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From Cornerstone to Capstone: Students' Design Thinking and Problem Solving

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From Cornerstone to Capstone: Students' Design Ideation in Project-Based Learning Courses

DEED Category: Pedagogy (or Intervention) and Assessment

Abstract

Engineering projects provide an opportunity for STEM students to participate in hands-on and active learning, which isn't available in a typical lecture-based course. These projects are expected to scaffold students to expert level engineering thinking. Participation on projects addressing real-world problems and enables students to become better design thinkers throughout their undergraduate education. In this study, students were surveyed from the first-year cornerstone course, the Vertically Integrated Projects Program, and the capstone design courses to determine if and how their design thinking ability changes with the amount and variety of project-based learning courses that they have completed. The study participants each completed a design canvas to address and determine a solution for a hypothetical need in an engineering design scenario. The design canvas was assessed based on students' creativity, decision-making ability, and the fundamental concepts they considered in their design. The results do show noteworthy differences in novelty and quality across students' designs. This study also expands on current developments in methodology that has implications for expanding this study in order to better relate students' design experiences to their design ability.

Introduction

Engineering students have a wide variety of educational experiences throughout their undergraduate career within and outside of their required coursework. The goal of these various engineering opportunities is to develop students into engineering professionals, that not only succeed but are also able to make a better, safer, more sustainable world [1]. There are essential topics in which students should become competent [2,3]. These key knowledge and skill areas are considered the most essential across disciplines, including communicating effectively, designing solutions, applying knowledge, honing skills, and being able to solve problems [4,2]. But within these, *design* and *problem-solving,* have been found by recent engineering graduates and professional engineers to be the most important skills for an engineer to have [3,5].

Design and authentic problem-solving are mostly found to be "bookends" in engineering curricula, whereas theoretical and scientific courses are common during the "middle years." The subject matter that students are learning in the middle years is often content knowledge based and quizzing of this content takes priority over its application. This is despite the fact that the same information is prevalent in project-based learning (PBL) courses and hands-on extracurriculars [6]. These engineering design courses and experiences also have the additional benefit of helping students retain information and practice social entrepreneurship [7,8].

As a note PBL courses, in this study, refers to project-based learning courses, not problem-based learning which is a different pedagogical approach that often uses the same acronym. PBL is a student-centered pedagogy, as opposed to instructor-centered lecture and exam-based courses, that enables students to focus on design and authentic problem-solving. [9-11].

Many courses at NYU Tandon School of Engineering focus on teaching content knowledge and determining student proficiency in that content through written exams, often using well-structured mathematical assessments (i.e., "given-calculate," "plug-and-chug" question types). NYU Tandon School of Engineering also offers many courses that focus on the application of engineering content knowledge through PBL. For this study, project-based courses are defined as courses which have an open-ended project that is at least 20% of the final grade. At NYU Tandon, PBL engineering courses include the first-year cornerstone course that is required for all engineering students, discipline specific courses, and final-year senior design courses within each department. NYU Tandon also has Vertically Integrated Projects (VIPs) which are non-required PBL courses that are taken over several semesters and focus on research and engineering design for students to work on solve real-world problems.

Design and problem-solving are the basis of engineering design, and with so many learning opportunities it is critical to determine what factors are impacting undergraduate students' engineering design ability [12-15]. This can help improve the layout of engineering curriculum and ensure that engineering students are professionally prepared to design a better world. In this study, a survey was used in order to assess undergraduate engineering students design ability and determine which opportunities help them to develop expertise in design. The survey contained a design scenario and a design canvas to guide students through the design ideation process. This data was analyzed based on quantity, variety, novelty, and quality in order to evaluate the student's level of design ideation expertise.

Background

The phases of engineering design are often taught as having a circular, iterative nature. An engineering product or process is designed through phases of (i) defining the problem, (ii) brainstorming solutions, (iii) planning a solution, (iv) prototyping, (v) evaluating the solution, and finally (vi) reflecting for iteration, shown in Figure 1.

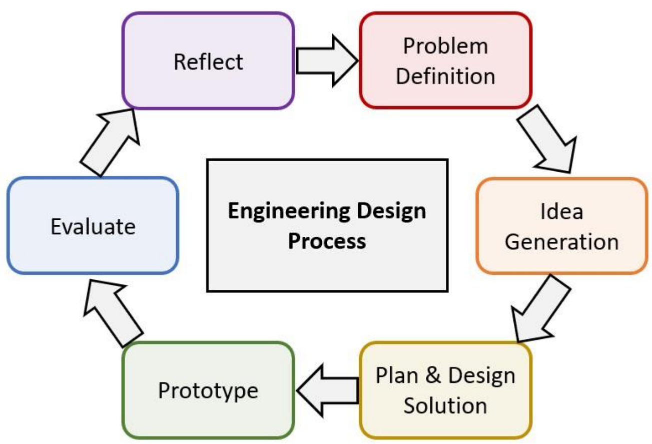

Figure 1: Simple infographic conveying six phases of engineering design iteratively.

In practice, the activities associated with each engineering design phase are highly interdependent and do not simply progress in a neat iterative circle, as implied by common infographics for the engineering design process. PBL experiences in engineering design education are essential for students to understand the interrelated nature of engineering design activities throughout the design process.

While all phases of the engineering design process are interconnected and experienced collectively in PBL courses and activities, some aspects of the engineering design process may be emphasized more than others. For instance, it is not typical for students to iterate, i.e., building multiple prototypes within the limits of academic terms. The academic calendar restricts the entire design cycle into a period of weeks or months, something which is often much longer in engineering practice, up to years and decades.

The *brainstorming* phase of design (also referred to as *idea generation* or *ideation* phase) is similarly disadvantaged by the short timescales of PBL courses in engineering design education. Brainstorming is characterized by divergent, creative thinking that aims to expand and explore the possible design solution space, temporarily withholding criticisms regarding feasibility or specific constraints, before converging on a chosen solution [16]. The academic calendar restricts the time available for engineering design projects, pressuring students to make progress on a chosen design. This pressure is not conducive to the divergent thinking ideal for brainstorming novel and high-quality solutions.

In addition to the short timescales common to engineering design education, the middle years of engineering undergraduate curricula tend to lack engineering design education overall. Students' development of competencies related to the engineering design ideation phase tends to be limited in their typical degree required courses.

Vertically Integrated Projects (VIP) Model of Experiential Learning

One curricular solution to integrate PBL in the middle years and extend the timescale of engineering design education is through the Vertically Integrated Projects (VIP) Model. The VIP Model has been implemented at over 37 institutions around the world with varying institutional structures and student populations. The VIP Consortium was recognized by ABET with the 2019 Innovation Award for implementation of and community-building around the VIP Model [17].

"VIP teams" comprise faculty and students from across disciplines working together to conduct large-scale projects that require multidisciplinary teamwork to accomplish real-world objectives. An essential characteristic of the VIP Model is that students enroll in the same, repeatable PBL course for credit for at least 1.5 years. In other words, each student participates on a VIP team for at least 1.5 years. This long-term curricular structure of the VIP Model expands the timescale on which students participate in design education and fills the gap in engineering design PBL between the first-year cornerstone courses and final-year capstone courses.

"Vertical integration" refers to the composition of all levels of undergraduate students, graduate students, and faculty on a single team. This structure, combined with long-term participation, enables an organizational structure to the teams. Students begin early in their academic program in a supportive, apprenticeship, mentor/mentee role in which they learn from more senior students. Over time, students grow into leadership roles, sustaining peer-to-peer learning relationships with newer members. Through long-term engagement, students have time to gain insights and develop proficiency with the various yet interrelated activities of engineering design on a project that has real-world implications.

The VIP team objectives range from faculty-embedded research and discovery efforts to entrepreneurial and service product development to industry-sponsored design competitions. Students' variety of engineering design experiences in different PBL cornerstone courses, VIP courses, and capstone courses leads to uniquely individual and contextualized knowledge and skills. Each engineering discipline also teaches particular standards, practices, and ways of thinking about engineering design. Assessing design competencies across this diverse scope of knowledge in a repeatable and scalable manner is not simple. In this study, we focus on the assessment of competencies associated with the engineering design ideation phase.

Assessing Design Ideation

Shah, Smith & Vargas-Hernandez identified four "metrics to measure ideation effectiveness of a design idea generation method" [16, p. 112]:

- *Quantity*: "the total number of ideas generated"
- *Variety*: "a measure of the explored solution space" across all ideas generated
- *Novelty*: "a measure of how unusual or unexpected an idea is as compared to other ideas"
- *Quality*: "a measure of the feasibility of an idea and how close it comes to meeting the design specifications"

Conceptually, the *quantity* and *variety* across a set of ideas represents the total explored design solution space. *Novelty* and *quality* of an individual idea represents expanding the design solution space. Together, these four metrics can be applicable in a vast array of contexts to evaluate the "goodness" of a formal idea generation method, such as design scenarios and design canvases [16, p. 116].

Design scenarios are story-like descriptions of an authentic context, need, and set of constraints or requirements which motivates and scaffolds an engineering design activity. This is a type of *germinal* idea generation method, i.e., a method that aims to "produce ideas from scratch" [16, p. 112]. Design scenarios have been employed as useful assessment tools in research to measure students' abilities to address novel design challenges [18].

Design canvases are often depicted as a 1-page collage of rectangles, each with a prompt that directs consideration of key aspects of engineering design ideation (stakeholders, features, value, constraints, etc.). Design canvases scaffold idea generation and elicit details underpinning the final design generated. A design canvas activity is a type of *organizational* design idea generation method that scaffolds and standardizes responses. This method has been used for research in many design disciplines [19].

Research Goal

The goal of this research study is to develop an assessment activity that elicits engineering students' design ideation process. This data can then be used to evaluate their ideation competencies across a variety of PBL contexts and to report its initial use. By combining formal germinal and organizational idea generation methods, we aim to develop a broadly applicable, yet standardized and repeatable assessment of design idea generation competencies. This assessment will facilitate the evaluation of design ideation development at a program level, across many contexts and courses. With this information, we can begin to understand how students' experiences in engineering design PBL courses are impacting their engineering design competencies. We hope to develop a methodology and documentation that is repeatable and scalable, yet versatile to be effectively shared across the VIP Consortium.

Methods

A survey was sent out to undergraduate students enrolled in common PBL courses at NYU Tandon School of Engineering, an urban, private, 4-year engineering institution in the Northeast US region. These courses include the first-year cornerstone engineering courses, the Vertically Integrated Project courses, and the engineering senior design capstone courses. In total, around 1000 students received a link to the Qualtrics survey via a mass email invitation. 22 student responses were submitted, 18 of which consented to participating in the research which was required to access the survey questions. 10 responses had complete responses to all questions. These 10 responses are used for this study. This study was approved under NYU IRB protocol IRB-FY2020-3869.

The survey consisted of a design scenario and design canvas prompts in order to guide the students through the design ideation process and make sure they consider aspects of their design that are relevant to assessing their level of expertise. The survey also included questions regarding each student's PBL courses, their time spent pursuing an engineering degree (in years), and demographic information. The full text of the survey is in the Appendix.

The design scenario prompted students to generate an idea for an article of clothing that would improve someone's daily life who has a disability or injury. The disability was not specified in order to provide students more freedom and creativity when coming up with designs (full text of survey in Appendix). The design canvas was composed of 9 boxes: (1) stakeholders, (2) actors, (3) features, attributes, and values, (4) designs, (5) components, (6) modes, (7) interactions, (8) inputs/outputs, (9) functions. Each box also includes guiding prompts in order to structure the details to be included in each box.

The ideation responses to this survey were then analyzed for *quantity*, *variety*, *novelty*, and *quality* of their design solution. The process of evaluating these four metrics was informed by the methodology descriptions and example cases provided by Shah et al [16]. Quantity measured how many total design ideas were generated (1 per participant). Variety measured the total number of unique design characteristics that were mentioned. Each new, novel characteristic expanded the design solution space, i.e., increased variety across the set of design ideas.

We took a similar approach to Shah et al. in deriving a novelty score for each design idea [16]. The novelty calculation was based on the total number of characteristics and calculating the novelty weight of each characteristic which was inversely proportional to the number of times it appeared. To calculate an individual's total novelty score, the novelty weights were added together for the characteristics that were mentioned by the individual, then divided by the total number of characteristics. Together this calculation captures how many of the characteristics were mentioned and the uniqueness of those characteristics within the set of ideas. The derived equation for the novelty score results in a higher score for individuals who mention more characteristics and for individuals who include a characteristic that is less common amongst the full set of responses.

The quality of each design canvas response was evaluated using four sub-categories which represent the feasibility of the design idea: *manufacturability*, *usability*, *cost*, and *practicality*. The three authors each evaluated all 10 design ideas in these sub-categories on a scale from 1 (poor) to 3 (very good). If no information was provided the sub-score was zero. We discussed any discrepancies in rating between researchers to reach a consensus on scores. The sub-category ratings totaled an overall quality score for each design idea, out of 12 points.

Results

A survey was sent out to collect data to better understand the impact that engineering projects have on their design abilities. In the survey, students were asked to develop a design based on the given prompt, described by answering prompts in a 9-box engineering design canvas. This canvas was used with the intention of guiding students through fully developing an idea. Students' designs were then evaluated using four metrics: quantity, variety, novelty, and quality. These responses are listed in Appendix B.

Quantity

There were 10 completed survey responses making up the set of design ideas collected.

Variety

We defined 22 unique characteristics identified by one or more students throughout the 10 responses. The characteristics are listed in Table 1. They represent the total design space explored by the students. For example, three of the ten separate designs discussed the importance of a design that allows people with disabilities to be more independent in their daily activities. The following quotes were characterized as *Independent*:

> "*Independence of the disabled*" (Case 1)
> "*ie not having someone else help you complete the task of dressing yourself*" (Case 9)
> "*without assistance*" (Case 10)

These quotes directly or indirectly reference the same concept of increasing independence in the actor's daily lives.

As we discovered new characteristics that students considered in their designs, the total variety of all responses was expanded. For example, only one case discussed a product which would assist an individual with motor issues, categorized as *Assistance with motor issues*:

> "*limited need for fine motor movement*" (Case 3)

Some less-novel characteristics were easy to categorize, having been directly referenced in several responses. Three cases described a design that would improve the user's comfort:

> "*comfort experienced … Level of comfort throughout the day*" (Case 2)
> "*Comfortable*" (Case 3)
> "*design is comfortable*" (Case 7)

Ideas that were similar, only differing in minor or superficial ways, were grouped together in this way. The full original text of the characteristics as described by each participant are included in the Appendix.

Table 1: Design characteristics from all survey responses, listed by descending number of occurrences.

Design Characteristic	# Occurrences	Design Characteristic	# Occurrences
Ease of Use	8	Fashionable	1
Affordable	4	Reusable	1
Independence	3	Flexible	1
Comfort	3	Mass Producible	1
Time Saving	2	Climate	1
Environmental	2	Size	1
Washable	2	User Rating	1
Assistive	1	Pain	1
Assembly	1	Ergonomic	1
Lightweight	1	Inclusive	1
Warm	1	Certified	1

Novelty

Novelty of the various designs was determined through quantitative analysis of the number of characteristics mentioned (Table 1). The novel characteristics expanded the design solution space by describing a characteristic that was not present in the other designs (e.g., Inclusive), while less-novel characteristics were repeated across responses (e.g., Affordable).

Certain students expanded the design space by specifying a completely unique characteristic. Fifteen of the 22 characteristics were only mentioned by one case, such as "*Mass producible*" (Case 5) and keeping "*health regulations in mind*" (Case 10). Each of these are useful characteristics that are much more novel than a characteristic such as Ease of Use, which was mentioned by 8 of the 10 cases. Ease of Use cases included: "makes it easier" (Case 2), "ease of use" (Case 3), "user defined ease" (Case 4), "simple to put on" (Case 7). This illustrates that the ease of use for a product for people with disabilities is an important design characteristic for undergraduate engineers. The other most common attributes included affordability, comfort, and the independence that the product provides to the user.

Once all ideas were analyzed, we determined the number of times each attribute was used overall, and the number of times each attribute used by each individual. The novelty score for each case was calculated by summing the novelty weights of each attribute that was mentioned and dividing by the total variety score. So, for an individual who had mentioned the attribute of independence, which was mentioned in three designs, one of their novelty weights were 1/3. This would be summed together with all other novelty weights for the specific attribute and divided by the variety, or total design space. Individuals who used a higher number of attributes total, and/or used attributes that few others mentioned will have higher novelty scores.

Table 2: Novelty scores for each survey participant.

Student Case	1	2	3	4	5	6	7	8	9	10
Novelty	0.06	0.04	0.30	0.03	0.22	0.01	0.07	0.05	0.08	0.15

Case 3 had the highest novelty score for a design that utilized "*weighted magnet attachments for shoes, jackets, pants, ect, where you can use gravity by bending over, lifting your foot, ext to close the seam and therefore keep your clothing on your body*." This design was calculated to have the novelty score, 0.30. Case 3 presented 10 out of the 22 total characteristics, of which 5 of them were entirely novel: easy assembly, reusable, fashionable, warm, and lightweight.

Case 2 had one of the lowest novelty scores. Their design was a piece of clothing with a top to bottom zipper so that the clothing would not need to be pulled on over the body. This case mentioned three characteristics: ease of use, time saving, and comfort. All three characteristics were also mentioned in other cases, which resulted in a novelty score of 0.04. While the student did not include many characteristics in their design canvas, they did expand on the topics with commentary such as "*the level of comfort throughout the day should be higher in value relative to the amount of time to put on the clothing*."

Quality

The quality score was based on 4 metrics that represent the feasibility of the design idea: manufacturability, usability, cost, and practicality. Each metric was rated on a scale 1 to 3, least to most advantageous, and then summed in order to determine the overall quality score of the students' design. For example, Case 1 scored low on a wide variety of sub-categories by giving a creative but unfeasible design using an auto-dressing robot. This contrasts with Case 10 who had a relatively high score by designing a shirt with an integrated arm sling.

Table 3: Quality sub-scores of each case for manufacturability, usability, cost, and practicality.

	Student Case									
Quality	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Manufacturability	1	2	3	0	3	1	3	3	3	2
Usability	2	2	3	1	2	3	2	3	2	3
Cost	1	1	3	0	3	1	3	3	3	2
Practicality	1	3	3	0	3	2	2	1	2	3
Total Score	**5**	**8**	**12**	**1**	**11**	**7**	**10**	**10**	**10**	**10**

Case 5, who had one of the highest quality scores, developed a design of a piece of clothing that could be assembled into various styles depending on the need of the disability. This design was described as having "*adaptive clothing which should be stretchy, using either large tab zippers or Velcro closures, removal of buttons, straps…*" which features being "*Affordable, Environmental, Assistive, Ergonomic, Inclusive, Malleable, Mass-Producible, Impactful*" and "*widely available in different retail environmental and medical environments.*" This case had one of the highest quality scores of 11 points. This student received a score of 3 on manufacturability, cost, and practicality, and scored a 2 on usability. This style of clothing would be able to be easily manufactured with current technology. All of the materials are relatively cheap to acquire, and the student mentions the need for the product to be “*available to all income classes*.” The design is feasible with current technology and infrastructure. It also has the potential to actually help individuals with disabilities in their daily lives. This design scored a 2 on usability because the design was based on using zippers to remove and attach clothing items. The usability of Case 5 was evaluated as a 2 because the design incorporated zippers which could be difficult.

Case 1 had one of the lowest quality scores. This case designed a robotic arm that would assist the user in getting dressed and would be controlled via an app on the user’s phone. This case scored a 1 on manufacturability, cost, and practicality, but scored a 2 in usability, with a final quality score of 5, the second lowest score. We considered the robotic arm to be a design that can help someone get dressed, would be difficult to manufacture with current technology, and would be very expensive. The design was not considered practical because it would not be possible to develop at the moment, though this product would be able to help the user get dressed.

Figure 2 below graphically represents the design ideation scores of each case and includes relevant student information. The size of the circle corresponds to the number of PBL experiences and the color corresponds to academic major.

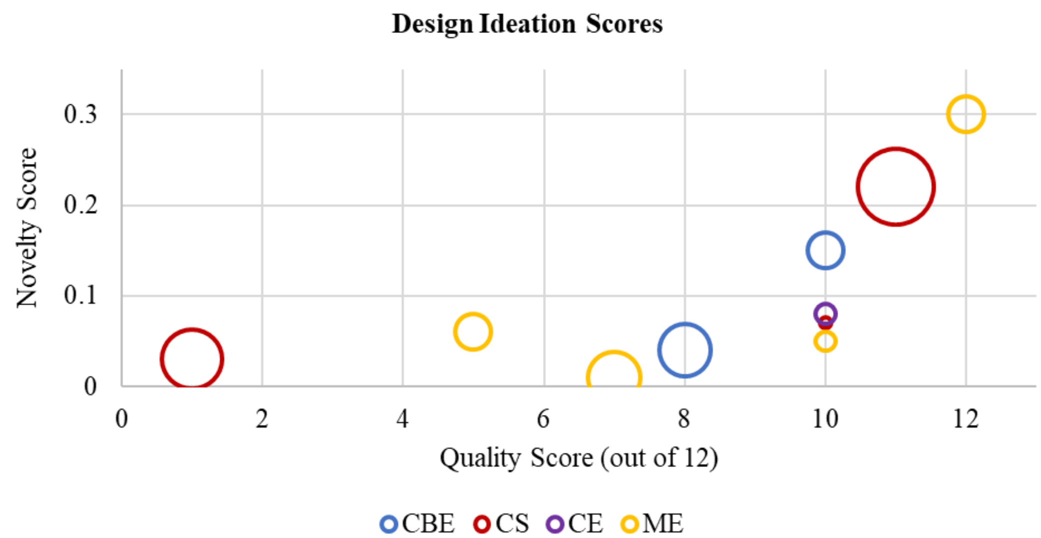

Figure 2: Plot of ideation novelty versus quality scores for each participant. Circle size represents # PBL experiences (range: 2-10) and the color represents academic major (CBE = chemical & biomolecular engineering, CS = computer science, CE = computer engineering, ME = mechanical engineering).

Three cases presented both high quality and high novelty designs relative to the other cases as shown by their location in the upper right corner of Figure 2. These three students are each from a different major and have a range of PBL experiences from moderate (5; CBE and ME students) to high (10; CS student). The remaining seven cases had relatively low novelty scores (less than 0.10). Across these low-novelty design ideas, there was still a wide range in overall quality scores (1 – 10, out of 12).

Ultimately, the small sample size is not intended for any statistically significant quantitative conclusions and this visual representation of the quantitative data is meant to holistically represent the data and results rather than support inferences. A large data set is required across multiple class levels to determine whether a correlation exists.

The novelty and quality of the design ideas do not appear related to the number of PBL experiences or student major. However, we have yet to examine relationships among the type of PBL experience and design ideation competency. The next steps will be to gather a larger data set and specifically examine the impact of different PBL courses and more specifically VIP experiences.

Discussion

This study presents the first round of our data collection using a qualitative survey methodology by combining a design scenario and a design canvas to scaffold and elicit students' thoughts during design ideation. We present our major takeaways from students' responses and discuss modifications to the methodology for future iterations.

While we saw some similar characteristics across many of the designs (low variety), there were still noticeable differences in quality and novelty. For instance, three designs each mentioned zippers and three other designs each mentioned magnetic strip closures. While these designs appeared similar at first glance, the responses had vastly different quality and novelty scores depending on the number, nature, and depth to which they considered the design characteristics. This is in part due to some students listing attributes (e.g., Case 3, Case 5) as compared to other students who would describe the attribute in more detail (Case 2). The design prompt did not specify a particular physical limitation to be accommodated by the piece of clothing, yet over half of the responses still presented similar solutions. Some students specified additional information to better contextualize their design idea, whereas some other students provided vague responses that were more difficult to conceptualize as the evaluator.

The student with the most PBL experiences, Case 5, had a high quality and novel design. However, the relationship between amount of PBL experiences was not consistently related to the "goodness" of design ideation response. For example, Case 7 demonstrates how students with very little PBL experience were able to produce high-quality designs and Case 4 showed that students with more PBL experiences may still produce low quality and incomplete designs. Nonetheless, the study was able to evaluate students' design idea generation proficiency using a replicable and scalable method.

The cases also demonstrated that several students did not have a clear understanding of some of the design canvas boxes and did not address those aspects in their design solution. For instance, Case 2 used questions marks in their descriptions for the boxes of Inputs/Outputs and Functions, indicating uncertainty in how to communicate that aspect of their design idea. Case 9 replied "None" to these same boxes on the design canvas, showing some misconception of the concept being asked. Even the high quality and novel answers, Case 3 and Case 5, gave short and noninformative responses, even "N/A" (Case 5, Functions). These aspects of the design canvas did not elicit descriptive and rich responses that were useful or impactful in the qualitative evaluation of the design idea. These portions of the design canvas may be changed or removed to refine and shorten the overall survey.

Future Work

We learned several ways to improve the survey and data collection process for future iterations, refining the design scenario and design canvas prompts to reduce the overall response time while improving the response quality. For instance, the design prompt did not specify a particular disability or injury as context for the design solution, and therefore the scope of the design solution space was increased.

These results will act as a first step to make the data collection and analysis more efficient and effective. In the following academic years, a similar survey will be sent out to the same population of students with increased coordination through the instructors. This population includes students participating in the school's engineering first-year cornerstone design course, Vertically Integrated Projects, and senior design capstone projects.

The design canvas boxes that students did not seem to understand or the ones that were filled out with little useful information will be removed including Modes, Interactions, Input/Output, and Functions. This is to make the survey shorter and quicker for the students to fill out in an effort to increase survey response rate. Additional questions will be asked to further specify their design experiences inside and outside the classroom so that the design results can be compared to these experiences.

Our goal is for these survey and evaluation matrices to be use in other contexts to develop a versatile and informative dataset. The survey and the evaluation matrices could be used by other studies to evaluate design thinking surveys.

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Appendix 1: Full Survey Text

This survey has three parts:

(1) indicate your project-based learning experiences at NYU,
(2) complete an open-ended design prompt,
(3) indicate your attitudes while completing the design prompt.

The questions that relate to the design prompt are meant to help you quickly layout of your design idea.

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1. Which of the following project-based courses have you taken? Only select the courses if a project counted as 20% or more of your grade when you were enrolled.
    - EG-UY 1003 Introduction to Engineering and Design
    - CBE-UY 1002 Introduction to Chemical & Biomolecular Engineering
    - CBE-UY 4163 Chemical and Biomolecular Process Design I
    - CBE-UY 4263 Chemical and Biomolecular Process Design II
    - CS-UY 2204 Digital Logic and State Machine Design
    - CS-UY3083 Introduction to Databases
    - CS-UY4523 Design Project
    - EE 4XX3 Design Project I
    - EE 4XX3 Design Project II
    - EE-UY 4001 ECE Professional Development and Presentation
    - ECE-UY 2004 Fundamentals of Electric Circuits
    - ME-UY 2112 Computer Aided Design
    - ME-UY 4112 Senior Design I
    - ME-UY 4113 Senior Design II
    - Pre-Capstone Innovation Experience Course

2. How many semesters have you participated in a Vertically Integrated Project (VIP)? This includes volunteering for a VIP without receiving course credit.
3. How many STEM courses have you taken for which a project counted as 20% or more of your grade (not including those selected above)?
4. How many NYU-affiliated extracurricular STEM projects have you been involved with (over 10 hours of work)?

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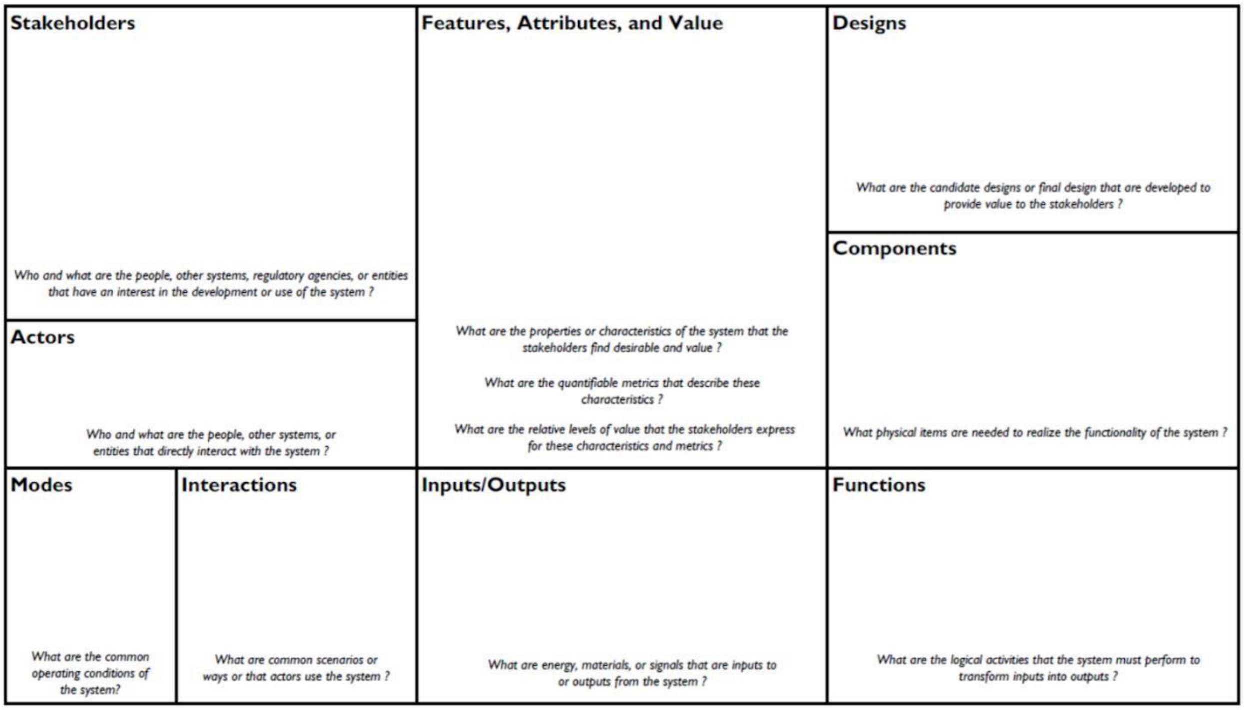
The following is an open-ended engineering design prompt. You will use the prompt to develop a product and complete an engineering design canvas (image and questions below) which asks about different aspects of your design. You are free to use scratch paper, but please do not use any additional resources. Remember that this is not graded and you do not need to spend significant time refining your answers.

> **Engineering Design Scenario**: There are a variety of physical and mental disabilities or injuries that may impact a person's ability to complete simple daily activities. One of these activities is getting dressed and having clothing that works with your disability or injury making it either easier to put on or use throughout the day. Please design any article of clothing that could be used by someone who is disabled or injured. This design should hone in on what makes this disability challenging and creatively makes their life easier.



1. **Stakeholders:** Who and what are the people, other systems, regulatory agencies, or entities that have an interest in the development or use of this system?
2. **Actors:** Who and what are the people, other systems, or entities that directly interact with the system?
3. **Features, Attributes, and Value:** What are the properties or characteristics of the system that the stakeholders find desirable and value? What are the quantifiable metrics that describe these characteristics? What are the relative levels of value that the stakeholders express for these characteristics and metrics?
4. **Designs:** What are the candidate designs or final design that are developed to provide value to the stakeholder?
5. **Components:** What physical items are needed to realize the functionality of the system?
6. **Modes:** What are the common operating conditions of the system?
7. **Interactions:** What are common scenarios or ways that actors use the system?
8. **Inputs/Outputs:** What are energy, materials, or signals that are inputs or outputs from the system?
9. **Functions:** What are the logical activities that the system must perform to transform input into outputs?

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Please answer the following questions about your experience completing the engineering design prompt questions.

1. Rate your **degree of confidence** (i.e., belief in your current ability) while performing different aspects of the design process as listed below. Scale: 1 = no confidence, 6 = fully confident
    - conduct engineering design
    - identify a design need
    - research a design need
    - develop design solutions

- select the best possible design
- construct a prototype
- evaluate and test a design
- communicate a design
- redesign

2. Rate your **degree of motivation** while performing different aspects of the design process as listed below. Scale: 1 = no confidence, 6 = fully confident
3. Rate your **degree of anxiety** (i.e., apprehension, stress) while performing different aspects of the design process as listed below. Scale: 1 = no anxiety, 6 = high anxiety

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1. What is your major?
    - Chemical and Biomolecular Engineering
    - Civil Engineering
    - Mechanical Engineering
    - Electrical Engineering
    - Computer Science
    - Computer Engineering
    - Sustainable Urban Environment
    - Applied Physics
    - Biomolecular Sciences
    - Mathematics
    - Integrated Digital Media
    - Other STEM
    - Other Non-STEM
2. How many years have you been pursuing an engineering degree?
3. What is your gender identity (select all that apply)?
    - Female
    - Genderqueer or gender fluid
    - Nonbinary
    - Male
    - Trans
    - Prefer to self-describe:
    - Prefer not to answer

Appendix 2

Table 1: Features, Attributes, and Values from each student participant response

Student Case	Design Characteristics	Total
1	{1} Independence of the disabled, {2} ability to communicate ideas effectively	2
2	{3} Makes it easier for injured or disabled people to put on clothing, allows them to function closer to a "normal" life. Quantifiable metrics are the {4} amount of time it takes to put on clothing each day and level of {5} comfort experienced by the disabled or injured person(s) in comparison to normal clothing. Level of comfort throughout the day should be higher in value relative to the amount of time to put on clothing.	3
3	{3} ease of use, {6} limited need for fine motor movement, {7} lightweight, {8} warm, {9} cheap, {5} comfortable, {10} fashionable, {11} environmentally friendly, {12} reusable, {13} washable	10
4	{4} time it takes for someone to put on the clothes, {3} user defined ease	2
5	{9} Affordable, {11} Environmental, {0} Assistive, {20} Ergonomic, {21} Inclusive, {14} Malleable, {15} Mass-producible, {0} Impactful {3} Disabled individuals should be able to use the product as a means to solve certain tasks without creating new problems The finished product needs to not only be affordable for all income classes, but also be wildly available in different retail environments and medical environments	7
6	{3} Easy to put on clothes that require little to no effort	1
7	{5} the overall design is comfortable and {3} simple to put on. the {16} adaptability of the design to various climates/temperatures (zippers). there are five zippers: one around the waist, one by the shoulders/top of the arms and one around the hood, and one for from neck to waist for an added option of wearage. not an overly complicated design, simple to wear.	3
8	I believe that the magnetically buttoned and features for both shirts and pants would make the product both {0} abstract and {0} desirable for the disabled. {17} The products would range from small to XXL. I believe these characteristics would hold high value to stakeholders	1
9	{9} Most stakeholders would want something cheap (including the client), {1} but they’d want an effective product as well that makes it worth it (ie not having someone else help you complete the task of dressing yourself). Quantifiable measurements include price of the device and {18} ratings from the targeted demographic on its {3} ease of use.	4

10	It’s a shirt with a built in sling. {3} The user can put it on simply through the side opposite the injury. {19} The shirt reduces the need to raise their arms above the head (which is painful) and can easily be put on {1} without assistance. The shirt can be modified to suit the user’s injuries (the side of the injury) and their shoulder heights). The shirt will be made to be {9} affordable, and is{13} machine wash safe. There is no other article of clothing on the market that is being sold with these characteristics, which makes it unique on the market. The shirt will be made of cheaper materials like nylon that can lower the cost of the shirt. The sling component will be designed with {22} health regulations in mind.	6