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Determining Student Self-Efficacy as Engineers Through a Multi-Cohort Mechanical Engineering Design Project

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Abstract

A multi-class design project was conducted in the mechanical engineering program at Slippery Rock University. Sophomore students in Dynamics (ENGR 240), Junior students in Machine Design (MECH 410), and junior/senior students in Manufacturing Processes (MECH 320) worked together in groups to design, analyze, build, and test trebuchets meant to launch baseballs. This design project occurred during the entire spring semester of 2023. The different courses completed their responsibilities and handed them off to the next course in the project throughout the semester starting in Dynamics, then Machine Design, and finally Manufacturing Processes. Upon the project's completion, the instructors made observations that influenced future student survey development and project iterations. This work presents the initial details of the project, faculty observations, and future data collection tools for project-based pedagogical research. The goal of the research is to use this project to identify when students self-identify as engineers and what events contribute to their perceived identities. Self-reflections and design competence surveys will be collected from the sophomore and junior students participating in this project and as seniors when they complete their capstone design course starting in Spring 2024.

Keywords

Self-efficacy, Project-based Design, Design Project, Mechanical Engineering

Nomenclature

SRU—Slippery Rock University
ME – Mechanical Engineering
PBL – Project-based learning
DBL – Design-based learning
DBEL – Design-based engineering learning
CAD – Computer-aided design

Introduction

Improving the quality of education is motivation for many who pursue careers in academia, and two common topics that appear are active learning and student self-efficacy. Active learning puts students in a position where they are discovering knowledge on their own rather than passively receiving information from an educator. Knowledge transfer through active learning strategies whether it be design-based learning, project-based learning, or problem-based learning is more effective than passive learning methods. In 2014, Freeman et al. conducted a meta-analysis of over 200 research studies investigating the effectiveness of active learning in STEM courses[1]. Through their analysis they found that the failure rate in courses utilizing active learning was 21.8% compared to 33.8% failure rate among traditional lecture-only style courses. Engineering specifically averaged a 9% lower failure rate in an active learning environment. This work illustrates that active learning works and outlines an implementation of it using a multi-cohort trebuchet design project. After discussion of the student designs and their teams' performance, the topic of student self-efficacy, i.e. their perception that they are capable of accomplishing a task[2], is presented for future research. In addition to learning the technical information of engineering, students must also build self-identification as an engineer. If they are confident in their abilities, they will persist in their degree program and in their career[3]. An ideal learning environment guides students through experiences that help them learn the material and gives them confidence in their abilities to create solutions to complex problems.

Project-Based Learning and Similar Projects

One such learning environment can be fostered using a project-based learning (PBL) approach. PBL is an active learning-focused teaching strategy that grants students autonomy while they work toward a relevant project solution[4]. By engaging with an open-ended problem, students are encouraged to learn the course concepts at their own pace and seek out other sources of information. Numerous studies have been conducted that demonstrate the efficacy of PBL in undergraduate engineering education[5–7]. Another approach called design-based learning (DBL) incorporates the concepts of PBL with an emphasis on the design process, and its origins can be traced to improving secondary science education[8–10]. In the past few decades, DBL's concepts have been integrated into engineering education. This learning approach prepares students to function in an engineering role by placing an emphasis on solving open-ended design problems. Wei et al. found that DBL has been shown to enhance engineering students' learning outcomes, especially when utilizing a systematic mode of engagement over a sequential one [11]. With proven success with PBL and DBL, engineering educators can choose to implement this technique in different ways.

There are several approaches that engineering educators have used to implement PBL and DBL into their curriculum. One option involves using sequenced courses working on a single project within a consistent engineering cohort. In his paper, Fumo utilized this implementation by requiring students in a thermal-fluids lab course and a measurements lab course to design components for use in their Capstone design course[12]. Morris also applied this method with two second-year courses focused on community-based team projects[13]. In both papers, students were exposed to a scaffolded real-world project, and results showed increased student engagement across all courses.

PBL has also been applied in an interdisciplinary education setting. Michael et al. studied students working on a project to design a low-cost 3D printer[14]. In their work, student teams included a freshmen-level Mechanical Engineering (ME) graphics class and a university robotics development group consisting of electrical and software engineering students. The design objectives were successfully met by the student teams, and students reported improvements in their Computer Aided Design (CAD) skills, understanding of electrical and mechanical integration in complex machines, and ability to function as a member of a team. This approach has also been used in capstone design courses by creating teams consisting of students from different disciplines[15,16,17]. In each case, the authors reported satisfactory project results and student experiences.

Another theme observed in the literature was the use of a joint project among multiple cohorts within the same engineering discipline. This application is most relevant to the methods discussed in this paper. Mynderse et al. implemented PBL modules in Mechatronics, Fluid Mechanics, and Heat Transfer courses for the design of a fluid-powered gantry crane[18]. Indirect assessment of all students indicated that their method contributed to student learning on topics covered in lecture and students' ability to synthesize new information not covered in class. Miller and Xu implemented a common project among mechanical and aerospace engineering undergraduate and graduate students to design a robotic mission to perform scientific experiments on the Moon[19]. While they did not collect data on the project's impacts, students demonstrated their enthusiasm for the project's realism and its connection between the courses.

Regardless of the implementation, research shows that PBL is an effective teaching method. However, as with all processes, its use alone does not guarantee students success, and the implementation of PBL can be improved and optimized. One such factor that can be addressed is how the PBL experiences contribute to students' self-efficacy, or their confidence, motivation, and ability to complete tasks.

Self-Efficacy

Self-efficacy is an important characteristic of successful engineers and can be cultivated during their educational experience. It is the perception that one is capable of completing a task, and it is associated not just with that perception but also motivation, outcome expectancy and anxiety[20]. Outcome expectancy is the person's prediction of what will happen based on their current skills; whether they believe they will be successful in the task. Anxiety is related to the person's fear of adverse consequences from their action. These four characteristics are affected by enactive experiences, vicarious experiences, social persuasions, and physiological/emotive states[2]. What students do in the course are those enactive experiences, so any learning activity should consider how it will affect self-efficacy in addition to student achievement. However, these experiences can be beneficial or detrimental to students depending on how they are implemented and the preparedness of the students. These enactive experiences are of most interest to the current work, since we are trying to identify which are the most impactful on the students.

The importance of self-efficacy is its positive relation to student achievement and persistence in engineering. Engineering self-efficacy is a better predictor of achievement in engineering courses and persistence in engineering as a career than prior accomplishments[3]. Understanding how students perceive themselves will allow educators to better tailor enactive experiences to grow students' self-efficacy. Another benefit, noted by Mamaril et al., is that students tend to be intrinsically motivated to master material when they believe they can do so[3]. Students will be willing to generate solutions for complex engineering problems, and that is of interest for engineering programs because that is one of the ABET learning outcomes[21]. There are benefits to improving students' self-efficacy, and the difficult task is quantifying it and identifying what enactive experiences are most effective in improving efficacy.

With the topics of active learning and self-efficacy in mind, at Slippery Rock University (SRU) a multi-cohort design project has been implemented in the mechanical engineering curriculum. Through this project and their capstone design courses, data will be collected and analyzed on student achievement of learning outcomes and engineering self-efficacy. This is done to identify the experiences that are most impactful as students develop into engineers. The goal is to use this knowledge to tailor the engineering curriculum to emphasize experiences with positive impacts to improve the student capability, self-efficacy, and persistence in engineering.

Project Description

A multi-cohort project was assigned to students in the Dynamics (ENGR 240/PHYS 315), Manufacturing Processes (MECH 320), and Machine Design with Lab (MECH 410) courses during the Spring 2023 semester at Slippery Rock University. The Engineering Design Tools (ENGR 120) course, which introduces students to CAD software, was also indirectly involved in the design process. However, ENGR 120 groups were only tasked with creating CAD models of the ENGR 240/MECH 410 teams' designs, and they were not directly involved in the design process. The objective of the project was to collaborate on the design, analysis, construction, and testing of a trebuchet that would launch a standard MLB baseball. There were 4 teams consisting of students from each course, with team assignments determined by the course instructors. The student teams had to adhere to the following design requirements:

- Must launch an official MLB baseball.
- Minimum range of 200 ft, maximum range of 300 ft
- Minimum factor of safety of 5
- Maximum trebuchet height of 6 feet
    - Includes a 6 feet limit on all links within the trebuchet.
- Must be able to be lifted by 2 people (without counterweight)
- Counterweights must consist of round weightlifting plates with 1 in ID.
- Budget limit of $500 per team
- Trigger assembly must be custom machined.

The student groups were also constrained to the use of the following materials in the construction of their trebuchets. This constraint was used to provide design experience like what students can expect in industry and to ensure that orders could be placed quickly and at a lower cost.

- 2x4 studs
- PVC pipes/fittings
- Plywood
- Framing brackets
- 1” Aluminum rod
- ½” PVC sheet

The overall project plan, seen in the Appendix in Figure 6, was modeled after the NASA Systems Engineering Processes and Requirements to include milestones of a preliminary design review (PDR), critical design review (CDR), and a final inspection before launch which would correspond to a system acceptance review (SAR)[22]. The motivation behind this was to introduce students to the design process and the concept of design reviews in their fourth semester. In this way, students will have experienced and be more familiar with the design process before they take their Capstone Design course. Students taking Dynamics in Spring 2023 who will take Machine Design in Spring 2024 will also get to experience both sides of the project. Moving forward each phase of the project will now be discussed in further detail.

The Spring 2023 project was first assigned to the students in the Dynamics course. During week 2 of the semester, students from the Dynamics and Machine Design courses met for a brainstorming session to kick off the project. The instructors were present during the brainstorming sessions and acted as facilitators. Attendance from the Manufacturing Processes and Engineering Design Tools teams was optional. Notes from this meeting were kept and uploaded to each team’s Microsoft Teams page, which were created to encourage engagement and communication between all course teams throughout the project. The Dynamics teams were then responsible for background research, design concept generation, and design concept selection. The main deliverables to the Machine Design students from this phase were the kinematic analysis, energy requirements, and recommended parameters of the trebuchet design. This process is outlined in the flowchart seen in Figure 1.

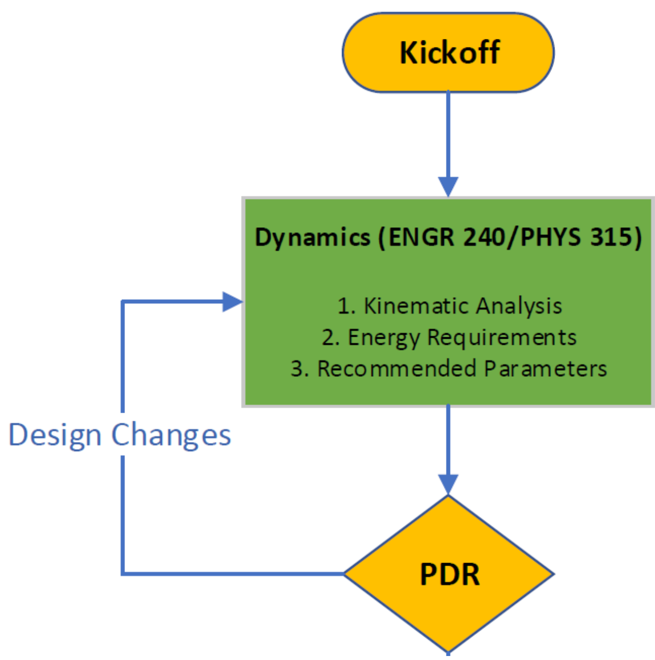

Figure 1: Project kickoff and Dynamics course deliverables for PDR

In week 5, the Dynamics and Machine Design teams met again for the PDR and project turnover. Again, the Manufacturing Processes and Engineering Design Tools teams' attendance was optional. Another brainstorming session was held after the PDR briefing from the Dynamics teams and notes were again retained and stored on the Microsoft Teams pages. Again, the instructors acted as facilitators, ensuring the effective transition of knowledge and responsibility for the project. At this stage, Machine Design students were able to question the initial design concepts and suggest design changes. At the conclusion of the PDR, the Machine Design teams assumed control of the design process and worked toward the main deliverables of eliminating stress concentrations, selecting materials, standardizing components, developing an initial CAD model, and determining factors of safety. This phase of the project can be seen in Figure 2, which led to the CDR meeting.

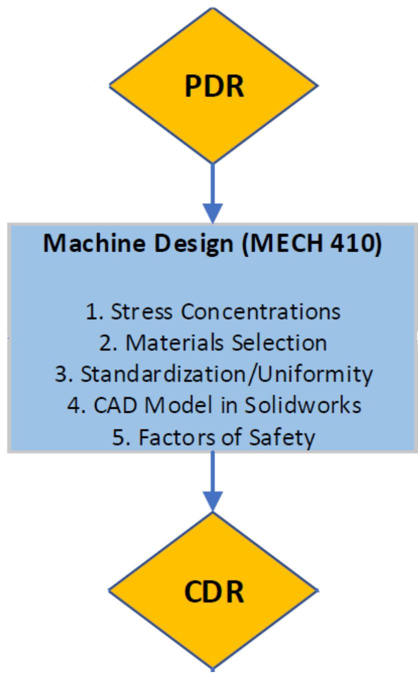

Figure 2: Machine Design phase and main deliverables for CDR

In week 10 of the semester, students from Dynamics, Machine Design, and Manufacturing Processes were required to attend the CDR meeting. At this point, the Machine Design groups presented their final designs with an emphasis on the deliverables to the other courses' teams. The Manufacturing Processes teams then assumed the responsibility of machining necessary components, assembling the trebuchet, and coordinating with the Machine Design teams on any design changes. In addition, the Dynamics teams were tasked with taking the CAD model of the final design and performing motion studies to simulate the design's performance, analyze forces between components, and analyze the projectile's impact. This analysis allowed the Dynamics students to learn how to use simulation tools and apply a more in-depth look at the designs by considering rigid body dynamics. The Engineering Design Tools groups were also tasked with developing the technical drawings of the provided CAD models to supply to the Manufacturing Processes teams. This phase of the process, seen in Figure 3, was the most dynamic since several teams could determine the need for design changes.

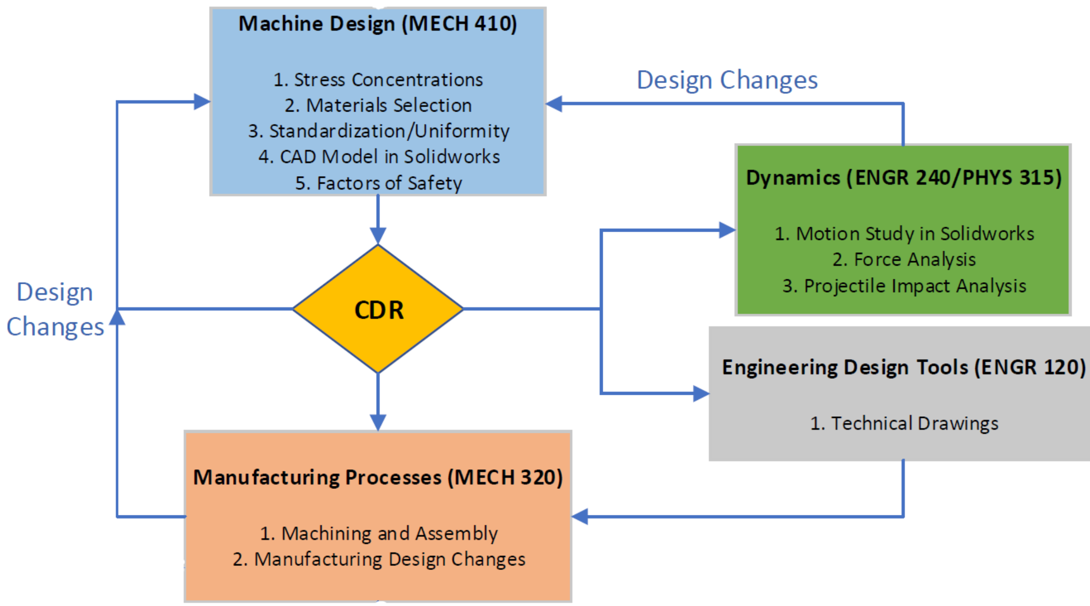

Figure 3: Post-CDR design and re-design process involving all four courses' teams.

At the conclusion of the project, teams from the Manufacturing Processes and Machine Design courses met in week 15 of the semester for final inspection of the trebuchet. The Machine Design teams were responsible for determining if the trebuchet was built as designed, and if there were any unsatisfactory factors of safety changes. If the trebuchet assembly was satisfactory, the Machine Design teams gave the final approval, and the trebuchet was cleared to launch a baseball in the demonstration. This process can be seen below in Figure 4. Each multi-cohort team successfully assembled and approved their trebuchets and participated in the demonstration.

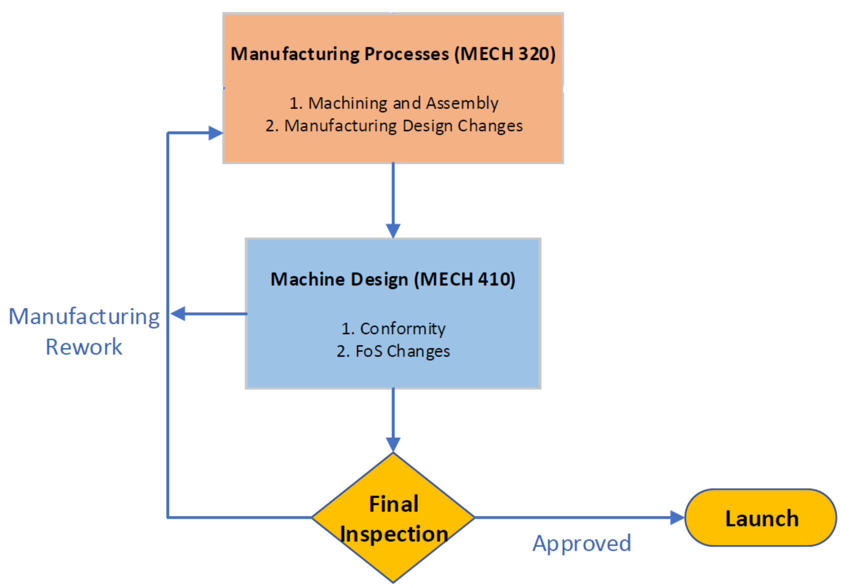

Figure 4: Final inspection and launch decision process.

The trebuchet demonstration was held at the SRU recreation fields and provided insight to improving the project in future iterations. The design requirements defined a required range of between 200 and 300 feet. However, since this was the first iteration of this project, the range requirement was removed. Each team's achievable range was recorded to serve as a benchmark for future project implementations. Out of the four teams, two were able to successfully launch a baseball multiple times. An example of one of the successful trebuchets can be seen in Figure *5*. The other two teams' trebuchets suffered catastrophic failures, after less than 3 launches. These failures were attributed to the general dimensioning, manufacturing issues, and failure to account for dynamic loads. One of failed trebuchets did not account for the warping of the wood beams in their design, and their counterweight arm would impact the frame on launch leading to its failure. The other failed trebuchet used a non-traditional whipper trebuchet, and after launch the throwing arm continued moving until it impacted the counterweight.

Figure 5: Example of a student-built trebuchet in Spring 2023

Instructor Observations and Project Improvements

Upon completion of the projects, the instructors met to discuss the plan for future iterations of the project. From the observations, several adjustments were made to the project deployment. The most notable is that the Spring 2024 project will begin with the Machine Design teams responsible for design, and the Dynamics teams will begin their analysis post PDR. This enables the Machine Design teams to have more time and control over the design choices and the Dynamics teams to have better foundational knowledge on rigid body dynamics before starting their analysis. The ME curriculum was modified to offer Manufacturing Processes in the fall semester starting in Fall 2023, so they will not be involved with future iterations of the project. As a result, the fabrication responsibilities will fall to the Machine Design teams.

The purpose of the project is to expose students to the entire design process in a simpler process to prepare them for the more complex projects they will see in the capstone design. To evaluate achievement of this goal, a survey addressing the engineering self-efficacy of the students was constructed from existing tools in the literature. The survey should be able to identify if the trebuchet project is a positive influence on the students' perceptions of their own engineering ability. This survey will be given to the students before and after the project each year they are in the engineering program. This is intended to follow each student cohort as they progress through the ME program to assess the self-efficacy of their engineering skills and which experiences most influence them. The motivation for and process of developing this survey for pedagogical research data collection is presented in the next section.

Future Self-Efficacy Data Collection

Students' perceptions of their own ability, or their self-efficacy, has been the topic of study for numerous education papers in engineering and other fields. As with most topics self-efficacy is a complex topic that is not constant for a person for all fields or times. Someone may be confident in their ability to do one task, but at a different time they may be unsure of themselves due to outside events. If the topic of that task changes so does their own perceived efficacy. In the context of engineering self-efficacy, Mamaril et al. described three different measures: general academic-self-efficacy, domain-general engineering self-efficacy, and skill based self-efficacy[3]. General academic self-efficacy refers to the students' belief in their ability to accomplish tasks in an academic setting regardless of the topic. Domain-general self-efficacy refers to general engineering tasks within their chosen field. Do they see themselves as being able to complete engineering tasks? Finally, skill-based self-efficacy refers to specific engineering skills such as completing different steps in the engineering design process. When quantifying students' self-efficacy researchers first identify which measure they are trying to capture.

Two of the common tools used to capture these self-efficacy data are Likert-based surveys and coding of open-response questions. The study conducted by Mamaril et al. developed and validated a Likert scale survey to measure the general engineering and skills specific measures of self-efficacy in undergraduate engineering students[3]. Their work showed that the general engineering self-efficacy is unidimensional, and the Engineering skills efficacy is multidimensional with factors of experimental skills, tinkering skills, and design. A more specific study was conducted by Carberry et al. who developed a Likert-based tool to study design self-efficacy, motivation, outcome expectancy, and anxiety in the design process while accounting for the effect of engineering experience[20]. Their work showed statistical differences in Self-efficacy when accounting for engineering experience, positive correlations between efficacy, motivation, and outcome expectancy, and negative correlations to anxiety. The tool they developed and validated addresses the same design efficacy of interest to this research study and will serve as a foundation to the data collection.

The other tool used is coding responses to open questions. This method asks participants to respond to open or close-ended questions verbally or through written responses. The responses are then classified into pre-determined categories based on the participants' descriptions. Hutchison-Green et al. conducted semi-structured interviews and analyzed the responses in this manner[23]. They investigated the self-efficacy, expectancy, values, and career plans of first-year engineering students. Through their 12 interviews they found that their first-year students were susceptible to basing their self-efficacy on comparisons to their peers rather than on their own mastery experiences in engineering classrooms. Additionally, their work showed that efficacy better predicted engineering achievement, and values better predicted career plans in their students. Chen et al. used a method recommended by the prior study to investigate the development of self-efficacy in different genders[24]. The methodology in this study focused on general engineering self-efficacy, in particular what are the experiences or events that are pertinent in its development, a similar goal to the current work.

In the work in progress study being presented, the purpose of the study is to identify significantly impactful experiences that improve student self-efficacy during their undergraduate education. This will be done through a cohort study of undergraduate mechanical engineering students at SRU. Starting in their sophomore year students at SRU begin their discipline specific courses, and in the mechanical engineering program they participate in the previously described trebuchet design project. In the beginning and end of each spring semester, participants will be asked to complete a survey meant to capture their design specific self-efficacy and general engineering self-efficacy. This survey will be conducted starting in their sophomore, junior, and senior years to track changes through time, and to better identify when specific experiences occur.

The survey will consist of three parts and is included in the appendices. First, demographic information will be captured to connect the yearly responses for each participant. In addition to demographics, participation in pre-collegiate/extracurricular engineering activities will be collected. In the study by Fantz et al., they investigated pre-collegiate factors that affect engineering self-efficacy[25]. They identified seven statistically significant pre-collegiate activities that positively affected engineering self-efficacy in first year students. It would be worthwhile to track these seven activities as they could present confounding effects. Second, the survey will utilize the Likert tool developed by Carberry et al. to capture the design specific self-efficacy, outcome expectancy, motivation, and anxiety[20]. With this it is hoped to capture when students' perceptions of their own abilities change through the study. Last, open-ended questions will be coded to identify what experiences may be affecting their engineering self-efficacy. These questions are based on the ones used by Chen et al., and will give students to the platform to specify which events affected them most[24]. The proposed survey is included in the appendix of this document.

One area that would be of interest for future analysis is investigating the effect of gender on student self-efficacy. Studies have identified statistically significant differences in self-efficacy levels and how they are development in men and women[24,26,27]. Investigating this immediately would not be practical with the low participant pool. As of Spring 2024 the number of students in the Mechanical Engineering program at SRU is growing, but still low, 14 seniors with 80 total students. With a limited number of possible participants identifying as women. Future expansion of the data collection to other universities could enable this axis to be explored in more detail.

Conclusion

At SRU a multi-cohort design project was implemented to increase the use of active learning in the Mechanical Engineering curriculum. This project asked sophomore and junior students in Manufacturing Processes, Machine Design, Engineering Design Tools, and Dynamics to design, build, and analyze a trebuchet in small groups. Students' interpersonal and collaboration skills were also emphasized throughout the project. Of the four trebuchet teams, two successfully launched multiple projectiles, while the other two teams suffered mechanical failures due to dimensioning, manufacturing errors, and neglecting dynamic loads. Positive student response to the project and instructor observations prompted the continuation of the project in Spring 2024. In the future, this project will be expanded into a study on student self-efficacy to better understand which experiences are impactful and beneficial as students develop into engineers.

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Appendices

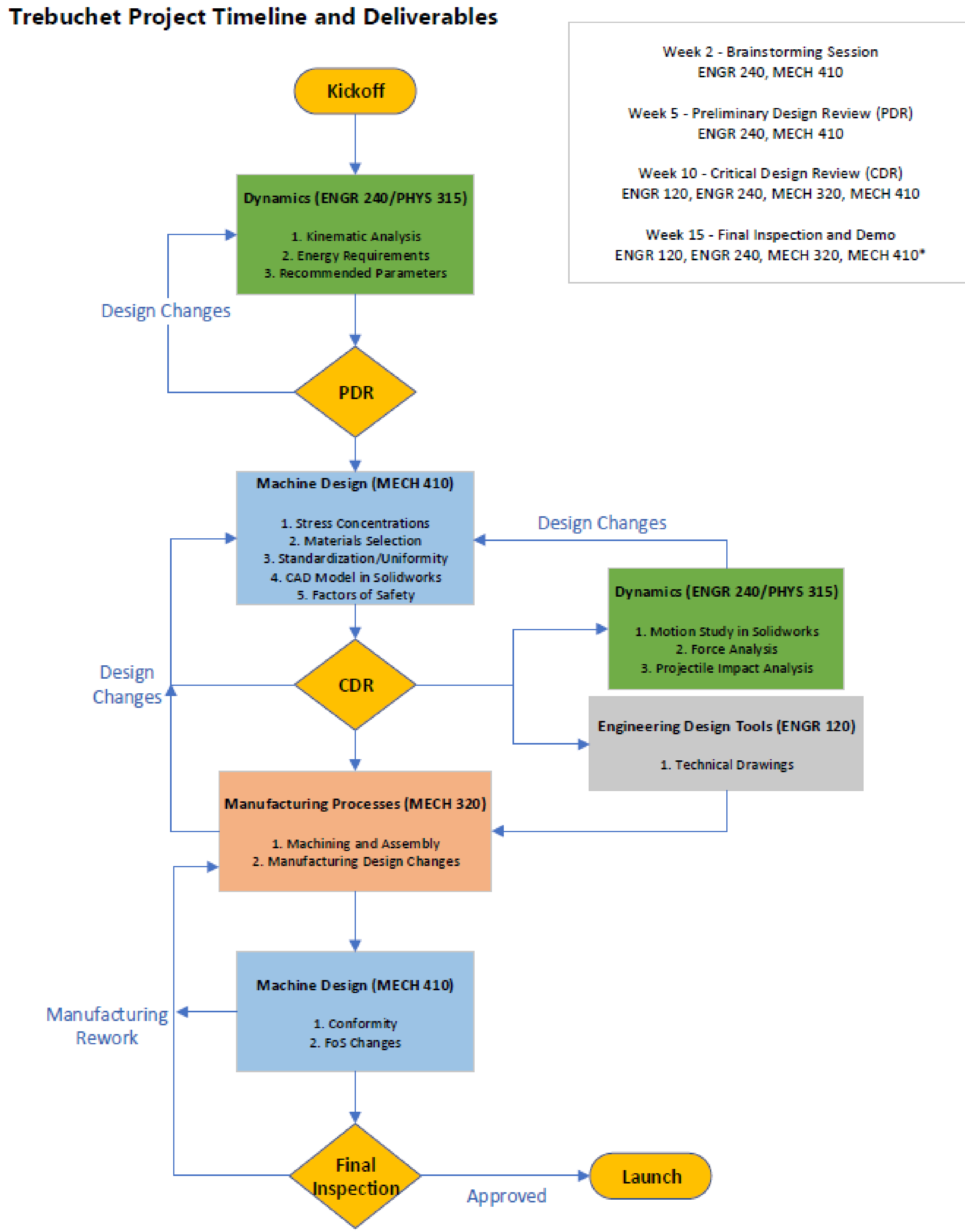

Figure 6: Trebuchet project design process among all classes involved.

Self-Efficacy Data Collection Survey

<u>Part 1, Demographic Information</u>

- What is your first name?
- What is your last name?
- What is your birth year?
- What is your gender identity? (use the other category to self-describe)
- What is your major?
    - Mechanical Engineering
    - Civil Engineering
    - Petroleum and Natural Gas Engineering
    - Industrial and Systems Engineering
    - Other
- Prior to coming to starting your undergraduate education, select each of the following that you participated in?
    - Programming as a hobby
    - Electronics as a hobby
    - Technology class
    - Producing video games as a hobby
    - Engineering class
    - Robotics as a hobby
    - Model rockets as a hobby

<u>Part 2, Design Skill Self-Efficacy</u>

*Based on your **current** abilities,* rate your **degree of confidence** (i.e. belief in your ability) to perform the following tasks by recording a number from 0 to 10. *(0=cannot do at all, 5=moderately can do, 10=highly certain can do)*

*Based on your **current** abilities,* rate **how motivated you would be** to perform the following tasks by recording a number from 0 to 10. *(0=not motivated, 5=moderately motivated, 10=highly motivated)*

*Based on your **current** abilities,* rate **how successful you would be** in performing the following tasks by recording a number from 0 to 10. For the "Test" category please rank it 2. *(0=cannot expect success, 5=moderate expectation of success, 10=highly certain of success)*

*Based on your **current** abilities,* rate **your degree of anxiety** (how apprehensive you would be) in performing the following tasks by recording a number from 0 to 10. *(0=not anxious at all, 5=moderately anxious, 10=highly anxious)*

(Each prompt will ask participants to fill in the following table)

Task	1	2	3	4	5	6	7	8	9	10
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										
Test (please rank at 2)										

<u>Part 3, Experiences and Self-Efficacy</u>

Please answer the following free response questions. There is no minimum or maximum response length but do reflect on your answer before writing. All questions are optional, and you may exit the survey at any time.

- What events have affected your confidence in your engineering skills? How did the event(s) affect your confidence?
- Can you think of a specific event that made you feel more confident in your engineering abilities?
- Has anyone encouraged or inspired you to be an engineer? If so, who? How did they encourage or inspire you?
- Describe how you typically feel when doing engineering work.