle stage

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not difficult at all	○	○	○	○	○	○	○	○	○	○	Extremely difficult



2/4/22, 2:17 PM Interest Form: Life Cycles of Making in Small Scale Fabrication Spaces

53. Please explain your rating

54. To what degree are new practices and technologies needed (as opposed to those currently being used) in order to achieve the most sustainable outcomes during this life cycle stage?

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Current practices and technologies have the potential to achieve the most sustainable outcomes	○	○	○	○	○	○	○	○	○	○	Entirely new practices and technologies a

55. Please explain your rating

56. Can you describe what the Use stage looks like to you in a perfect world?

Disposal

This stage in the life cycle of small scale fabrication spaces concerns all outputs of small scale fabrication spaces. This may include finished products or prototypes, scraps, recyclable materials, etc.

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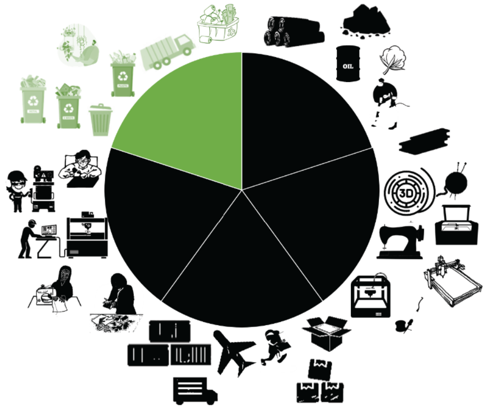
Stage 5: Disposal



57. When you imagine what Disposal looks like for small scale fabricaiton spaces, what activities come to mind?

58. What actors or stakeholders would be involved in these activities?

59. What do you think are the most important decisions that actors and stakeholders make during this life cycle stage?

60. What kinds of activities do you think are involved in the Disposal stage of small scale fabrication spaces?

61. Based on your previous responses, how environmentally sustainable are the activities that are practiced at this life cycle stage?

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Extremely unsustainable	○	○	○	○	○	○	○	○	○	○	Extremely sustainable

62. Please explain your rating

63. How difficult would it be to introduce more effective environmentally sustainable practices at this life cycle stage

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not difficult at all	○	○	○	○	○	○	○	○	○	○	Extremely difficult

64. Please explain your rating

65. To what degree are new practices and technologies needed (as opposed to those currently being used) in order to achieve the most sustainable outcomes during this life cycle stage?

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Current practices and technologies have the potential to achieve the most sustainable outcomes	○	○	○	○	○	○	○	○	○	○	Entirely new practices and technologies ar

66. Please explain your rating

67. Can you describe what the Disposal stage looks like to you in a perfect world?

Final Thoughts

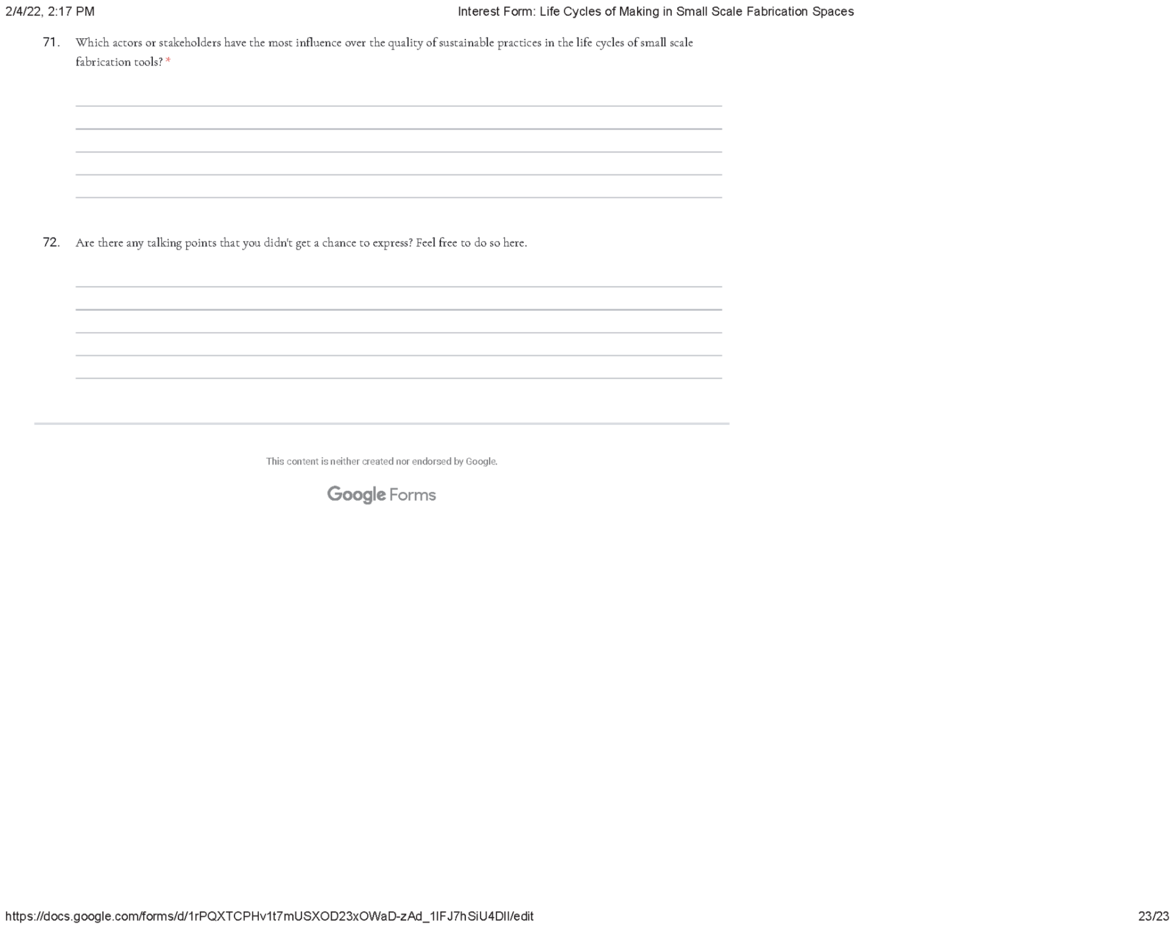
68. Overall, how would you rate the sustainable practices of the small scale fabrication space life cycles (including all stages)?

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Achieving lowest potential outcomes for environmental sustainability	○	○	○	○	○	○	○	○	○	○	Achieving highest potential outcomes for environmental sustainabilit

69. Please explain your rating

70. Thinking about the entire life cycle for small scale fabrication spaces, what sticks out to you as the most important factors concerning environmental sustainability? *



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71. Which actors or stakeholders have the most influence over the quality of sustainable practices in the life cycles of small scale fabrication tools? *

72. Are there any talking points that you didn't get a chance to express? Feel free to do so here.

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9 Appendix C

Semi Structured Interview Guide

Part 0. Introduction

I appreciate you taking the time for an interview. Before we begin, I would like to preface the conversation with some details about the scope of this work and assumptions that we are making in our approach. We are studying small scale fabrication spaces that primarily create tangible products and use digital fabrication tools. This includes, but is not limited to, makerspaces, FabLabs, Techshops, and hackerspaces. The key goals of this work are summarized below:

- ❖ Gaining insight into the full Product Life Cycle of small scale fabrication spaces. The stages of the product life cycle include Raw Material Extraction, Processing and Manufacturing, Distribution and Transportation, Use, and Disposal.

- ❖ Identifying the types of actors that are most likely to provide reliable information about each life cycle stage for small scale fabrication spaces

Part I. Establishing Interviewee Affiliations with Small Scale Fabrication Spaces

- Would you mind sharing your affiliation to small scale fabrication settings?
    - What kind of role(s) have you played in these spaces?
    - How long have you worked in small scale fabrication settings?
    - What part of the small scale fabrication experience would you consider to be most familiar to you? (what's your expertise or area you feel most comfortable talking about?)
- Which of the following priorities BEST describes the type of small scale fabrication space(s) that you've been involved with the most? (we understand that some spaces may have aspects of all three; however, we'd like to get an idea of which of these priorities seemed to be the most characteristic of the spaces that you've interacted with.)

    - Educational and Concept Design

    - Design and Initial Prototyping

    - Final Prototyping and Production

- Similarly, how would you describe the source of motivation for the makers that frequent your space?

    - Makers exploring their creativity through fabrication (focused on enjoying the experience rather than the actual product)

    - Makers that wish to further develop their technical skills (focused on getting better at using fabrication tools and equipment)

  - Makers with entrepreneurial aspirations through fabrication (focused on a creating a product that could go to market
- If applicable, feel free to share an explanation to your response.

Part II. Life Cycle of Making in Small Scale Fabrication Spaces

Raw Materials & Inputs

  - Who would be the best person to contact about the decision making process of purchasing the ***initial*** equipment and tools for your fabrication space? How about for materials required for operating the space? How about purchasing additional equipment and tools?

  - Are you familiar with where your fabrication spaces have received materials? If so, could you estimate the breakdown of where the materials came from? (local [city], regional [state], national [country], global [international])
    - Can you think of a time when you or your colleagues had to make a decision about where to get materials for your space? If so, could you describe how your team navigated this?

  - Could you list the key types of materials that your makerspace ordered on a regular basis? (Preferably in order of highest volume).

  - What kinds of equipment has your fabrication space purchased? (Was it inherited? Was it purchased locally, regionally, nationally, etc…?)

  - Do you know or remember what your team used as a resource for identifying which kinds of equipment to purchase?

  - Can you think of what sustainable practices look like during the Raw Materials & Inputs stage of small scale fabrication spaces? How about unsustainable practices?

Processing & Manufacturing

  - Can you think of any special processes that these materials needed to go through before they were readily usable by your fabrication space users? (For example, wood being cut to specific sizes to fit equipment specifications of laser cutters and CNC mills).

  - How about special processes that your team had to perform in-house before the materials were readily available by the fabrication space users?

    - Were there any routines or procedures that you thought were really innovative that your team implemented?

- Could you describe one of the most difficult procedures related to preparing the materials for use?

- Can you think of what sustainable practices look like during the Processing & Manufacturing stage of small scale fabrication spaces? How about unsustainable practices?

Transportation & Distribution

- ○ Where did your fabrication space primarily purchase materials from? (local, regional, national, international). Why?

- ○ How often were purchase orders made? Why?

- ○ Who in your fabrication space was in charge of this decision making process?

- ○ What factors do you think influenced the decision making the most?

- ○ Can you think of any scenario(s) when your team, or person in charge of material orders, had to make a critical decision about purchase orders? How would you describe their decision making process?

- ○ Can you think of what sustainable practices look like during the Transportation & Distribution stage of small scale fabrication spaces? How about unsustainable practices?

Use

- ○ How did (or do) users in your space interact with the materials in your space?

- ○ Can you offer a detailed example of how a user might interact in your space -- from start to finish?

- ○ What types of materials were most commonly used by members or makers in your space?

- ○ What kinds of tools and equipment does your space use? Could you rank how often these tools are used from most to least?

- ○ How are materials disposed of in your small scale fabrication spaces?

    - What are the most significant sources of material waste in your makerspace?

    - Could you describe a typical maker's decision making process as they decide what to do next with the materials that they have used for their work?

    - Can you think of what sustainable practices look like during the Use stage of small scale fabrication spaces? How about unsustainable practices?

Disposal

- Could you list all the things that come to mind when you think about the outputs of fabrication spaces that you've been a part of. (This could include actual products/prototypes, by products of equipment, equipment disposal, etc.)

- What would you consider to be the most significant kinds of waste that were present in the fabrication spaces that you are or have been affiliated with? (i.e. material waste, end of life for equipment.)
- How often is equipment upcycled? If so, what's the decision making process for this like?

- How are materials disposed of in your small scale fabrication spaces? Could you list all the different ways?

- What are the most significant sources of material waste in your makerspace?

- Could you describe a typical maker's decision making process as they decide what to do next with the materials that they have used for their work?

- Can you think of what sustainable practices look like during the Disposal stage of small scale fabrication spaces? How about unsustainable practices?

<u>Part III. Reflection & Wrap Up</u>

- Based on the questions that we navigated through, which of the 5 stages of the fabrication space life cycle do you feel most confident speaking about? Could you rank them from most confident to least?

- Which of the life cycle stages of small scale fabrication spaces would you say is most influential over minimizing (or maximizing) overall environmental impact?

- What activities across the entire life cycle are most critical to achieving the most sustainable practices (minimizing environmental impact)?
- Which decision makers have the most influence over the environmental impacts of small scale fabrication spaces?

- Would you like to revisit any questions or talking points from earlier in our discussion?
- Do you have any questions for me?