

**Student Team Decision-Making Processes and Assessment Criteria  
in Early Stage Engineering Design**

by

Amy Q. Fang

Submitted to the  
Department of Mechanical Engineering  
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

May 2020

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## **Abstract**

**Background:** Lab meetings are observed at the beginning and the middle of a senior product design capstone course for mechanical engineering students.

**Purpose:** This paper seeks to understand how social team decision-making processes and assessment criteria affect the quality and process of group coherence and communication for mechanical engineering students

**Design and Method:** Audio and video meeting recordings with written transcripts, mid-term product milestone evaluations, and course materials are analyzed through qualitative observation and thematic analysis. Pivotal moments and key differences between teams and within the same teams over time are noted in relation to the ideation and decision-making process.

**Results:** Emerging themes that affect decision-making are compared across teams and lab meetings, and influential teamwork dynamics and assessment criteria are qualitatively noted as well.

**Conclusions:** Novice student designers are solution-oriented in prioritizing technical feasibility and product details in selecting product design ideas. Across teams, they vary in levels of acceptance of undefined key terms in navigating ill-defined design problems. In the context of design education, class materials and instructor feedback play an influential role in shaping team meetings, discussions, and assessment criteria.

Thesis Supervisor: Maria Yang

Title: Professor of Mechanical Engineering

**A special thank you to Antti Surma-aho and Prof. Maria Yang for the mentorship and guidance in supervising my thesis. Additional thanks to the MIT Department of Mechanical Engineering for an excellent education and incredibly rewarding senior capstone project experience.**

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# **Student Team Decision-Making Processes and Assessment Criteria in Early Stage Engineering Design**

## **1. Introduction: Exploring Influences on Design Idea Selection**

Factors that influence idea selection in early stage product design are innumerable, vast, and interdependently complex. From an idea-oriented perspective, these factors can span across the ‘what’, ‘how’, and ‘why’ of how ideas are selected. For example, how an idea is represented, such as through varying levels of fidelity in hand sketches or computer models, influence ‘what’ ideas are selected (Häggman et al., 2015), team-based structured engineering methods, like Pugh charts (Pugh, 1991) or ranked House of Quality charts (Akao, 1990), influence ‘how’ ideas are selected, and internal assessment criteria, such as the varying personal interpretations of what picking the “best” idea entails (Rietzschel, Nistad, & Stroebe, 2010), influence ‘why’ ideas are selected. An additional example includes how ideas selected with an elimination strategy differ from when those same ideas are selected with a direct selection strategy (Cross and Clayburn Cross, 1998).

Alternatively, from a human-centered perspective, evaluating idea quality can also be influenced by how people experience the context in which an idea is selected, through factors like group leadership dynamics, decision-making methodology, personal satisfaction, and perceived productivity and timeliness of the process. The key here is that people evaluate experiences and events through a personal lens, and individual perceptions of reality often do not perfectly align with actual reality (Yang, 2010). Additionally, a person’s level of experience, and in this discussion, people such as novice student designers and expert designers, affects how one will approach design thinking in the idea generation phase. While novices tend to be more solution-oriented and practice internal problem decomposition with top-down control strategies, experts are more problem-oriented, draw upon previous relevant experiences, and utilize external problem decomposition techniques (Liikkanen and Perttula, 2009).

There are numerous factors to consider and account for when analyzing design idea selection. This paper focuses on two factors in particular: how novice student designers engage in team decision-making processes as understood through structured engineering methods and group social dynamics, and how they internally prioritize and later externally communicate the assessment criteria that shape their idea opinions and decisions. Examining the synthesis of these two factors, as in how they may understandings can highlight amateur misconceptions of the design process. Especially in engineering classes that intend to emulate professional product design practices, analyzing these situations is invaluable for evaluating and improving college-level design education, and also how students generally work together in collaborative team settings. Three skills that characterize great working teams are technical skills, interpersonal skills, and decision-making skills (Katzenbach and Smith, 1993). In turn, a high quality design curriculum should not only be responsible for teaching design principles and domain-specific knowledge, but also broader skill sets of communication, teamwork, empathy, and decision-making.

Understanding how students as novice designers navigate the complex processes of product design and large team dynamics can give insights into improving design education. Specifically, the unprecedented value of this work lies in the access to an extensive dataset of real-time student work that correctly and directly represents how novice student designers solve problems. In comparison, experimental and controlled settings can isolate influencing factors, and results can only suggest without absolute certainty how students will truly behave in real life, where unstaged dilemmas have greater stakes and nuanced complexity. Just like in real world design situations, the variety and synthesis of many factors influences the ideation and selection process. As a result, research that evaluates multiple co-influential design factors as an inseparable whole, rather than as segmented, separable pieces, is crucial in emulating and revealing deeper insights into real world practices.

## **1.1 Background on Team Decision-Making Processes**

As mentioned earlier, external and internal forces shape idea understanding and idea selection, and team decision-making processes are ultimately social forces that can be interpreted as external influencers. This can be seen in research that has proven that idea selection differs when decided by multiple people as opposed to an individual leader in group settings, or how the difference between single leader versus group consensus decision-making processes influence idea perception and satisfaction (Yang, 2010).

Not only are explicit leadership dynamics important, like the number of people running a meeting or who is in charge, but other critical tools that give meetings structure are also important, like structured engineering methods and Pugh charts. How people incorporate these methods, and subsequently how these methods influence idea selection through decision-making, is critical in the design process.

How verbal interactions affect team collaborative learning has also not been thoroughly explored in current engineering education teamwork research (Purzer, 2011). However, the quality of verbal interactions, as well as the use of leadership styles and structured design methods, critically impacts effective team collaborative learning. For example, a structured engineering method like Pugh charts is not only useful to order visual organization and verbalize explicit design rationale, but has also proven to be instrumental in establishing shared team understanding through discussion (Bucciarelli, 1994). How time is spent in a meeting is a powerful way of visualizing and understanding what aspects of decision-making are emphasized. This can differentiate problem-oriented and solution-oriented discussions, and be optimized to encourage processes that lead to the best-informed group decisions.

It is also possible that student teams may interact in ways that are not productive or learning-oriented. Through a qualitative observational study of two senior engineering capstone design teams, Kittleson and Southerland (2004) found that “both teams used the cooperation approach (i.e., divide-and-conquer) rather than employing collaborative learning approaches. While students’ strategies mirrored a workplace environment, matching the expertise of the students with a given task, their approach did not promote co-construction of new learning” (Purzer, 2011). In this paper, understanding team decision-making processes, like team leadership styles and structured engineering methods, that student design teams utilize to co-construct, can be directly linked to the effectiveness of group efforts, new learning, and high quality communication.

## **1.2. Background on Assessment Criteria**

Separate from social team factors is the valuation of assessment criteria, which are inherently internal factors that are only revealed when they are voiced and expressed to a larger team. This is useful in establishing mental continuity, to confirm that everyone is on the same page. People have different priorities in what makes ideas high quality and “good”, which is often already an ambiguous and not explicitly defined term. Rietzschel, Nistad, & Stroebe (2010) have shown that people tend to prioritize the selection criteria of feasibility and desirability over creativity and originality when tasked to pick the “best” idea out of a pool of brainstormed ideas. In fact, studies have found that people are very poor at recognizing creative ideas (Faure, 2004; Putman & Paulus, in press; Rietzschel, Nijstad, & Stroebe, 2006) and despite even the use of structured engineering design methods, simplifying strategies like pre-choice screening (Beach, 1993) to reduce cognitive complexity may cloud clear judgement (Rietzschel, Nistad, & Stroebe, 2010). Thus, communication is crucial in establishing a team well-aware of peer ways of thinking. In other words, external forces like team decision-making processes need to be internalized, while internal forces like assessment criteria need to be externalized. This optimal situation allows mentally aligned teams to make efficient and high quality idea selection and product decisions. Understanding how assessment criteria change as product problems become more well-defined over time is an additional axis of relevance.

In the circumstance of design engineering education, students do not operate in completely self-reliant or autonomous environments, and are often influenced and guided by authority figures and guidelines. Voices of authority can take the form of advice from mentor instructors or even assignment objectives that require students to follow and prioritize certain guidelines. This structure of teaching can be rigid and form-fitting, and create an influential environment in which assessment criteria are created, and where team leadership dynamics and engineering methods are utilized. Relevant to this study is how the implication of a design education environment nudges and encourages certain behaviors to be adopted and prioritized in student teams and meeting sessions.

## **2. Design and Methodology: Student Teams in Early Stage Engineering Design**

The two focus areas of this paper are collaborative team decision-making processes and assessment criteria. Each of these themes plays a role in the functioning of student engineering design teams, and have been previously studied to varying degrees in design education literature.

Examining the design process rather than the final outcome of student teams is more accurate in assessing what students learn over time throughout a design course. This dataset gives unique insight to the intermediate progress of student design teams through multiple rounds of design “milestone” presentations and weekly recorded lab meetings. Due to the nature of design and product development, assessing the progress and process of student design teams is usually difficult to gauge in terms of cognitive understanding and learning (Agogino, Shuang, & Hey, 2006).

## 2.1. Research Questions

In the most general sense, what this paper aims to understand is how student teams are making decisions in early stage engineering design during a project capstone course, and more specifically, how social team decision-making processes, like self-determined meeting agendas and structured engineering methods, and assessment criteria, affect design outcomes. In this specific capstone project class, students receive peer, team, and instructor feedback after each of six design “milestones”, as well as periodically throughout the semester. This feedback framework allows students to grow within and be guided by design education principles, without straying from achieving curriculum goals. This particular way of how the course is set up also creates a powerful opportunity for analyzing and studying effective design education methods, understanding how people grow and change throughout a course rather than just appreciating the end product. The proper education of product design is ultimately process-oriented.

Thus, this paper examines the following research questions to further improve upon the methodologies of design education:

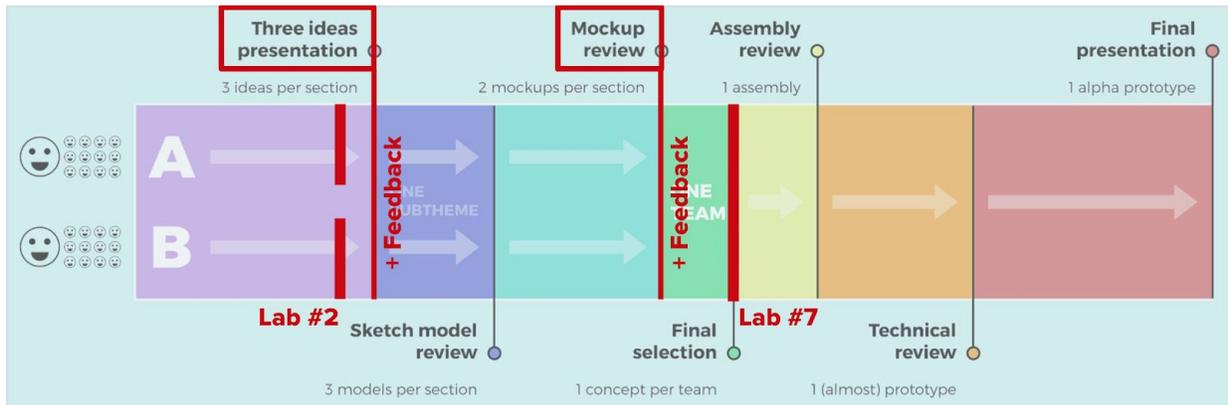
1. What assessment criteria do students prioritize in product decision-making processes, and does this change over time, depending on the stage of development?
2. What forms of social decision-making processes and structured design methods do students engage in during team meetings, and how is meeting time planned and spent to accommodate these processes?
3. How do qualitatively observed differences, especially in assessment criteria and social decision-making processes, between student teams affect design approaches and outcomes?

Access to lab meeting videos, design “milestone” presentation videos, accompanying instructor feedback, and class materials provides multiple avenues of analysis of mechanical engineering student design teams over time. Compared to results from standard, short-term structured experiments where participants may feel less personal obligation, this case study is more representative of how novice designers truly behave. In fact, there is no direct manipulation or topical engagement involved that would affect course experiences when this data was collected from lab meetings. “We know very little about how teamwork supports student learning”, but by observing social team decision-making processes and assessment criteria across different lab meetings, we can see how teams think, learn, and evolve over time (Purzer, 2011).

## 2.2. Background on Engineering Capstone

This paper studies students in a mechanical engineering capstone project class focused on product design. Large teams of 15-20 senior undergraduates develop a high quality functioning alpha prototype of a novel product by going through stages of the product development process: identifying opportunities, brainstorming and selecting ideas, iterating on sketch models and mockups, incorporating user and instructor feedback, and finally, constructing and presenting a fully-functional alpha prototype. The course is designed to emulate professional practices, so students not only learn about product design, but also role management, group communication, and effective team dynamics.

## 2.2.1. Engineering Capstone Course Timeline



**Figure 1. Annotated Engineering Capstone Project Workflow (MIT Mechanical Engineering 2020)**

As seen in Figure 1, for the first half of a 14 week-long semester, two subteams independently go through an extensive ideation process before reconvening as a larger team in the middle of the semester to ultimately deliver a fully functional alpha prototype. With each design milestone, students iteratively generate higher fidelity prototype models to further explore design implementations and better understand the many problem spaces. These insights and learnings help student teams pinpoint design challenges, refine project focuses, and make well-informed decisions when selecting a final idea.

Two pivotal labs that indicate a team’s progress through the ideation and product definition phase of product development are analyzed. Each weekly lab is three hours long, and follows a meeting structure outlined by a lab agenda, which is provided early on by the course staff. Teams must follow lab agendas to complete their objectives, and these agendas often outline strong suggestions of how meetings should be run, and what structured engineering methods should be used to help facilitate decision-making and idea selection processes. As students are expected to follow directions in the design thinking process, strict and detailed lab agendas may inhibit their learning, as they prevent students from independently generating and deciding for themselves important product factors or useful decision-making tools. Going through the design process through a set of rigid instructions is very different from discovering and learning about the design process independently by learning from mistakes. Besides team lab objectives, other student deliverables come in multiple forms of individual homework, team project milestones, and participating in team feedback.

### 2.2.1. Labs and Officer Roles

Labs are mostly self-guided and independently run by students, whose roles are determined at the beginning of the semester through officer positions (see Appendix A), although multiple instructors and mentors are always present to mediate discussion and jump in when necessary. Levels of involvement from instructors and mentors vary from team to team but tend to be mostly hands-off. They are there to provide excellent points of feedback and external experienced knowledge, and help teams move along when they get stuck. The most prominent officer role is the system integrator, who is responsible for creating meeting agendas, leading discussions, and organizing subteams to make sure everyone is on the

same page and on track. They have the most influence in shaping the social atmosphere, and how teams organize and interact during meeting time.

Lab 2 and Lab 7, which are numbered by the week in which they occur, are analyzed in this study, and annotated and condensed lab meeting agendas can be found in Appendix B. In Lab 2, every student is expected to bring several sketched ideas that were generated independently and from small groups. These same ideas are also expected to be backed by initial user research, either from talking to contacts or from observing real life situations. By the end of the lab meeting, three sketches will be selected to be presented for the first project milestone. The ideas are undeveloped and untested, and only exist visually in sketch form, as opposed to physically in prototype form. This is a prime situation of ill-defined problem-solving, where despite many unknown variables, students are expected to narrow down their ideas and come to a consensus through decision-making processes.

Lab 7 is the first time the two subteams combine into a larger team. Each subteam brings two further-developed ideas for a total of four ideas, and the lab objective is to select a final product idea from the four. In the span of the past five weeks, teams have had the opportunity to expand, test, redefine, and research problem opportunity spaces to further develop their products. As seven weeks is exactly halfway through the semester, the large team only has seven more weeks to turn their mockup prototype into a functional, looks-like and works-like, alpha prototype.

### **2.2.3. Data Sources and Analytic Methods**

Two sources of data provide the structure for analysis of two student design teams from this engineering capstone course, as taught in 2018. The first are lab meeting transcripts supplemented by audio and video recordings from two different design phases (Lab #2 and Lab #7), from two different teams. This gives a total of six lab meeting transcripts: Lab #2 Team 1A, Lab #2 Team 1B, Lab #2 Team 2A, Lab #2 Team 2B, Lab #7 Team 1, and Lab #7 Team 2. As outlined in Table 1, the multi-step process of thematic coding was conducted on these transcripts to code assessment criteria for making informed design decisions. In addition, qualitative observations were recorded on social team decision-making processes, including leadership styles, general meeting dynamics, structured design engineering methods, and critical details captured in audio and video recordings but lost in written transcripts. Finally, time stamps were marked to give a high level overview of how meeting time was spent, as influenced by students' level of preparation for the lab meeting, assessment criteria discussion priorities, particular structured design engineering methods, and instructor involvement. Differences between teams and differences within teams over time, in assessment criteria, social team decision-making processes, and meeting timelines, are noted. These observed differences are attributed to differences in design process outcomes, with accompanying potential explanations.

The second data source is class-provided materials, such as officer roles, lab meeting agendas, and milestone objectives, which can be referenced in Appendix A, Appendix B, and Appendix C, respectively. These documents are also analyzed through thematic coding, and cross-referenced with meeting discussions to examine how the structural guidance of design education influences student and team behavior.

**TABLE 1: Steps of Thematic Coding for Lab Meetings**

Step 1. Listening and watching meetings recorded by audio and video
Step 2. Meeting transcription (by services like Rev.com, or by hand)
Step 3. Isolation of segments of interest
Step 4. Identification of general themes (first pass coding)
Step 5. Assigning thematic codes (second pass coding)

### **3. Results: Revealing Team Decision-making Processes and Assessment Criteria**

#### **3.1. Team Decision-making Processes**

Team decision-making processes, as seen through meeting timelines, structured engineering methods, and social influences, varied between teams as well as within teams over time from Lab #2 and Lab #7. Many factors can make positive contributions to team coherence if applied correctly, but these same factors may cause confusion if overused or misconstrued. For example, planned meeting specifications can be beneficial in creating temporal boundaries from conversation tangents and setting team and project expectations, but they can also be detrimental to team efficiency when over planned and executed even if team focus has shifted to different priorities.

One situation that illustrates these inefficiencies occurred during Team 2B's lab meeting, where members first specified that they needed at least 8 ideas to map on a Pugh chart before delving into idea discussions. After an initial round of voting with four sticky notes clearly revealed the majority of interest in the top 7 ideas, a non-insignificant amount of time was dedicated to debating and choosing an 8th option, only for it to be immediately eliminated after Pugh chart scores were tallied up. Focusing on particular specifications like needing 8 ideas on a Pugh chart, without addressing the underlying reasons and motivations for why 8 ideas are necessary, will cause additional time spent on topics that most people are already less interested in anyway. Members of the team may have experienced an anchoring effect of sticking to 8 as a magic number, either because authoritative sources like the lab agenda recommended it (see Appendix B), or because people had already pre-decided that a Pugh chart always needs at least 8 ideas to be effective.

##### **3.1.1. Meeting Timelines**

How do students decide to structure their meetings, and where do they actually spend their meeting time? How much of meetings are planned, and if new information reveals spontaneous changes to an agenda, how are these circumstances taken into account? Figures 2 and 3 below illustrate how lab meetings were logically organized to make decisions. The figures highlight the sequential logic of the meeting flow, but is not spatially accurate in representing the amount of time spent on the specific types

of tasks. This is because categorical importance is not necessarily based on how long a task takes, but rather what information was communicated or expressed through the category’s framework. Table 2 is a color-coded key representing the categories and explanations of different meeting blocks. These meeting block categories were decided on through an iterative process of understanding which category processes are most influential in informing, changing, and bringing together individual understandings and opinions on design ideas.

**Table 2: Color-Coded Categories of Meeting Timelines**

<b>Color Key</b>	<b>Explanation</b>
<b>Instructor</b>	Instructors mediating, guiding, or critiquing student teams.
<b>Pugh Chart</b>	Discussing Pugh chart categories, selecting weights (if applicable), or the process of filling it out as a visual and group decision-making tool.
<b>Preference Voting</b>	Majority voting, people may have different reasons for voting for certain ideas over others, but these differences are not illustrated in voting results
<b>Sharing Information</b>	Presenting newly discovered information to the rest of the team, like usability studies, technical testing, or researching background information.
<b>Logistics</b>	Planning and organizing the team and meeting
<b>Discussion</b>	Open-ended, either to clarify and communicate new information, or to argue perspectives and differing opinions
<b>Decision Checkpoints</b>	Narrowing down and elimination of ideas through multiple rounds, to make final decision-making less complicated and less resource intensive.

Instructors, as respected figures of authority, had power in influencing how meetings were structured. In most circumstances, instructors did not explicitly dictate what ideas to choose or why, but rather how to go about thinking about the design process. At the beginning of Lab #2, where ideas had not yet elaborated on, each instructor reviewed the expectations of the idea sketches assignment in communicating user needs with clarity, originality, and thoughtfulness, but at the same time in being “reasonable” in understanding technical solution constraints and considering the objective impact value of product ideas for people and the environment. Setting the precedent in explaining how idea sketch quality is evaluated can be influential in changing existing interpretations of what makes ideas good, and what qualities should be considered or prioritized over others. It can also be helpful in aligning people on the same datum to recognize consistent and appropriate metrics for evaluating idea quality.

In addition, instructors also helped remind students of the design process from a more informed, expert-minded, and experienced design perspective, such as specifying that the purpose of early stage ideas is to pinpoint user needs and to focus on problems rather than solutions for Team 2A. This affirms previous research that has revealed that novice designers tend to be more solution-oriented before scoping out the entirety of problem spaces, and that expert designers are more problem-oriented in the ideation phase of product design (Cross and Clayburn Cross, 1998). Instructors also played a pivotal role in making sure students filled out a Pugh chart collaboratively as a group rather than individually, which was initially more attractive to students from a timing and efficiency perspective. Instructors reminded Team 2B that the ultimate purpose of a Pugh chart is to be a discussion tool that sparks conversations and addresses contrasting perspectives, and that the means of filling out a Pugh chart is actually much more productive than the ends of having weighted and scored points across categories (Bucciarelli, 1994).

One final example of the important role of instructors is in establishing new structured engineering methods to utilize when making large scale decisions. In Lab #7 Team 2, when team members were extremely split between two product ideas, an instructor proposed the spectrum voting method over a second round of voting on a Google Form. The spectrum voting method, optimal for spaces that have enough room for people to move around and see everyone else, involves students physically standing in locations along a metaphorical scale with two ends to represent the strength of their opinion between two options. The spectrum voting method allowed every team member to voice their concerns, preferences, and beliefs between the two options, which is an additional layer of personal complexity and knowledge learning that is not accessible through other preference voting methods like Google Forms.

Lab #2 Team 1A	Lab #2 Team 1B
Instructor comments on idea sketch quality: wants user needs, technical solution, clarity, and thoroughness	Instructor comments on idea sketch quality: wants clarity, originality, thoughtfulness but also reasonableness addressing user needs, environment, and value
Organizing officer roles and agenda note taking	Organizing announcements, storage tools, and setting team common practices
Each task force has 10 min, 3 themed task forces present 16 total ideas	In 25 min, 2 task forces present 13 total ideas.
Idea 13: Clarifying usability	Selecting 5 Weighted Pugh Chart categories.
First-round voting with 3 sticky notes each, clarifying Idea 6 use case and Idea 7 product definition	First-round voting with 4 sticky notes each
Narrow down to 7 Ideas for Pugh Chart: Ideas 4, 6, 7, 9, 12, 13, and 16.	Discuss popularity of Ideas 1, 8, and 9. Eliminate Idea 3, a product detail from Idea 1, and remaining 0-1 vote ideas. Narrow down to 8 ideas for Pugh: Ideas 1, 2, 7, 8, 9, 11, 12, 13.
Selecting 7 Pugh Chart categories	Picking a baseline: Idea 7, which "has the need, has the potential, is feasible".
Picking a baseline: A doable product idea where you can think "oh we we could totally make this" and have the clearest idea of what it is.	Discuss and fill out Pugh Chart together. Weighted scores are +4 for Ideas 8 and 12, +1 for Idea 3, -2 for Ideas 1 and 11, -3 for Idea 2 and -5 for Idea 9.
Discuss and fill out Pugh Chart together.	Idea 13: Clarifying product definition
Second-round voting with 3 sticky notes, non-binding to see where everyone is at.	Questioning the validity of weighted scoring, which should be used as a guide for conversation facilitation.
Idea 4: Clarifying users	Idea 9: Addressing unknown use case, customer needs, market potential, and legality
Idea 16: Clarifying use case and product details	Idea 7: Clarify use case and novelty
From second-round voting, final selection is Ideas 6, 13, and 16.	Idea 9: Clarify product definition and novelty differentiation
Organizing for upcoming project milestone	Idea 1: Discuss technical details
	Idea 11: Discuss problem-solving ineffectiveness and potential danger
	Idea 12: Discuss use case, novelty differentiation, and background information
	Voting with one vote between Ideas 1, 9, and 12, and Idea 1 wins. Final selection is Ideas 7, 8, and 1.
	Organizing for upcoming project milestone

Figure 2 ab: Color-coded Meeting Timelines of a) Team 1A and b) Team 1B

Lab #2 Team 2A
Roundtable discussion of 11 unique user research observation locations. Team B had new ideas with sketches, while Team A observed locations and took notes.
4 themed task forces have 45 sec strict time limit each to present 14 total ideas.
Instructor comments that the purpose of early stage ideas is to pinpoint user needs
Idea 5: Clarify background information and existing products.
First-round voting with 5 sticky notes and double votes allowed.
Eliminate 5 ideas, keep Idea 6 because of importance of the problem as a social issue, rather than the solution. Narrow down to 8 ideas for Pugh: Ideas 6, 7, 8, 9, 10, 11, 12, 13.
Recognize there are known uncertainties, Selecting 6 Pugh Chart categories.
Discuss and fill out Pugh Chart together. Idea 7 is first selection choice.
Second-round voting with unlimited votes for personal interest for Ideas 6, 9, 11, 12, and 13. Idea 6 and 11 are eliminated.
Third-round voting with two votes for Ideas 9, 12, and 13. Ideas 9 and 13 are selected. Final selection is Ideas 7, 9, and 13.
Organizing for upcoming project milestone

Lab #2 Team 2B
Organizing meeting expectations, officer roles, and individual presentations.
Individuals get 40 sec each to present 21 total ideas backed by observation insights.
First-round voting with 4 sticky notes clearly reveals top 7 ideas, expressed interest for Idea 21 to be included in top 8.
Idea 19: Eliminated because the product already exists, there is no novelty.
Idea 11: Clarifying product detail and use case.
Idea 20: Concerns of technical feasibility in current product definition.
Second-round voting with one vote between Ideas 11, 20, and 21, Idea 21 is selected. 8 Pugh concepts are Ideas 2, 3, 5, 8, 13, 15, 16, 21.
Selecting 6 Pugh Chart categories.
Instructor reminds that Pugh is a discussion tool not to be filled out individually, as the team is deciding on an efficient approach.
Picking a baseline: Idea 20, because "I'm arbitrarily deciding that this one is the baseline."
Discuss and fill out Pugh Chart together, eliminate Ideas 2, 3, and 21 immediately.
Idea 5: Address difficulty of product details and potentially dangerous use case.
Idea 13: Eliminate because pointless and has no real impact.
Idea 5: Discuss potential technical feasibility and ease of use issues.
Idea 5 and 15: Both extremely difficult or nearly impossible to test.
Third-round voting with one vote between Ideas 5 and 8, Idea 5 is selected, Idea 8 is a backup.
Idea 15: Clarify product details.
Organizing for upcoming project milestone

Figure 2 cd: Color-coded Meeting Timelines of c) Team 2A and d) Team 2B

### 3.1.2. Ill-Defined Problems in Early Stage Ideation

A single, well-regarded approach to idea selection in early stage engineering design is nearly impossible to define. In deciding on a direction to pursue during the ideation phase, the inherent and perennial issue of decision-making is precisely how undefined the problems and the proposed solutions are. As seen in Figure 2, all sub teams navigate this exact problem, and must decide on appropriate trade offs to make, while also acknowledging the existence of multiple acceptable problems and multiple acceptable solutions within a single problem that can be pursued further.

Several approaches were taken to simplify and clarify the ambiguity present in navigating ill-defined problems, and some were more successful than others. These approaches involved hypothesizing user needs for a novel product and changing market directions, estimating and quantifying market sizes, solution-oriented pricing predictions, and delaying making decisions by acknowledging the lack of adequate information. In brainstorming product ideas, the criteria of market impact and novelty was heavily emphasized, and discussing an idea's potential advantages involved pointing out holes in the

market and predicting how markets are shifting to accommodate innovation and changes in society. Most of these claims in ill-defined problem-solving were purely assumptions and not facts, although they were treated as seriously as other claims that were backed up by some form of research. However, the validity of this research also can not be attested to, as they came from various sources, such as the internet or talking to potential users, and were expressed in varying levels of detail. Some highlighted examples of market predictions and existing product assumptions are as follows:

**“Some technology exists, people aren't using it for a reason.  
So it probably just gets annoying.” -Team 1B**

[In attempting to understand existing products that feature similar technology as a proposed solution, this team member quickly assumes the problem lies in its usability being “annoying” rather than contemplating a variety of alternative reasons or acknowledging a lack of information.]

**“I don't know how popular they are... I don't think if it's going to be this  
technology or another one, but I do think that the market is moving towards that.” -Team 1A**

[This individual goes to the gym, which may or may not give them the authority of correctly predicting where the gym equipment market is heading. However, by saying “I think”, they are acknowledging their opinion, although by the strength of their opinion, they say so in a convincing way.]

Another ambiguous comparison metric utilized to compare market impact across different product ideas is comparing the size of the markets. This can be seen as being assumptuous in several ways. First, even if the correct market and customer audience was pinpointed, the market size and the success of a product can not be seen as linked or comparable, as this assumes that everyone in the market would be equally interested in a product. Several students' arguments for or against a product would involve pointing out the product category's market size, but these two concepts are not interchangeable or necessarily related at all either. Just because more people exist who could potentially be users does not mean that one product is more worthy of pursuing, and these estimations of the user market are equally opinionated and assumed, not factual.

**“There are more people in wheelchairs than there are in construction I think.  
That's probably true. I don't know.” -Team 1B**

**“They have much more bikers than baseball [players].” -Team 2A**

**“More people ride bikes than have children? I don't know.” “I don't think that's true.  
Children ride bikes. People who ride bikes may have children too.” -Team 2A**

**“I don't think it's bigger than bikes because all these [elderly] people will have  
ridden a bike at one point in their life.” -Team 2A**

[As a Pugh chart metric, these statements should not make a product idea more or less attractive, as it assumes that if more people exist in a market, that is the same as more people also desiring the product.]

**“Well, I think people in a wheelchair want this more than construction workers want this.  
The market potential is like the size of the market.” -Team 1B**

**“I think this goes back to like I think hobbyists would like this more than construction workers  
would like that, but the markets might be different sizes.” -Team 1B**

[These statements acknowledge the difference between market size and user need, but still assume the needs of potential users without addressing why. These beliefs become valid arguments because of limited currently-accessible information, and a lack of stronger reasoning from other team members to disprove them otherwise.]

The following additional statements address multiple aspects of valuing products, from being intensely solution-oriented by confirming product detail and definition conceptions, conveying aspects of personal preference through storytelling, and most importantly, acknowledging a lack of adequate decision-making information during the ideation stage. The key points to keep in mind during this stage is to remain problem-oriented and not extremely solution-oriented, as the underlying mechanisms and functionalities of product ideas can often be reconfigured and applicable to additional, unrelated markets, and product ideas are guaranteed to evolve and change over time as new information is introduced, but existing problem spaces and user needs will not change. There is a difference between uncovering existing information and being problem-oriented, like conducting background research of existing problem spaces and discovering user needs and current practices, and creating new information and being solution-oriented, like brainstorming and conceiving of new product details, features, form factors, and appearances. The latter can not function effectively without the former, and it is also easier to change the latter later. Exploring, understanding, and setting up a specific problem is the foundation for discovering an optimal solution, so it is critical to not get too invested in specific product details so early on.

**“I don’t know how well that \$80 [existing product competitor] sells, but, I mean,  
I would like to have this in my kitchen, I don't know.” -Team 1B**

[Being one’s own customer can be convincing for creating a product that other people would want or find useful. ]

**“I think that [market] size, if we go super niche luxury, we would be effectively making the  
same money as a very commonplace cheap thing, but both of those are big markets.” -Team 1B**

[Specifying a products’ customers within a particular market, like differentiating between luxury and cheapness, is too solution-oriented if the user need for the product is not Identified and confirmed first. Also, this individual seems to equate user need and attractiveness with how much money the product can make, but these are different concepts. ]

**“But the rest of this week you're gonna be looking into the ones that you've chosen to learn more  
about them, how many people would be interested with the market size, and so on, and so on. When  
you do that, you may discover that one of them isn't such a good idea.” -Team2A**

[There is a difference between believing that one knows the unknowns, and knowing that one does not know the unknowns. Further exploring ill-defined problems was also mentioned to varying degrees in other lab meetings and teams as well.]

In navigating ill-defined problems, the incorrect way of solving them is being satisfied with and making decisions based on the existing information at hand. In fact, properly solving ill-defined problems ultimately involves making them more well-defined, because new information and insights can often raise additional concerns, create more complexity, and refute and redefine earlier assumptions. Some assessment criteria require objective research and analysis, while others can be supplemented with personal opinions and reasonable assumptions. For example, assumptions surrounding technical feasibility are more knowledgeable and appropriate than those of market impact and business potential, because students have experience and an educational background in mechanical engineering, and are often aware of their technical capabilities. However, focusing too much on this is also detrimental as a product's technical details and feasibility can only be properly evaluated once the problem focus, user need, and product definition are confirmed and defined.

These limitations of ill-defined problems are constrained only to the very initial phases of product design, as ideas inevitably become more clear and defined over time. Thus, the process of navigating ill-defined problems is much more constrained and applicable to Lab #2 discussions, as seen in Figure 2 above, and less relevant in Lab #7 discussions, as seen in Figure 3 below. By the time students meet in Lab #7, they have had five weeks to further research user needs, test and remake prototypes, and develop technical mechanisms.

Lab #7 Team 1	Lab #7 Team 2
Summarize goals, rules, and prepared agenda.	Summarize pros, cons, and project milestone feedback from each of 4 subteams.
Summarize pros, cons, feedback, and information from each of 4 subteams.	Roundtable discussion of personal values and what individuals want out of the course.
Picking a baseline: Previous course capstone project.	First-round voting with Google Form voting ranking the four ideas. First-rank votes are 14 for Idea 1, 5 for Idea 2, 3 for Idea 3, and 0 for Idea 4.
Fill out Pugh charts individually, Selecting 7 Pugh Chart categories.	Idea 4: Eliminated because it received 0 first-rank votes.
For each category idea, everyone discusses and agrees on each group vote on the Pugh chart (+,-,0).	Idea 3: People who ranked it first discuss why
With weighted category values, immediately eliminate Ideas 3 and 4 because they have the lowest scores. Idea 1= 3.8, Idea 2= -0.93, Idea 3= -1.04, Idea 4= -4.74	Idea 3: Eliminated
Idea 1: Discuss technical challenges and unknown use cases	Ideas 1 and 2: Unstructured discussion of pros and cons. From first-round of Google Form, the ranked votes were for Idea 1: 14, 5, 3, 0 and for Idea 2: 7, 14, 2, 1.
Idea 2: Eliminated Idea 1: Final product	Suggested second-round voting on Google Form.
	Instructor suggests Spectrum Voting to measure the strength of peoples' feelings
	Roundtable discussion of what individuals think of each idea
	Third-round voting with one vote: Idea 1: 17, Idea 2: 1, Abstain: 4. 85% quorum (18 people) reached because abstains count for the majority. Idea 1: Final Product

**Figure 3ab: Color-coded Meeting Timelines of a) Team 1 and b) Team 2**

### **3.1.3. Structured Engineering Methods**

Three primary structured engineering methods utilized during these lab meetings were preference voting, multiple rounds of elimination decisions, and Pugh charts. Each method has its advantages and disadvantages in conceptually aligning team members, improving time efficiency, increasing overall productivity in covering information, and optimizing personal satisfaction.

#### **3.1.3.1. Preference Voting**

This methodology refers to any form of decision-making that involves casting votes and subsequently gauging and then choosing the majority. Towards the beginning of early stage design meetings, preference voting in the form of multiple sticky notes was used to immediately rule out unfavored ideas, and all four sub teams engaged in this initial elimination process with a varying amount of available votes from three to five. Preference voting is a useful tool when there are too many options and not enough cognitive power capable of thinking about all ideas all at once. Preference voting is extremely fast-paced with a quick turnaround speed, but one major issue is that the votes can not and do not speak for themselves. The binary simplicity of a vote does not highlight the complex assessment criteria or formulated mental model of the idea from the voter that went into their decision of selecting for or against the idea. Preference voting is not effective as a standalone tool for highly productive and highly satisfied decision making, and so is often coupled with group discussions of reasoning behind the votes, which can be observed very well in Team 1B and Team 2B. These discussions can often lead to input only from either highly marginalized minority voters or the more outwardly expressive and loudly opinionated voters. In the first circumstance, understanding the opposing perspective is important but does not mean that everyone who had the same vote utilized the same assessment criteria or reasoning for why they voted for the same option. To understand how people are thinking and interpreting these situations, having a greater quantity of input from a greater amount of people is critical, because every voice, assenting and dissenting, comes from a unique background and mental mindset. The second circumstance can also skew and bias others in believing that louder opinions are the more important opinions, or are more prevalent and popular than they actually are. Ensuring that group buy-in is not diminished during preference voting discussions increases team member satisfaction and an objective alignment with a truer reality, how people are actually feeling and what they are actually thinking about.

Since preference voting is such a time efficient tool in quickly gauging idea preferences, they are often used multiple times, from two to even three times throughout a meeting to check-in and get a quick feel for the room, as seen in Team 2A, Team 2B, and Team 2. Voting outcomes vary depending on the number of options to be voted on, as well as the previous expression of information and opinions on the options preceding the vote.

Although internal assessment criteria are not explicitly addressed or revealed through these forms of preference voting, it is almost entirely certain that when people are voting between two ideas, they are prioritizing their personal interest in the idea over the distribution of other qualities such as user need, technical details, or product testability. Thus, preference voting, which unlike Pugh charts, usually does not recognize the existence of multiple factors in influencing what makes an idea “better”, asks voters either to perform such mental gymnastics internally inside their own heads, or force them to simplify their preferences to align with one or two of their most prioritized assessment criteria. I suspect preference

voting, which is ultimately asking voters for their “preference”, is biased towards people voting with the reasoning of their personal opinions and personal preferences, which is not necessarily the best selection criteria for a successful engineering product prototype.

To highlight Team 2B as an example, the assessment criteria of being “cool” is brought up multiple times to supplement and support, but not always successfully, decision-making. The idea of “cool” implies personal interest, but the term is just as vague as the term “best” in deeply understanding the motivations behind why someone may think an idea is “cool”. For example, an idea could be considered “cool” because the idea is novel, challenging, relevant, funny, relatable, or a combination of so many other unknown factors. A personal preference for “cool” is brought up in a variety of circumstances throughout this meeting for Team 2B, and specific examples are listed below in chronological order:

**“I think [Idea 21] is super cool. I think it's super cool but it's super hard. That's why I didn't vote for it.”**

[This individual prioritizes technical feasibility over idea “coolness”, but acknowledges how “coolness” influenced their decision-making process in preference voting. ]

**“But like in this class, we want to make a project that is cool, right? So, maybe we just get rid of this boring, stilted format, and talk about what we really want to do.”**

[This individual dislikes the framework of Pugh charts in addressing multiple assessment criteria for each idea, and seems to believe that the most important criteria for idea selection is making something “cool”.]

**“I think we all agree here that [Idea 21] is pretty cool though. It's very cool.”**

[Although it is eliminated first after completion of the Pugh chart, many people acknowledge how “cool” an idea is, which still makes the idea valuable and noteworthy.]

**“Wait but, [Idea 5] is the coolest one.” “Yeah it's the coolest one.”**

[At least two people are unwilling to part with an idea because it is “cool”, despite the idea’s low Pugh chart scores.]

Not all forms of preference voting are overly simplified or straightforward. An excellent alternative form of informative preference voting occurred during Team 2’s final decision between two product ideas with the spectrum voting method. As mentioned earlier, the spectrum voting method not only communicated everyone’s preference, but also the strength of their preference and an explanation of why they felt that way. This structured engineering method provided great clarity, detail, and alignment for the entire team.

### **3.1.3.2. Multiple Round Elimination Decisions**

Performing multiple rounds of elimination is necessary for reducing the cognitive complexity of decision-making, and each lab meeting utilized elimination to simplify final decision-making. Direct selection of ideas, as an alternative to the elimination strategy, did not occur in any lab meeting. Ideas were eliminated because they did not receive enough votes through preference voting, or because their scores were extremely low from structured engineering methods like Pugh charts.

### 3.1.3.3. Pugh Charts

Pugh charts are powerful decision-making tools that allow users to compare multiple concepts against each other and across multiple criteria categories in reference to a single neutral datum. Typically, these comparisons are marked with either a positive (+), neutral (0), or negative (-) rating in comparison to the reference point, which has neutral (0) ratings across every category. In more complex Pugh charts, weights can be assigned to categories, which affects the total scores that ideas have at the end. Pugh charts are an excellent visual communication tool that allows people to discuss and argue ratings when filling one out collaboratively. Although Pugh charts are successful in achieving team engagement and allowing team members to verbalize their internal assessment criteria, a critical aspect of Pugh charts is setting them up correctly with proper assessment criteria and relevant ideas worthy of discussion.

Every team except Team 2 utilized Pugh charts to aid in their decision-making, and this may either be because both lab agendas suggested it, or because people have had prior learning experience and good associations with Pugh charts. The former hypothesis is more convincing for multiple reasons. First, at least in Team 2A, only two members had experience with Pugh charts previously, so most people on the team were not directly familiar with how to use them, or of their effectiveness as a decision-making tool. Second, at least in Lab #2 across all four sub teams, the assessment criteria suggested by the corresponding lab agenda were copied nearly verbatim by teams for their own Pugh chart assessment, which is visualized in Figure 4. This indicates that since teams were following the assessment criteria lab agenda suggestions, there is also a high probability that they were choosing structured engineering methods like Pugh charts based on lab agenda suggestions as well. In Figure 4, each plain gray box indicates the use of an identical or nearly identical assessment criteria terminology compared to the lab agenda's suggestion, which is the first column. Only Team 2A and Team 2B proposed new criteria not outlined by the agenda, and only Team 1B and Team 1 assigned weights to their Pugh chart categories. The written codes indicate a difference in meaning but are still under the same general idea of suggested and provided Pugh chart assessment criteria.

	Lab #2 Agenda	Team 1A	Team 1B	Team 2A	Team 2B	Team 1	
<b>Pugh Chart Category</b>	Personal Interest		3			Team Excitement and Interest	
	Market and Business		2	Market Size	Market	Understanding the Market	
	Technical Feasibility		1			Understanding Tech. and Context	
	Strength of Customer Need		3		Impact and User Need	Strong Connection to User Need/User Contact	
	Ability to Test /Testability		Access to User /Testability (1)			Ability to Test /Demonstrable	
	Novelty						
	Appropriateness of Scope						
	Clarity					Clear Vision	
	Technical Interest						
	[New Category]				Severity of Danger	Cost	Value Proposition or Realness

Figure 4: Pugh Chart Assessment Criteria, as specified in a Lab Agenda and in Team Meetings

Borrowing suggested assessment criteria is not necessarily a bad thing. However, borrowing becomes problematic when assessment criteria are misunderstood or misinterpreted amongst team members, like Team 2A attempting to clarify the difference between “Severity of Danger” and “Market Size” to a team member midway through filling out a Pugh chart, or when assessment criteria are especially ambiguous, like Team 2B calling one Pugh chart assessment criteria as “Market”, but letting it be defined in multiple ways as referencing market space, market impact, and positioning and pricing to make a product marketable “so they're all rolled in together, but they're different in a way.” Since each definition of market has different implications which are not differentiated within a Pugh chart, the scores can not reflect the nuanced approaches team members may be taking in determining total scores and personal scoring methods.

Team 1 is the only team that generated a completely new set of Pugh chart assessment criteria with weighted scoring, which indicates a high level understanding of the team’s goals for a final product and successful project, as well as a strong and purposeful approach to fully utilizing the Pugh chart; understanding, personalizing, and optimizing the tool rather than merely following lab instructions. As seen in Figure 4, Team 1’s new assessment criteria are explicitly problem-oriented and not solution-oriented, the criteria are focused on uncovering and discovering additional information to increase understanding. Instead of having Pugh chart assessment criteria of “Market and Business Potential”, “Technical Feasibility”, or “Clarity” which can sometimes be potentially confusing or ambiguous, they used “Understanding the Market”, “Understanding Technology and Context”, and “Clear Vision” instead. These criteria distinctions are critical, as they focus on not what the current proposed idea is, but on having a “clear vision” of what it could transform into in the future. With new information and a greater “understanding” of the problem space market and solution product idea technology and context, Team 1 acknowledges the inevitability of their initial product ideas evolving over time.

Team 1 is also the only team that took an unique approach of having everyone individually fill out the Pugh chart, and then making the aggregated results the central point of discussion in filling out the finalized version of a collective Pugh chart. Potential benefits of this approach include preventing students from making hasty, time-pressured decisions and saving time overall when completing the finalized group version, and potential weaknesses include letting opinionated students dominate conversations and students operating under inaccurate personal assumptions when assigning votes, as there is no conversation throughout the process that can keep everyone on the same page. Something interesting to note is that Team 2B wanted to take the same approach from an efficiency standpoint, but an instructor intervened to adamantly argue, “This is a discussion tool. This is a discussion tool, and you're going to be going through this. Now, one can sit there and each of you mark each box and do that. That makes a mess. But on the other hand, you could also have a discussion that should go through this box, giving a sense of the group about what it could be, then you have a scribe that sits there and puts those numbers in it.”

Settling a baseline is typically the last thing a team must do before they can start filling in a Pugh chart, and after they select appropriate assessment criteria and concept ideas to evaluate. Since Pugh chart scores are only relatively relevant, picking an appropriate baseline is critical to having proper and appropriate Pugh chart scores. Specifically, the lab agenda clarifies, “Choosing an appropriate datum (reference idea) is important... one that everyone on the team clearly understands, and is neither the strongest or weakest concept” (see Appendix B). From this instruction, teams still differed in approaches to selecting a reasonable baseline:

**Team 1A:** Baseline was an initial product idea not thoroughly discussed amongst the team beforehand.

**A doable product idea where you can think**

**"oh we could totally make this" and have the clearest idea of what it is.**

[This may have been selected because this initial product idea was simplistic in form and function and closely resembled existing products, which ensures that everyone has a very clear idea of the baseline.]

**Team 1B:** Baseline was a potential product idea that did become a final selection.

**A product idea that "has the need, has the potential, is feasible."**

**Team 2A:** Baseline was a potential product idea that did not become a final selection.

**"Which one do we understand the best? ... It's easiest to conceptualize."**

[Future work can explore the appropriateness of making a potential idea the baseline.]

**Team 2B:** Baseline was a product idea that was already eliminated earlier in the discussion.

**It doesn't matter, so "I'm arbitrarily deciding that this one is the baseline."**

[Problematic in skewing scores positively in the same direction, making them harder to differentiate.]

**Team 1:** Baseline was a final product produced by a previous team from the past year, the baseline was predetermined before the meeting so there is no indication of how the idea was decided.

#### **3.1.4. Social Influence**

There were many observed social factors that created differences between teams, although their degrees of influence on decision-making can only be qualitatively commented upon. This is due to uncontrolled variables, like physical differences between the teams themselves, that may also contribute to decision-making processes. For example, in making the final decision, each team started with four different ideas that had varying degrees of success as prototypes, and this influenced the difficulty of making a final decision as some teams were already more aligned than others going into the meeting.

However, although both teams had the same task, they reached the end goal of selecting a final product idea through different processes that catered to the ideals of the team, which influences how ideas are chosen. Team 1 was time-efficient; they set a predetermined meeting agenda with pre-selected Pugh chart assessment criteria and weights, and made data-driven decisions through filling out their Pugh charts first silently and individually, and then used those aggregated votes to quantitatively evaluate each group Pugh chart rating. Team 1 had a strict single leader-directed meeting style led by the system integrators, where team members were only allowed to talk when they had a "talking stick". The weighted Pugh chart scores of the top two ideas had a large margin, 3.8 and -0.93, which led to a deeper discussion of product details and clarifying the use case for the first idea rather than having an argument between the two. In fact, immediately after evaluating the scores, one team member commented,

**"Alright. So looking at the numbers, there is a large margin between our remaining two ideas.**

**I'm going to straight up propose that we go with [Idea 1]."**

Team 2 prioritized equal member participation with consensus-driven leadership, a loosely defined meeting structure, and an informal and humorous atmosphere. In the beginning of the meeting, everyone went around the room to voice their internal motivations of what they wanted to get out of the class. Towards the end of the meeting, everyone went around the room to voice their opinion between the two final ideas through the spectrum voting method. The first roundtable discussion revealed that most people were most invested in their own personal learning and what they can get out of the class from working on a technically challenging and “interesting” project, not necessarily optimizing the most need-driven product for the most users as in Team 1. The second roundtable discussion revealed the differences in evaluated assessment criteria in why people preferred one idea over the other. Team 1’s final product idea had a confirmed user need, confirmed users to test their product, and a confirmed definition of the product’s features, weight, and size, but Team 2’s final product idea was more undefined and selected based off of more personal metrics:

**“I’m just personally more interested in this problem and working with the user and the customers of [Idea 1].”**

**“All the things that we would be learning are things that we’d all be learning together [with Idea 1].”**

**“[Idea 1] has a lot more things that we’ll have to work together on, whereas with [Idea 2], we’ll mostly be divided most of the time.”**

**“I think with [Idea 1] everyone has mentioned there’s just more room for learning opportunity in more fields and it’s more integral.”**

**“I love [Idea 1] because I feel like there will be much more learning opportunities. The problem is more open. We still don’t have most of the solutions... I want more to work on this because I think there’s more things we can try out.”**

[Team 2 is more socially focused on emotional investment, personal learning, and team cohesion.]

The different structured engineering methods used between Team 1 and Team 2 influentially shaped the assessment criteria and social discussion format of the meetings. In Team 1, individual Pugh charts reduced argumentative commentary but ensured that all assessment criteria were equally evaluated for each product idea. For each category, the votes were “majority rules”, but individuals with minority or strong opinions were welcome to speak up on a score. In Team 2, Google Form preference voting and spectrum voting removed the visual organization of product ideas being evaluated across multiple assessment criteria, but ensured that everyone voiced their opinion and was heard. While in Team 1 individuals spoke on a voluntary basis, Team 2 increased team participation by asking everyone to speak, and created a social environment that easily allowed everyone to do so. Without required individual engagement, Team 1 had a higher probability of encouraging groupthink, where decisions are made in an environment that discourages individual responsibility and alternative ways of thinking. Team 2 had a higher probability of making poorly-informed decisions by overvaluing particular assessment criteria, as there was no visual communication to organize opinion ratings across multiple factors.

### 3.2. Assessment Criteria: Discussion Thematic Analysis

The assessment criteria that students use to evaluate product ideas can be determined from multiple sources. This paper analyzes two of them: the explicit assessment criteria used in structured engineering methods like Pugh charts, and the analytical thematic coding of the general themes discussed amongst students during meetings. Discovering whether the direct and indirect assessment criteria overlap can be used to decide whether the direct criteria are properly addressing the main concerns and points of discussion that students engage in. Teams want to ensure that their conscious decision-making metrics cover their subconscious concerns revealed through open-ended discussion and debate. Figure 5 compares the assessment criteria utilized in Pugh charts, which are the same categories as the first column of Figure 4, and the assessment criteria revealed from meeting discussion thematic analysis.

Although different teams did use different Pugh chart assessment criteria, most notably Team 1 with all independently created criteria, this figure intends to give a general overview of overarching themes present across all sub teams specifically in Lab #2 during the early stage ideation phase. Across the rows are related assessment criteria, but nuances in phrase diction reveal the core of the idea being evaluated from either a problem-oriented or solution-oriented perspective. Neither version of assessment criteria were completely problem-oriented or solution-oriented, but the primary takeaway is that the two columns do not match up.

Regarding user-specific conversation, although Pugh charts termed the phrase “Strength of Customer Need”, discussions focused more on specific use cases and usability of a solution, such as whether a product will be convenient and easy to use, how a user might interact and engage with a product through its form factor, and how a product will function in various situations. While Pugh charts illustrated an interest in a particular product’s novelty, people talked more about providing adequate background information to the problem space, like existing product technology and functionality, how people felt about such products, and the current industrial, legal, and social systems in place surrounding the problem space. Regarding clarity, the “clarity” of a problem space is more problem-oriented than the “clarity” of defining a product: how it will be used, what features it will have, what it will look like, etc.

<b>Color Key</b>	
<b>Problem-Oriented</b>	<b>Solution-Oriented</b>
<b>Pugh Chart</b>	<b>Thematic Code</b>
Personal Interest	Personal Learning
Technical Interest	
Market and Business Potential	Impact and Market
Technical Feasibility	Technical Feasibility + Details
Strength of Customer Need	Use Case
Ability to Test / Testability	Testing
Novelty	Background Information
Appropriateness of Scope	Class Scope
Clarity	Product Definition

**Figure 5: Comparison between Pugh Chart Assessment Criteria and Thematic Lab Meeting Codes**

As mentioned earlier, the assessment criteria directly evaluated in Pugh charts and indirectly evaluated through discussions slightly differed, and Table 3 contains more in-depth descriptions of the latter. Overall, discussions were focused on specific product conceptions, and more solution-oriented than the assessment criteria from structure engineering methods would suggest.

**Table 3: Thematic Analysis Lab Meeting Codes**

Code	Explanation
Personal Learning	Individual strengths, interests, and backgrounds. What students want to work on that is still engagingly challenging.
Impact and Market	The size of impact evaluated across novelty, size of market, and the difference the product can make for users.
Technical Feasibility, Technical Details	Defining how subsystems might mechanically or electrically function, and evaluating the difficulty of discovering or creating the mechanisms.
Use Case, User Needs	Specific use cases and usability of a product
Testing	Ability to test, environment setup testability, and ease of access to user testers
Background Information	Existing products and systems surrounding the problem space
Class Scope	Limited resources of time, budget, and manpower
Product Definition	How a product will be used, what features it will have, what it will look like. What a product should do for the user, but not how (technical details).

### 3.3. Design Education Structure

Within this senior capstone project course, there is a fine line between instructors and class guidelines guiding student teams, and student teams becoming dependent and reliant on them. In theory, student teams are independent and self-organized, but they follow the structure set by class materials and instructors, which can be heavily influential. An important aspect of teaching product design is teaching students how to think for themselves in evaluating ideas and making well-informed decisions. There is a difference between instructing, “**Do not** just hold a vote asking 'which do you like' to select ideas” and “You should make a choice on the basis of what is the best option, not on an emotional level. Be willing to change your mind as new information becomes available”, as the former simply “tells” students that informed decision-making is important while the latter instruction “shows” why (see Appendix B for more illustrative instructions). The types of assessment criteria and even the number of options selected to be included on a Pugh chart have been proven to be influenced by lab agendas and class materials.

## **4. Summary and Conclusions**

Self-directed student teams engage in a variety of leadership styles and structured design methods when making decisions in design meetings. Team 1 utilized a single-leader decision making process and an individual to group Pugh chart, which proved to be more time efficient than Team 2's group consensus leadership style meeting with spectrum voting and Google Form ranking. Depending on the team, students prioritize a variety of assessment criteria in product decision-making processes, including personal interest, market and business potential, technical feasibility, strength of user need, ability to test and testability, background information, appropriateness of scope, and clarity. In particular, students have shown to place high priorities in the assessment criteria of personal interest, user needs and use cases, and technical feasibility. Over time, assessment criteria evolved in further stages of product development to become more solution-oriented and less problem-oriented. During team meetings, students engage in multiple forms of social decision-making processes and structured design methods, such as preference voting (Google Forms, multiple sticky notes, raising hands) and spectrum voting, individual and group Pugh charts, multiple round elimination, single leader decision-making, and group consensus decision-making. To accommodate these processes, meeting agendas typically begin with information sharing and context debriefs, which then lead to a first round of elimination voting, next a Pugh chart or similar methodology that encourages group discussion, then one or more rounds of elimination voting coupled with the elaboration and argumentation of remaining ideas, and finally the selection of final ideas. Qualitatively observed differences between student teams that affect design approaches and outcomes include the social implications of choosing structured engineering methods, for example, with Pugh charts there is less opportunity to voice an opinion than in spectrum voting, the conscious selection of an appropriate baseline and assessment criteria in completing a Pugh chart, the level of pre-meeting organization in lab agenda and student information preparation, and leadership dynamics either dictated by assigned leaders like system integrators or as a cohesive group.

The value of team-based learning is extensive, as people make better decisions collectively in teams than individually (Michaelsen, Watson, and Black, 1989; Shaw, 1971) and communicating cohesively with team members can generate deeper levels of understanding, which can also be supplemented with visual learning tools like Pugh charts. The value of engineering capstone classes also lies in preparing students for successful work in teams and on real projects in the future.

### **4.1. Implications for Design Education**

Student experiences of product design are shaped by the structures created through design engineering education curriculum. Particularly for this course, students were guided through continuous instructor feedback in lab meetings and design milestones, and through instructions set through course materials like lab agendas and milestone objectives. Novice student designers first gaining experience in the field of product engineering have personal interpretations of appropriate assessment criteria and how to properly navigate a product development process. Design education is responsible for guiding without leading these students to have aligned priorities and encourage cohesive teamwork. Students are heavily influenced by class material guidelines, so teaching the foundations and process of design methods (such as why and how Pugh charts are powerful decision-making tools) is more informative than teaching outcomes or setting standards (needing 8 product ideas or suggesting explicit assessment criteria).

## **5. Limitations**

There are several limitations that affect the extent of this research. First, there are differences between real world professional practices, other design education courses, and this senior capstone engineering project, so the results of this paper may not be applicable to the expert product design process or even to other novice student designers who are taught differently. In particular, students in this capstone project lack resources in time, budget, and users, and are rushed to make decisions due to the physical time constraints of weekly meetings and class milestones.

Furthermore, in academic settings there is the possibility of unaligned personal motivations, where different students want different things out of a class. Students in this class experience less autonomy than in professional settings, as they follow predetermined lab agendas and schedules in the format of structured class. This also leads to external forces of instructors and mentors shaping the design process. Finally, individuals who take the class are engineering majors, and not necessarily familiar with design processes, and generally have little experience working in large teams.

In addition to differences from real world functioning design teams and other design courses, there are limitations to the access of influential data in this senior capstone course as well. In generating this dataset, there was no direct communication through surveys and interviews with students, so there are no insights as to how students felt and experienced large team collaboration. The data also could not and does not access all the communication channels that students utilized, including voluntary outside-lab meetings, Slack channels, email forums, informal discussions in person and online, etc. Finally, there is no access to physical productions of communication between students, such as sketches, developed CAD, prototypes and mechanisms created outside of milestone presentations, etc.

## **6. Future Work**

Two avenues for future work involve evaluating the legitimacy of student claims and appeals during product discussions and measuring the influence of instructor and user feedback during later stages of the product development process.

### **6.1. Well-Supported Claims and Appeals**

When students voice claims, how often do they back their arguments with well-supported evidence, and what kinds of evidence do they rely on most? For example, storytelling through personal experience, authoritative approval from instructors or class guidelines, conducting internet background information research, or citing user research and usability studies are all different methods of backing up ones' arguments. Assessing the level of supporting evidence of arguments and the validity of each evidence-based method can inform design researchers of the validity in which decisions are made. These insights can be directly taught in teaching decision-making skills particularly in early stage product design stages where ill-defined problems and a lack of supporting information is especially problematic. Revealing the distribution of claims and appeals can reveal a lack of supporting arguments, or that some appeals are more powerful than others, and whether such argumentative reasoning is reasonable or valid at all. Gathering useful and legitimate information through trusted means is critical in scoping out problem spaces and solutions for designers, novice students and experts alike.

## 6.2. Influence of Instructor and User Feedback

How often and how much do students incorporate feedback in their design decisions? Does this affect their assessment criteria, and if so, how? As mentioned before, particularly relevant in student design education is the ability to internalize and understand instructor feedback deeply enough so that they shape product design decisions. This can clarify the relationships and impact of the academic context on students' design experience, which has not been studied extensively (Zoltowski, Oakes, & Cardella, 2012). Understanding the role of this feedback, how it is most constructive and influential in team product decisions through potentially shaping assessment criteria, is important in evaluating the structure and quality of feedback currently present in design education. This can be done by assessing the significance and level of incorporation of instructor feedback in influencing assessment criteria, argumentation appeals, and defining the product and technical details for student teams, and also whether these priorities differ between teams.

Evaluating how these feedback nudges and suggestions influence team behavior is rewarding and of importance. A meta-analysis from Taconis, Ferguson-Hessler, and Broekkamp (2001) revealed that adequate learning does not come from group work alone, but needs to be supplemented with other methods like feedback and guidelines. Students can benefit from various sources of feedback, as well as consistent self-reflection and self-evaluation of group efforts (Purzer, 2010b). Different feedback sources include feedback from mentors and expert instructors and feedback from product users and stakeholders.

In product design education, feedback also does not always come from instructors, but users have input and agency as well. User feedback is useful not only for improving the usability and features of a physical product, but can also guide student designers to understand the process of product design in a new way, as more user-oriented than designer-oriented. However, it is not enough to merely give feedback, but rather to see how both instructor and user feedback are incorporated into design and process decisions. In fact, "Sugar (2001) looked at the effect of usability sessions on novice software design and found that, although the students thought the usability sessions were helpful, they had minimal effect on their designs. When they did make a change, they were one of two simplistic solutions (1. Delete: if something was a problem they simply deleted it 2. Band-Aid: when users don't know where to click or what the icons mean they decide to have written directions to assist users) that demonstrated only a surface-level understanding of the problem" (Zoltowski, Oakes, & Cardella, 2012). Although this study concentrated on the early stages of the product design process where user input is minimal, future work can examine student team levels of engagement in both user and instructor feedback, as seen through physical product developments and thematic analysis of design conversations, and how this may affect student internal models of appropriate and prioritized assessment criteria.

## 7. Appendices

The following appendices are relevant class materials extracted from the senior engineering capstone course website. Appendix B and Appendix C have been annotated and highlighted to emphasize the relevant information to this paper.

### 7.1. Appendix A: Team Officer Roles

<b>Resource title</b>	<b>Roles</b>	<b>Resource allocation</b>
System Integrators	Product and team integration	1 per section, giving 2 per team
Financial Officers	Managing budget	1 per section, giving 2 per team
Tool Officers	Maintaining workspace	1 per section, giving 2 per team
Information Officers	Interface to librarian	1 per section, giving 2 per team
Team Site Master	Team project site management	1 per section, giving 2 per team
Safety Officers	Product and team safety	1 per section, giving 2 per team
Yoda Officer	Facilitate teamwork excellence	1 per section, giving 2 per team
Video Log Officer	Capture the team's learning experience	1 per section, giving 2 per team

## 7.2. Appendix B: Lab #2 and Lab #7 Meeting Agendas

### Lab #2 Agenda

#### Preparation before lab #2

Be prepared to give a short summary of background work for the idea areas that you may have been assigned to in lab #1 (e.g., possible customers and their key needs, relevant existing products, market potential, and some technical feasibility analysis).

The system integrators should prepare an agenda for the lab.

#### As individual sections

Your system integrator should present an agenda and estimated timeline for the meeting. Adjust the agenda accordingly, based upon feedback from section members or the section instructor.

Have the section members/task forces responsible for additional background work related to ideas that were identified during lab last week present their findings. If new ideas were developed over the week they should be discussed as well.

Each group of students should present sketches of their new idea that is based upon the observation exercise. Be sure that the idea sketches are pinned up.

Decide on the 3 ideas that will be presented by your section at the 3-ideas presentation.

#### A suggested process for selecting your top 3 ideas is below.

-develop a short list of up to 8 ideas, drawing from the most promising projects identified by your section.

-develop a small number of key assessment criteria (no more than 6). Things to consider might include aspects that define a product opportunity: novelty and excitement about the idea; clarity and strength of customer need; market/business potential; and aspects of feasibility, including technical interest/excitement, ability to test, and appropriateness of scope. You **must** be able to identify at least one person or "client" who represents your customer. This person needs to be easy to contact for advice throughout the term.

**-Do not** just hold a vote asking 'which do you like' to select ideas. Use a rational process (such as the Pugh method) to select 3 ideas.

Choosing an appropriate datum (reference idea) is important... one that everyone on the team clearly understands, and is neither the strongest or weakest concept.

## Lab #7 Agenda

### Preparation for Lab #7

If possible, meet with your section to discuss the mockup review. What worked well? What did not? How will you do better next time? If there are additional issues that should be looked into before deciding on your project direction, work on them prior to the lab meeting.

**Prepare a short but informative presentation** about your opposite section's two concepts, highlighting strengths, weaknesses, risks, and open issues. Be sure to work with the opposite section and have their agreement on the key points of your presentation. In addition to summarizing the sketch models and mockups, please try to outline thoughts about key tasks that the team will engage in to carry an idea forward to a product prototype.

### Recommended Lab #7 Activities

Spend up to 20 minutes in total to present the short concept summaries prepared before lab, reviewing the team's four ideas and feedback from the mockup presentation.

System integrators should propose the decision process they have developed, and revisions should be made based upon input from the team. If the sections are different in size, be sure that your decision process is perceived to be fair. It should not be possible for one section to simply out-vote the other. You want to make the best choice regardless of who has worked on an idea.

A Pugh chart or similar rational process should be used to help elucidate and compare the strengths and weaknesses of the concepts relative to your team's project criteria. Think carefully about risks associated with your product concepts and negotiate the product definition for the final alpha prototype. Focus on the common goal of having the best-possible successful project, and in making a timely decision so that your team can move on to the next steps. You should make a choice on the basis of what is the best option, not on an emotional level. Be willing to change your mind as new information becomes available.

Be sensitive to team dynamics and focus on the merits of the concepts, not ownership of the ideas. For example, make statements like: the idea has significant technical risk rather than your idea has significant technical risk; the widget fulfills an important need rather than my widget fulfills an important need. Paying attention to how things are said can make a significant difference. Remember that consensus does not mean that every team member has the same opinion about what is the best direction to pursue. Consensus means that all team members agree that the direction has been chosen and that they will fully engage in helping the development effort succeed in the chosen direction.

## 7.3. Appendix C: Design Milestone Objectives

### 3-Ideas Presentation

#### Background

The 3-ideas presentation is a critical step in the process of choosing a direction for your team's project. Each section is allocated 2 minutes for three ideas.

This milestone is intended to help you learn how to prepare a 'clean' poster and describe a product idea in a very short amount of time—roughly the amount of time you might have to pitch a new idea to an executive when you see her while riding in a elevator. Hence, this type of presentation is called an "elevator pitch".

#### Requirements

Each idea poster should include a simple sketch and key talking points, such as potential customers, market, and technical feasibility assessment— all readable from 50-80 feet away. At a glance, a viewer should 'get the idea.' Also, on the back attach an 8.5"x11" sheet with supporting estimations, calculations, and data sources/citations for any quantitative information that is on the poster.

Remember that clean simple posters work well. Since the ideas are quite unformed at this time, using gestural sketch-like representations is more appropriate than realistic renderings or models. You can prepare the final poster by hand or using software. In your presentation, you must also identify at least one person/expert that is representative of your potential customer and be confident that they can serve as a resource during the term.

#### Grading

After class, the posters will be collected and all lab instructors will meet to discuss the 6 ideas presented by your entire team (three from each section). Based upon your work, the instructors will choose a product sub-theme and this will become the entire team's focus for the rest of the term. When making the selection instructors will consider: technical and educational interest; customer needs; project scope; and the product portfolio formed by all 8 teams in the class.

The posters will be photographed and your presentation will be videotaped. The materials will be put on the course website, with a review form, and you will receive presentation feedback from instructors overnight after the presentations (before your next lab).

## Mockup Review

### Background

The goal of the review is to inform classmates and instructors about the key challenges related to your section's two leading design concepts, and how these challenges will be resolved. The overall goal is to develop your concepts to a level that your team can confidently select their best product opportunity following the mockup review.

### Key review elements

Each section will present technical or visual mockups and drawings of their two concepts, focusing on illustrating the overall concepts, technical feasibility/operational principles of critical systems, preliminary product contracts, and user/product interaction. The presentation should focus on issues that are both potentially high-risk and critical to the concepts.

Key grading criteria are:

- thoughtfulness about, clarity, and vision for the design concept
- identification and resolution of critical issues/risks
- execution of mockups/models/simulations

### Part 1: Structured presentation

Present a clear product vision/design concept, its critical risks, key findings, and remaining concerns. Please include a preliminary product contract with your key ~3-6 customer needs, product attributes, and specifications. Things to make very clear are: what is the product, who will use the product and why, who will buy it and why, and with what user group you will be testing. You should also have a grounded number for a target selling price—what the purchaser is willing to pay.

### Part 2: Informal testing and discussion:

Instructors and mentors will be divided into 8 review teams and assigned to different sections. Every 10 minutes the instructors will switch to a different section according to the rotation schedule below. Spend 5 minutes on each of your section's concepts. The rotation is structured so that you will have 10 minutes on, then 10 minutes off. In total, you will have four 10 minute question and answer sessions.

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