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Electric Ceiling Hoist: A Semester Project with Competing Forces to Enhance Student Learning in Machine Design

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Abstract

Mechanical Engineering Design (i.e., Machine Design) is a pivotal course in any Mechanical Engineering or Mechatronic Engineering curriculum. This course marks the transition from learning fundamental mathematics and science to applying them for design of engineering solutions. Combined with its rigorous and varied content, the manufacture and build of said design solutions presents a definitive experience for undergraduate engineering students. At California State University Chico, Machine Design is a four unit class consisting of three weekly one hour lectures and a two-hour activity. The purpose of this paper is to consider the effectiveness of a hands-on semester design project facilitated through the weekly two-hour activity to improve the student learning experience. In other words, does requiring students to design, build, and test a machine help them to understand the course material of Machine Design better? The semester project in this study involved designing and building an electric ceiling hoist but with a novel twist. A point scheme incentivized teams to develop a higher lifting capacity, but stress, deflection, and lifting time were competing forces. Two surveys were administered to help quantify any said benefits towards an improved learning experience. The first one was given early in the semester to assess student background while the second was given upon project completion. A careful evaluation of student feedback and measured performances is presented herein.

I. Introduction

At California State University Chico, the mechanical and mechatronic engineering students are required to complete a junior level design course titled Mechanical Engineering Design, MECH 340. The expectations in this course are considerable given that students enter with only the basic courses in statics, materials, and strengths. Suddenly, students must learn in one semester how to design a complex engineering solution which may involve load determination, component design, power transmission, shafts, gears, bearings, couplers, fatigue, etc. The apt description for such a combination is machine and quite often it is known as Machine Design. For the textbook, the instructor utilizes the tenth edition of *Shigley's* [1]. With four units, the course model consists of both lectures and activities. There are three one-hour lectures and one two-hour activity every week. While the lectures are traditional in nature, the activity time present a special opportunity to support the course curriculum and enhance the learning outcomes. To appreciate the extensive nature of this class, the course outcomes are given below.

<u>MECH 340 Course Outcomes</u>: Students shall be able to:

1) Apply energy methods to relate the steady-state input/output characteristics of machines to relate quantities such as torque, force, velocity, and angular velocity.
2) Determine stresses in straight, slender bodies caused by combinations of axial, shear, bending, and torsional loads.
3) Determine stresses in curved beams.
4) Determine miscellaneous stresses in machine components such as direct shear, tearout, and bearing stresses that occur commonly with interconnected machine parts.
5) Apply stress concentration factors where appropriate.
6) Determine principal stresses due to combinations of simple stress states.
7) Size components using static failure theory.
8) Size components using fatigue failure theory.
9) Estimate and apply appropriate factors of safety for a given machine environment and loading, and apply them in selecting materials and sizing selected machine components.
10) Determine the appropriate size of a rotating shaft for infinite-life strength.
11) Select components such as bearings, gears, springs, threaded fasteners, clutches and brakes based on accepted practice and theory for particular machine elements.

Regarding effective teaching practices for such a course, there is considerable evidence supporting that a hands-on [2], [3] or project-based [4] approach improves student outcomes. Clearly there is a benefit to practicing the engineering design process in a real-world setting. As students learn the curriculum to design engineering solutions, tangible assignments such as product emulation [5] may bridge the connections between theory and application. Other examples include a vending machine [6] and water turbine [7]. Furthermore, software and its practice [8], [9], [10] play a critical role is supporting the engineering analysis due to the level of complexity often reached in analysis. Lastly, there is perhaps no better teaching moment than when a student attempts to make/machine the very thing that they designed. That is supporting students for machining experience [11] undoubtedly improves their engineering design skills.

II. Assignment

For the Fall 2019 class of Mechanical Engineering Design at Chico State, a hands-on semester project titled Electric Ceiling Hoist was facilitated through the weekly two-hour activity time. The assignment and outcomes of this project are the focus of this paper and a detailed account is presented herein. For the first five weeks of the semester, the two-hour weekly activities were individual assignments that focused on component design, report writing, and utilizing software such as excel or Matlab. These assignments paralleled the lecture and stepped up in difficulty and requirements. The last of these individual assignments was a paper design for a simplified version of the semester project. The motivation here was that every student must conduct the prescribed engineering design analysis before joining a group. This assignment is shown below.

The picture below represents a powered hoist mounted to a rectangular Aluminum beam with a 137*W* stepper motor providing torque to the solid steel shaft through a flexible coupling. You are tasked with investigating this system by considering both fixed and adjustable parameters and deciding on a maximum lifting capacity (i.e., *m*). Submit a summary report with the following items included:

- Title page
- Assumptions and system parameters (e.g., spool diameter, shaft *rpm*, etc.)
- FBD of beam and shaft, drawn within Microsoft Word
- Engineering analysis (e.g., max stress, deflections, slope through bearings, etc.)
- Equations typed with brief descriptions
- SolidWorks drawing of final configuration with dimensions

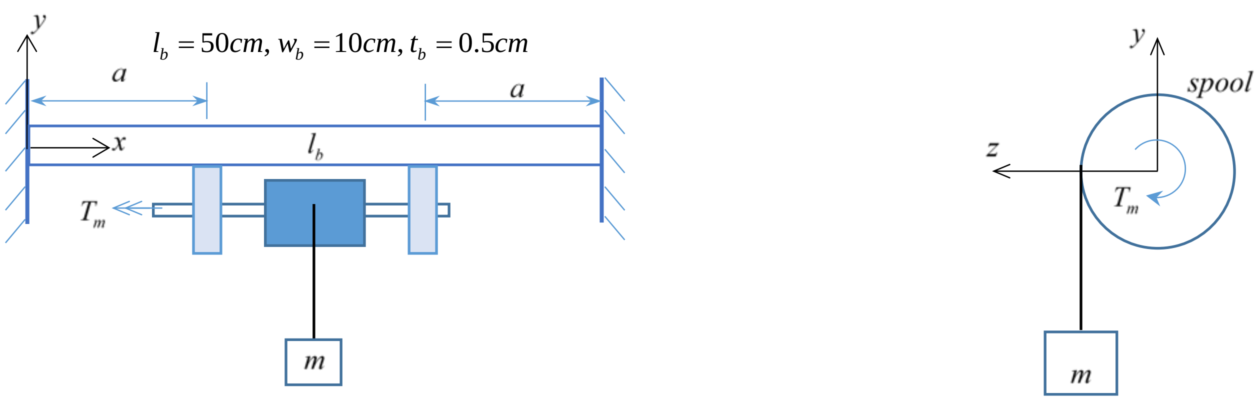


Figure 1. Individial activity assignment to prepare students for semester project.

By requiring them to determine maximum lifting capacity, the students quickly stumbled into a conundrum of competing forces and implicit relationships between maximum mass, angular acceleration, dynamic loading, minimum shaft diameter, and beam deflection. The level of consternation and discussion that ensued is difficult to capture here, but suffice to say that the students were both flabbergasted and enthralled. To solve this problem students developed Excel spreadsheets to investigate and plot the relationships between system parameters. After completing this assignment, students self-selected into groups of three or four for the official semester project. The project was essentially the same but with an added twist. Extra credit would be granted to the team which scored the highest points as determined by the natural log of their max lifting mass squared divided by the time required to lift. Although the $\ln(m^2/t)$ is not mathematically valid due to the dimensions of the argument, it allowed for a fun and competitive comparison between the teams. Moreover, it incentivized the teams to build a machine that could lift more but with diminishing returns. With gearing, any increase in lifting mass will be equally offset by an increased lifting time. All else being equal, these two parameters are theoretically the inverse of each other, hence the squaring of mass to produce an increase in points with added lifting mass. Assuming maximum power output from the 137W motor and a series of gear ratios to increase the torque output and thus lifting mass, a plot of the extra credit relation is given below in Figure 1 to illustrate the scoring scheme.

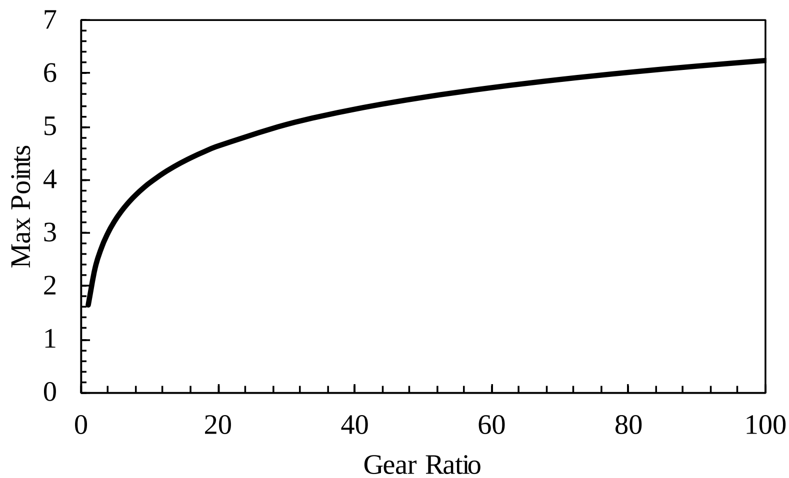


Figure 2. A theoretical points scheme for an increasing gear ratio.

All 12 teams were supplied with an identical 137W stepper motor, driver, power supply, and aluminum beam. They were tasked with deciding their target lifting mass and required gearing. Additionally, the beam's required mounting bolt pattern and tolerances was provided as shown below in Figure 2.

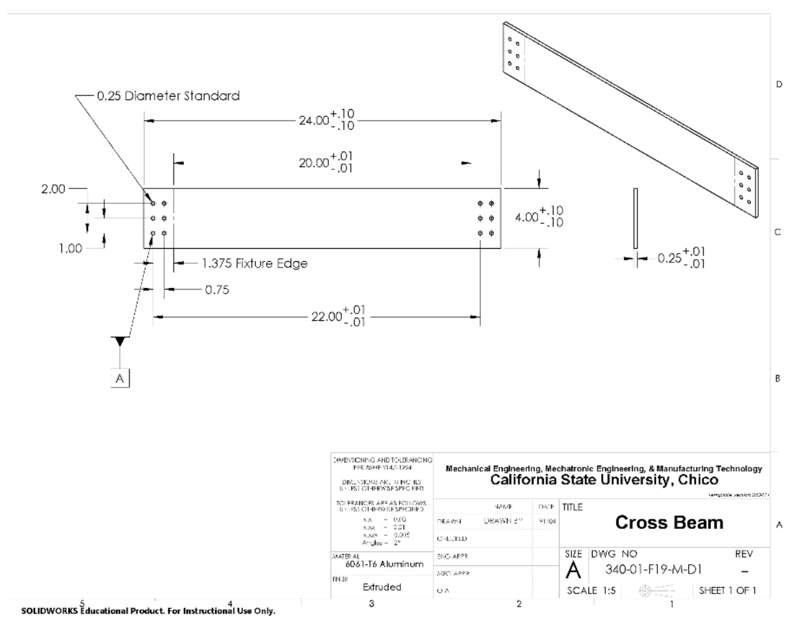


Figure 3. Mechanical drawing and bolt pattern of Aluminum beam.

The official semester project assignment is shown below in Figure 4. All of the detailed requirements and their respective points are described in the action items table within. Toward the end of the semester however, a judgment call was made to remove the strain gage requirement.

Course: MECH 340 Mechanical Engineering Design Fall 2019
Instructor: Dr. Dennis O'Connor, dmoconnor@csuchico.edu
Project: Electric Ceiling Hoist

You and your team are tasked with designing, building, and testing an electric ceiling hoist. Each team is given a $200 budget and must design against their own targeted lifting capacity and speed. There will be an extra credit bonus prize for the team that can safely lift the most in the least amount of time. The hoist must be mounted to the Aluminum beam between the supports as shown below in Figure 1. Each team will be provided with the beam and specifications for mounting to the fixed supports.

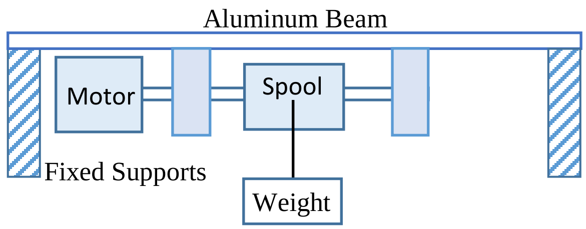


Figure 1. Simplified schematic of semester project.

Each team will also be provided with a 137W stepper motor, power supply and driver. Upon project completion, each team will install a strain gage on their Aluminum beam to compare with their predicted stress through engineering analysis with that during testing of their machine. The following table lists the required action items to include in your analysis and report.

Table 1. Actions items and grading rubric for team project report.

Items	Max	Score
Project Definition, Assumptions	5	
Lifting Capacity, Speed	5	
Loading Conditions, FBDs	10	
Engineering Analysis, Beam and Shaft	10	
Shaft Design, Shoulders, Keyways, etc.	10	
Fatigue Analysis	10	
Bearings, Fasteners, Couplers, Gearing, etc.	5	
Spool, Cabling	5	
Cost Report	5	
Assembly and Part Drawings	10	
Summary and Conclusions	5	
Format	20	
Total	100	

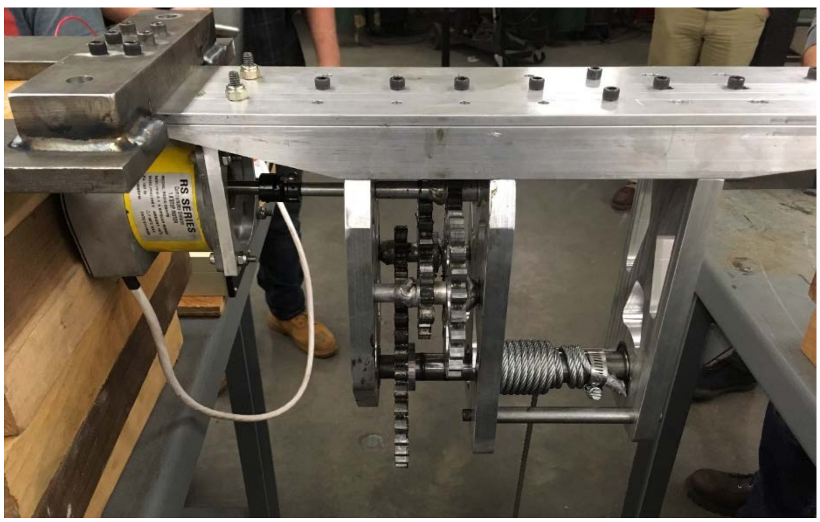
Figure 4. Semester project assignment which included grading rubric.

III. Student Projects

There were a total of twelved groups in the Fall 2019 semester of MECH 340. All but one group successfully finished and tested their machine. Three of the machines are featured here to illustrate the student experience. As can be seen by the following three examples, there was considerable variation in student background and experience with with respect to machining equipment such as lathes, mills, and CNC.

A. Sample 1: Group 2

The most impressive of all 12 projects, group 2 designed and manufactured an electric ceiling hoist with a triple gear reduction producing an overall gear ratio of 52:1. Their engineering analysis was a corroboration between hand calculations and SolidWorks simulation. Each shaft, gear, and bearing support was fully designed and then machined using an in-house CNC machine. Figure 5 below is a picture of their machine during testing and assemble drawing.

(a)


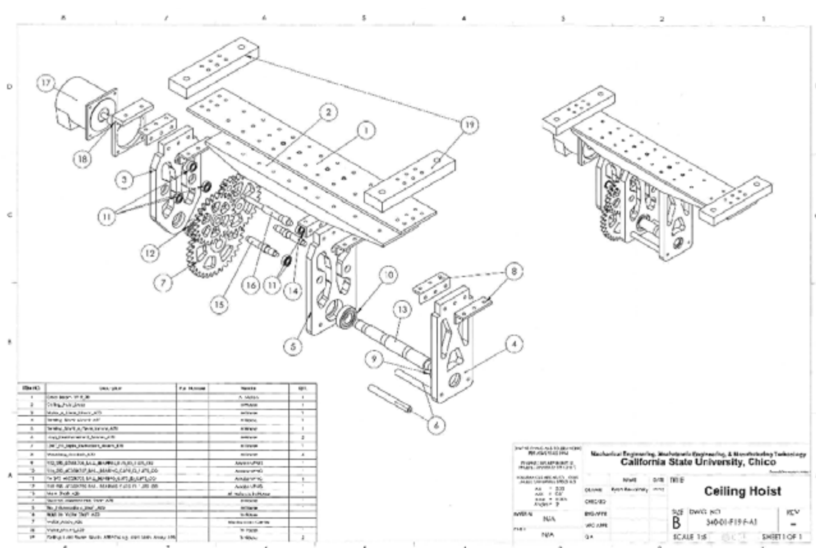
(b)


Figure 5. Electric ceiling hoist from group 2; (a) testing, and (b) assembly drawing.

B. Sample 2: Group 3

The students in group 3 did not have the level of machine shop experience observed in group 2, however their hoist managed perform reasonably well. This was the only group that utilized helical gears, and their single reduction produced a 2.5:1 gear ratio. Their engineering analysis relied on hand calculations, but their analysis was thorough and even accounted for the axial load produced from helical gears. The two shafts were fully designed and machined on in-house lathes including key-ways while their bearing supports were cut from wood using a standard band saw and drill press. Unsurprisingly, there was noticeable misalignment in the bearing supports which led to occasional binding in the gears. Indeed, these students learned an importance lesson on maintaining tolerances.

(a)

(b)

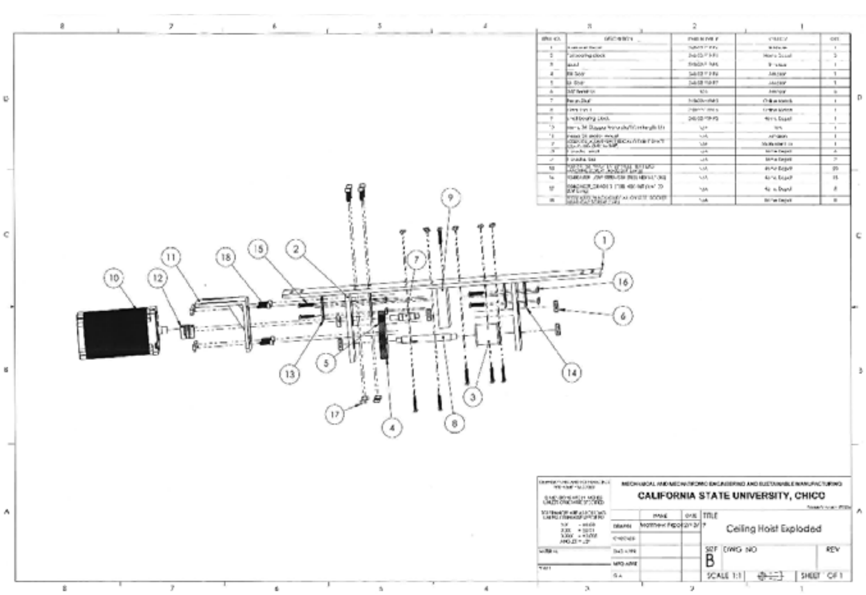
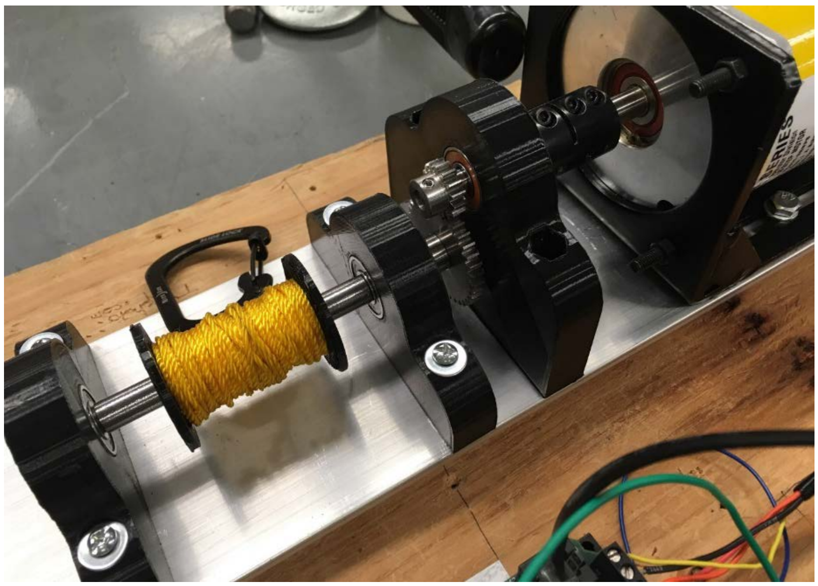


Figure 6. Electric ceiling hoist from group 3; (a) testing, and (b) assembly drawing.

C. Sample 3: Group 9

The students in group 9 designed their ceiling hoist with a 2.4:1 gear ratio using spur gears. By utilizing a 3D printer, their bearing supports held sufficient tolerances for a smooth and clean lifting operation. The bearings were glued with plastic epoxy into the 3D prints while the gears relied on set screws to fix onto shafts. Their shafts were properly designed for infinite life and machined on an in-house lathe. Their engineering analysis included both hand calculations and SolidWorks simulation for the Aluminum beam and shafts. Though difficult to illustrate here, their technical report was remarkably professional and thorough. Their attention to detail and documentation in every calculation was superlative.

(a)



(b)

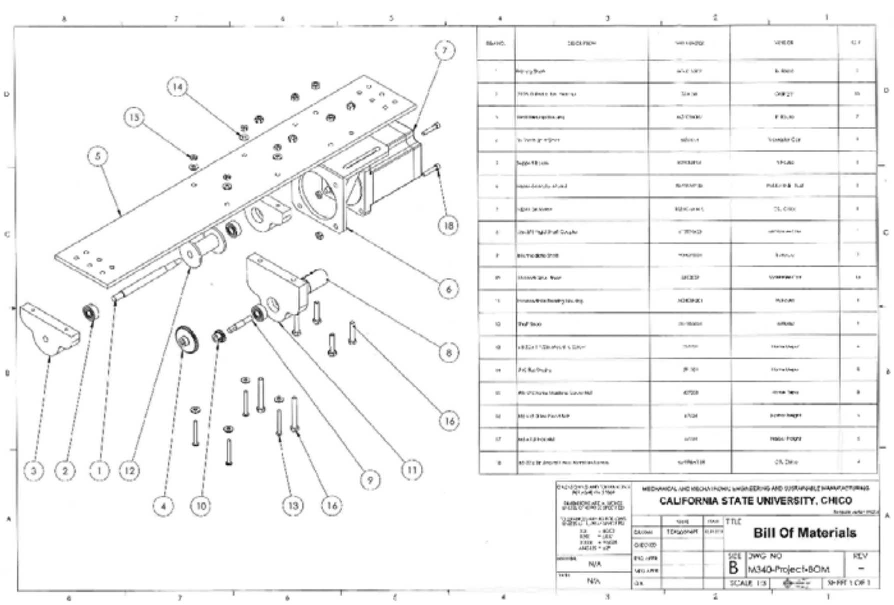


Figure 7. Electric ceiling hoist from group 9; (a) after testing, and (b) assembly drawing.

IV. Student Survey

Two in-class surveys were administered during the Fall 2019 semesester of MECH 340. The first survey was given during the second week of the semester to obtain an indication of student background and confidence. All 44 students enrolled completed the survey. Table 1 below summarizes the questions and response scheme ranging from 1 for none to 5 for substantial. The average response with standard deviation is also given below in Figure 8. From the responses to Question I, much of the class centered on only having *some* experience working on machines. Given that these students are Mechanical and Mechatronic Engineering majors, this was a bit surprising. On the other hand, the responses to Question II suggested an overwhelming preference to Learning-by-doing. This question was meant to gage the enthusiasm for a hands-on assignment. Further, as seen by Question III, much of the class had only some experience in the machine shop. From the comments section, this came from a one semester pre-requisite class in manufacturing. Finally, the last question was aimed at the level of self-confidence for being successful in this class. The responses were up-beat as the majority of the class answered with Lots.

Table 1. Summary of Survey 1 response scheme and questions.

None	Little	Some	Lots	Substantial
1	2	3	4	5

No.	Question
I	Your experience with building/working on machines (e.g., lawnmowers, cars, etc.)?
II	Your preference for Learning-by-doing?
III	Your experience with machine-shop equipment (e.g. lathe, mill, drill-press, etc.)?
IV	Your anticipated level of success in this class?

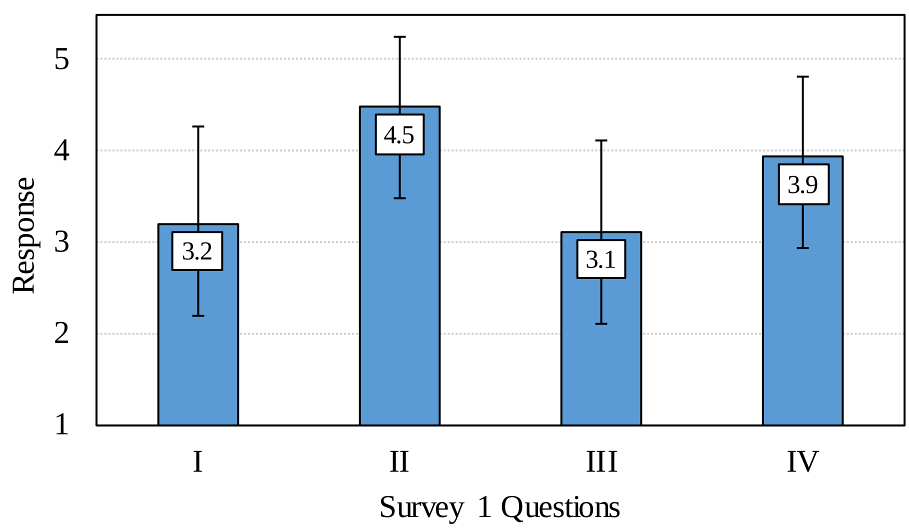


Figure 8. Survey 1 responses averaged with standard deviation.

In the final week of the semester, just before the project was due, the second survey was administered in regular class-time. Table 2 below lists the questions from this survey and Figure 9 gives their response. With only 32 of the 44 students in attendance, this was clearly an inopportune time to give the survey as many were busy in the machine shop trying to finish their project. Regarding Question I on whether or not such a semester project improved their level of understanding, their response was a resounding yes with most answering substantial. From the comments section, many students had terrific things to say. For instance:

"Being forced to create a prototype of a machine really helped me with the design process in general. Designing a shaft and picking bearings is much easier on paper with a theoretical machine."

Considering future iterations of this project, Question II sought to realize how it might be improved. Based on comments, many mentioned to order parts sooner while others complained about having insufficient machining experience. From Question III, a clear majority of the class had a favorable experience with many positive comments. For instance:

"I believe the experience was phenomenal. We had the opportunity to create our design instead of everything being theoretical."

For the last question, the motivation was to see if this experience boosted their self-confidence. Interestingly, the average response was strikingly similar to Question IV from Survey 1.

Table 2. Survey 2 questions given at end of semester class.

None	Little	Some	Lots	Substantial
1	2	3	4	5

No.	Question
1	The project enhanced your level of understanding of course material?
2	There were aspects of the project which could be improved?
3	Overall, your experience with the project was favorable?
4	Your anticipated level of success as a Mechanical/Mechatronic Engineer?

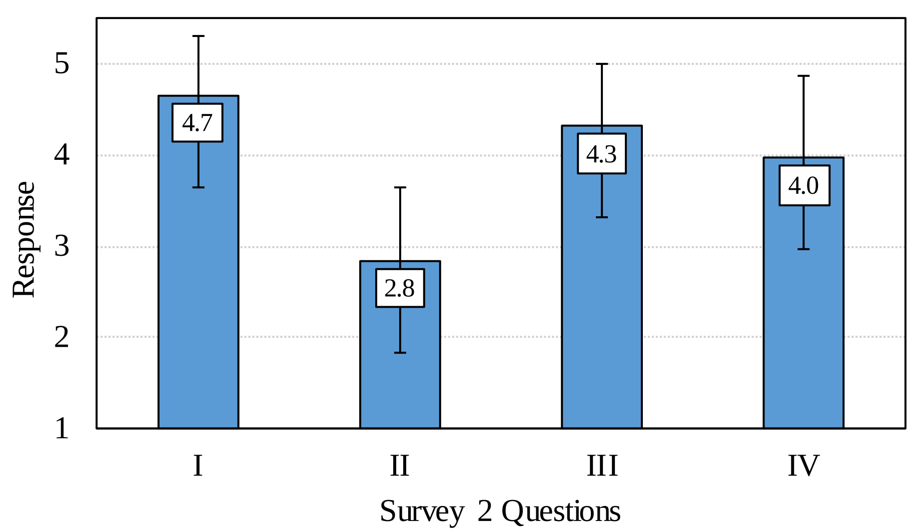


Figure 9. Survey 2 responses averaged with standard deviation.

V. Conclusion

Mechanical Engineering Design (MECH 340) at Chico State is a junior level class which essentially requires the students to learn how to design a powered machine all in one semester. From the aforementioned student outcomes, everything from load determination, power transmission, component design, fatigue, shafts, bearings, and gears, students are expected to fully understand. The semester project presented herein was designed to exactly parallel the course curriculum and enhance the student learning experience. Based on each group's technical report, their porotype, and surveyed responses, this project was a remarkable success. Having the preliminary assignment ensured that each individual student joined their semester project team practiced with the required engineering analysis. The extra credit incentive and novel point scheme created a friendly competitive atmosphere for "best" machine. Teams took extra care with their designs and optimization. Although there was varied background with machining experience, every group designed and machined their own shafts, including shoulders and keyways. Groups without CNC experience found other means to manufacture their prototype such as 3D printers and woodworking. The teaching moments were abundant throughout the semester. For many, having to reconcile their theoretical design with the reality of part catalogues was a source of great frustration and enlightenment. Indeed this was their first time looking to purchase bearings, gears, and round bar stock. From the comments section, one student captured what many had to say:

"This was my first real 'Design' experience and I discovered that I actually enjoyed the whole thing."

Indeed, for many students, this was their first design and manufacturing experience. In one semester, they learned and followed the engineering design process to manufacture a powered machine. For a one semester junior level course, this was no small achievement.

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