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Undergraduate Engineering Machine Design Projects

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Abstract: This paper reports on engineering design projects involving undergraduate students. The focus of the paper is on various design projects assigned to an undergraduate junior-level mechanical engineering machine design course. The paper summarizes design projects assigned over the past 20-years. These projects are varied and include many types: gear drives, optimization, design of various frames and projects where the students design a custom machine of their choosing allowing a great deal of creativity. The typical project defines a set of Design Functions and Design Requirements. Students work in teams of 3 throughout the semester. Various software tools are used and the final design is presented to the class. Each team must produce a detailed set of engineering drawings as well as a final design report. The design project is extremely valuable in teaching the importance of team project organization and timing, as well as tolerancing, manufacturing techniques, fits and producing detailed engineering drawings. Finally, the design project supported the ABET Student Outcome 5 and 7: Ability to function effectively on a team, and Ability to acquire new knowledge. These outcomes are assessed with an in-class survey and results reported.

1. Introduction

The use of design projects (or capstone projects) is an essential part of the engineering educational experience. Design projects are used to improve technical communication and engineering skills, develop new knowledge, and help students function effectively on a team. Design projects tend to be much more involved and complex than typical problem-solving and thus help students develop critical skills needed for a successful career in engineering. These skills may include project management, creating Gantt chart, and maintaining schedules.

The lead author has published significantly in the field of engineering design and capstone projects[1-6]. In [1], the design of a low-cost 3D printer is discussed. This was a collaborative project between a freshman level mechanical engineering graphics class and GUBotDev (Gannon University Robotic Development Group). GUBotDev produced an initial "rough" prototype of the low-cost 3D printer by using off-the-shelf and fabricated components. The printer was too expensive and unreliable to be used for outreach purposes. As a result of inter-departmental collaboration between the freshman graphics team, the electrical engineering department, and GuBotDev, a new low-cost 3D printer was developed. Ultimately, 50 high school students from Erie county built the low cost 3D printers with help from the GUBotDev team. This is an excellent example of how large design projects can be used to foster inter-departmental collaboration and expose freshman level students to upper classmen. The paper supported ABET outcome 5 "Ability to function effectively on a team."

Reference [2], shows how design projects can be used to foster self-directed learning (SDL). This paper details how various course design projects are used to help students gain knowledge of high-level engineering software programs through SDL while satisfying ABET outcome 7 to "acquire new knowledge."

Finally, References [3 – 6] detail various senior capstone projects whereby groups of students are partnered with industry and faculty to solve large, complex engineering problems. These papers are good examples of how senior capstone projects can support multiple ABET outcomes while giving students much needed industry experience.

2. Design Projects Incorporated into Machine Design

In the freshman and sophomore years of a mechanical engineering program, the student learns the tools of fundamental mechanics and design. In the junior and senior year, the student learns how to apply these tools to solve complex problems. An example of a complex problem would be the two design projects assigned in machine design. In these projects, several fundamental machine elements (components) are needed to form integrated subassemblies, and these are assembled into the final system. Principals of machine design and strength of material are implored. For the past two decades, machine design has been structured to include typical end-of-chapter homework problems, in-class quizzes, two exams, and two design projects. The two design projects account for a significant portion of the overall grade (typically 40 – 50%).

Design Project 1

The first design project is assigned around week 3 and students typically have 4 weeks to complete it. The assignment coincides with the completion of the strength of material and failure theory review. Consequently, design project 1 involves the design of a simple machine. The emphasis is more on structural design and less on machine elements. This first project mostly contains simple structural elements such as beams, axial members, trusses, columns, fasteners in shear, etc. Typical devices are shown in Fig. 1. Students are required to design these devices to meet a set of design functions and requirements. Design requirements include, but are not limited to, items such as: minimum factors of safety, all parts must be standard purchased components, operating loads, maximum deflections, and travel requirements, as well as maximum package size. Students work in teams of 2 or 3 and document their work in a formal report.

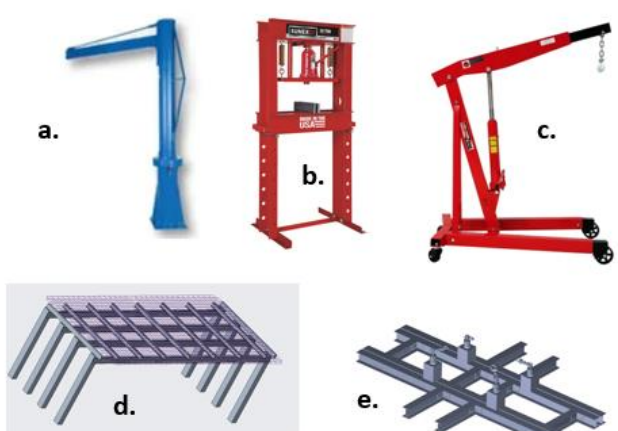

Figure 1. Typical devices for Design Project 1: jib crane (a), press (b), shop lift (c), shelving (d), airplane hoist (e).

The devices shown in Fig. 1 have been used for the first design project for multiple years. For example, the shop press shown Fig. 1b has been used 3 times. Each time, the load capacity requirement for the press has changed from 10 to 25 tons, and then to 50 tons.

In addition to supporting ABET outcomes 5 and 7, design project 1 also addresses a need for improvement identified by the ME Industrial Advisory Board. The Board is strongly influenced by small- and medium-sized manufacturers in northwest Pennsylvania. The board identified a need for improvement in CAD skills, drawing interpretation, and ability to create working and detailed drawings[7]. Since part of the project requirements include creating a detailed CAD model, assembly BOM, and detailed drawing for each critical component, this need for continuous improvement is addressed. Some examples of student work are shown in Fig. 2.

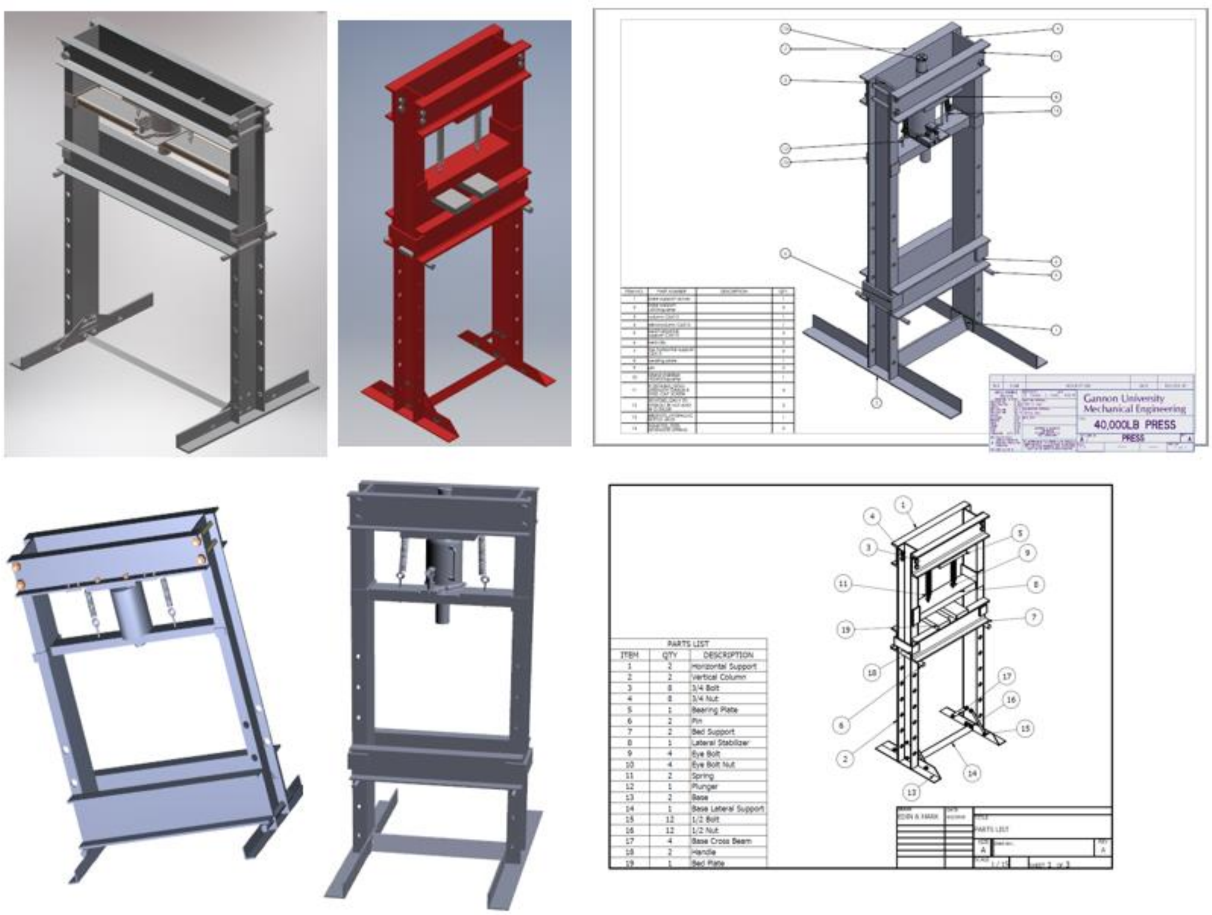

Figure 2. Examples of student work for 20-ton shop press. Students must create CAD assembly model, detailed assembly drawing with BOM and detailed drawings for each critical component.

Design Project 2

The second design project, usually assigned at week 6 or 7, is much more involved. Design of machine elements are incorporated into this project. The second design project either involves the design of a speed reducer (two-stage gear box) or it can be a student-selected project. The student-selected project must be preapproved and include multiple machine elements. For the past decade, the second design project has altered year-to-year between the speed reducer and student-selected project. There are pros/cons for each type. A detailed 10-question survey was given to the class for assessment purposes. The survey clearly shows advantages and disadvantages of each project type. This is detailed below in the Assessment section.

The Gearbox Design Project – Speed Reducer

This second design project option involves the design of a multi-stage, parallel shaft, gearbox. The outcome of this project is for the student to experience the open-ended, iterative nature of the design process, going above and beyond the well specified nature of the design of specific machine elements and to experience the collaborative nature of a design, involving several separate design phases that ultimately need to be integrated. However, a mastery of the design of machine elements is still needed to complete these tasks. Similar to design project 1, students work in groups of 2 or 3. Each time the project is assigned, the power requirement will change making the project "unique" for that class.

As seen in Fig. 3, the entire process is iterative if one desires a design that optimizes cost, quality, and schedule.

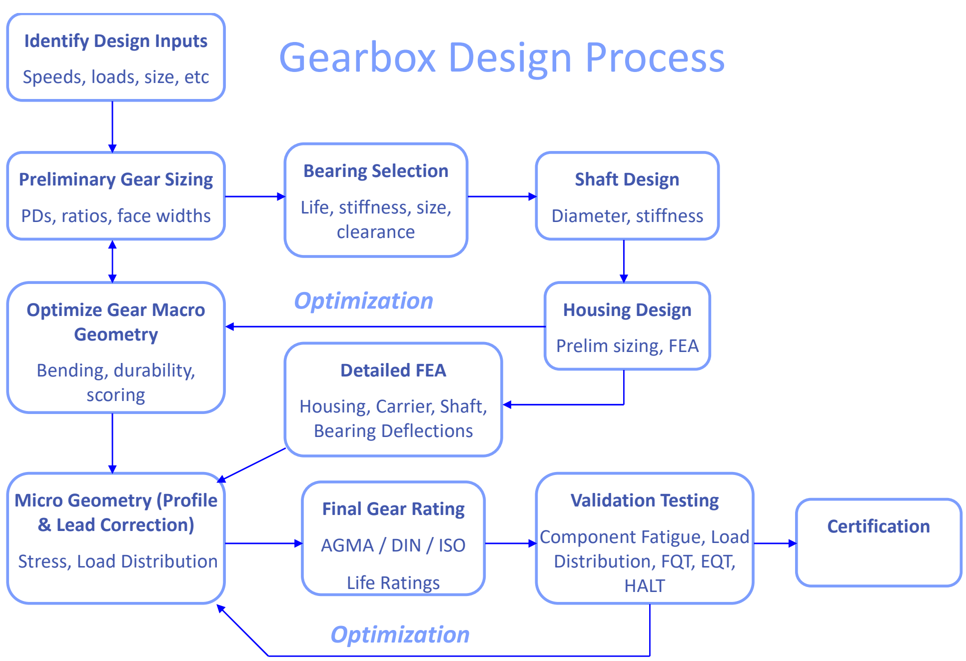

Figure 3. The Typical Gearbox Design Process

To accomplish the iterative nature of this project, modern computer tools will be needed. These tools will be shown to save time, as well as reduce the opportunity for errors in the iterative calculation process. The design of power transmission devices is often used as an example to show how computer tools can simplify the iterative design process[8].

For this project, students are first assigned the basic high-level requirements for a gearbox. These requirements are input and output speeds, horsepower, service factor, weight, size, reliability, cost, and schedule. The typical gearbox will involve 5 subsystems:

1) Gearing
2) Bearings
3) Shafting
4) Housing
5) Lubrication

The design problem will progress through the component selection of each subsystem, resulting in a 3-D solid model and 2-D drawings for the finished gearbox. Of course, the iterative nature of the design process will become quite evident early in the project. The project is divided into several sub-projects that are submitted throughout the semester for evaluation.

Starting with gearing, the student will be introduced to the concept of a gear tooth profile and the involute. A software program will be written such that the student can generate a typical involute tooth profile which will be needed for later design stages of the project. Most often this work can be done in Excel[9], Fortran[10], or Visual Basic[11] programming. The student will be given specific gearing macro-geometry as constraints.

The involute can then be expanded to form an entire tooth, using such 3-D CAD modeling tools as Pro-Engineer PTC Creo[12] (or equivalent), and then an entire gear is modeled. A suitable mating gear can be similarly generated and the two gears can be aligned at the proper center distances to form a kinematic model using a tool such as Working Model[13] (or equivalent). The gear teeth can then be progressed thru several degrees of rotation to show the contact points along the gear tooth involute profile as the mating surfaces.

Next the student will develop a preliminary gear ratio and diameters that will meet the stated requirements for input and output speed. The problem will be specified in such a way that a multi-stage, parallel shaft, gearbox will be required. This will be obvious after the design constraints for gearing and center distances are understood. To keep the problem less complicated, straight spur gearing is suggested.

The student will then develop preliminary gear face widths that will handle the stresses needed for successful life (bending and contact stresses). Gear material is also selected. This preliminary sizing is often referred to as the gearing macro-geometry design. Software programs such as Gearmaster[14], KISSsoft[15] or equivalent are utilized to show the student the benefit of handling the iterative nature of this preliminary optimization by using computer tools. These tools follow the rating procedure developed in AGMA 2001-D04 standards.

Next, bearings will be selected. Reliability will often drive the selection of the bearings. The students are presented with several load, life, and reliability requirements, and are asked to develop their own bearing life program for ball and roller bearings. This program is often created in Excel or Visual Basic and will be used for subsequent final bearing selection in the course of the project. Given an initial first pass layout of the gearbox (typically 4 gears and 3 shafts), bearings will be selected based on external loads, gearbox life requirement (revolutions), and gearbox reliability. Due to the fact that there will be at least 6 bearings, the student will learn how to apply a series reliability model to the bearing subsystem. This will show the student that much higher reliability is needed at the component level in order to achieve the final gearbox overall reliability.

Next, the student can select a first pass at the shafting needed for the gearbox. Of prime importance are the stiffness and the fatigue strength of the shafts. The gear life will be affected by misalignment at the contact surfaces and bearing life will be affected by misalignment. In this project, the student is given a shaft deflection program called CAE-SHAFT/Deflections[16]. This program will accept the bearing and gear locations, shaft material, and the loads at these locations. The resulting shaft deflections are calculated. The student will take these deflections, and translate them to the gears and bearings. If they exceed the prescribed limits, then the shaft design will be iterated. Through this process, the bearing bores may change, which will drive bearing design iterations, etc. Once the deflections are understood and managed, then the student will evaluate the fatigue life of the shaft to ensure acceptable life. This is done using standard shaft calculations as found in many machine element design textbooks[8].

Lastly, for this project the student will use a suitable CAD package such as Pro-Engineer to create a 3-D model of the final gear, bearing, and shaft layout. A housing will be developed to support the gear, bearing, and shaft subsystems, which will also contain enough volume for lubrication, and will contain necessary features for assembly and maintenance. At this time, the student may not have had a course in finite element analysis, so the structural integrity of the gearbox housing is not analyzed. Examples of student work can be shown in Fig. 4.

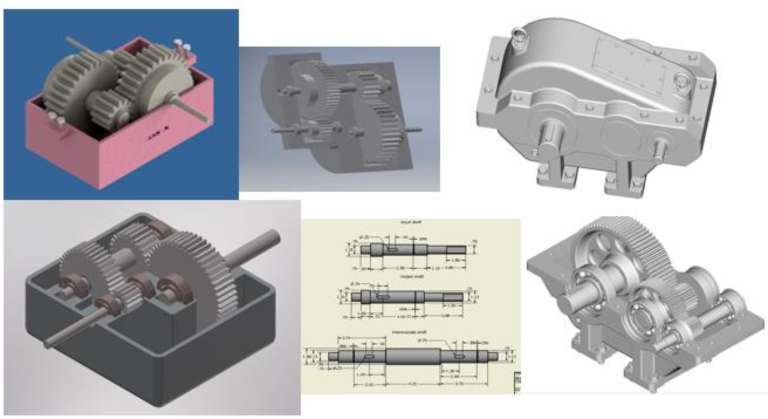

Figure 4. Student examples of speed reducer solid model.

Finally, similar to design project 1, a set of 2-D drawing for the gearbox components and assembly is created (Fig. 5). These drawings are properly dimensioned and notated with suitable bills of material. Proper title blocks would be included on the drawings. Throughout the design process the student will have maintained an engineering design notebook. This notebook, hardcopies of the final drawings, and the electronic copies of the models and drawings, are submitted as objective evidence for the final grade.

Future improvements include expanding further into gearing micro-geometry design, detailed lubrication subsystem design, and detailed structural housing design. At this time, the project is assigned to a student as an individual project. Another future enhancement could be to assign the project as a team collaboration, assigning specific engineers to each subsystem and component area.

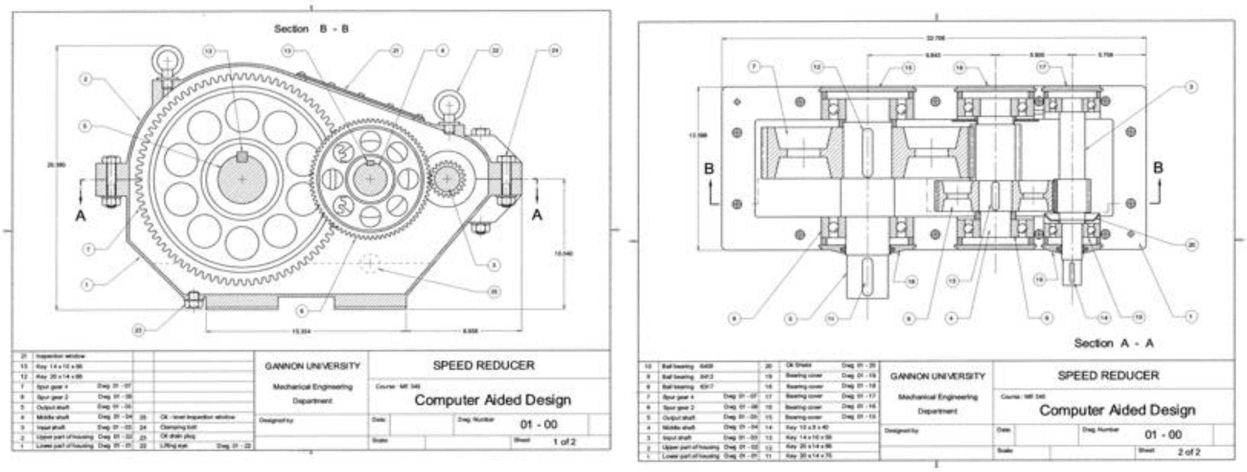

Figure 5. Detailed assembly drawing with BOM and detailed component drawings are required for design project 2 like design project 1.

In summary, this project exposes the student to the highly iterative nature of the design process, using the combination of distinct machine elements integrated into a gearbox assembly. Computer tools are shown to reduce the iteration time and to reduce the chance of mistakes during the iteration process. Although specific tools were mentioned in this paper, there are a wide variety of acceptable tools that can accomplish the same task. These tools are also evolving to allow for system level optimization of the components.

The Student-Selected Design Project

As mentioned previously, with the student-selected design project, the student(s) decide what machine or device they want to design. Students are required to submit a formal proposal (business letter) by week 7, and then have the remainder of the semester to work on their design. The project must involve the design of multiple machine elements. Once again, a CAD assembly model and detailed drawings are required.

Throughout the years, the student-selected option has become a ‘student favorite.’ Students can select a machine design that interests them: an automated log splitter, a custom rotisserie roaster, a coil winder, specialized construction equipment, a snow-mobile suspension, an ATV accessory, 3D printers, etc. The list is endless. Some examples of student-selected projects are shown in Fig. 6.

Students seem to be more engaged and enthusiastic when they select their own projects. They tend to ask more project-related questions throughout the semester. In some cases, students will build working prototype models and demo them in front of the class. This option allows the students to be more creative and embrace the design process. The downside is, in some cases, the project becomes less about machine design and more about aesthetics. Students tend to get bogged down with cosmetic issues and downplay the importance of machine design.

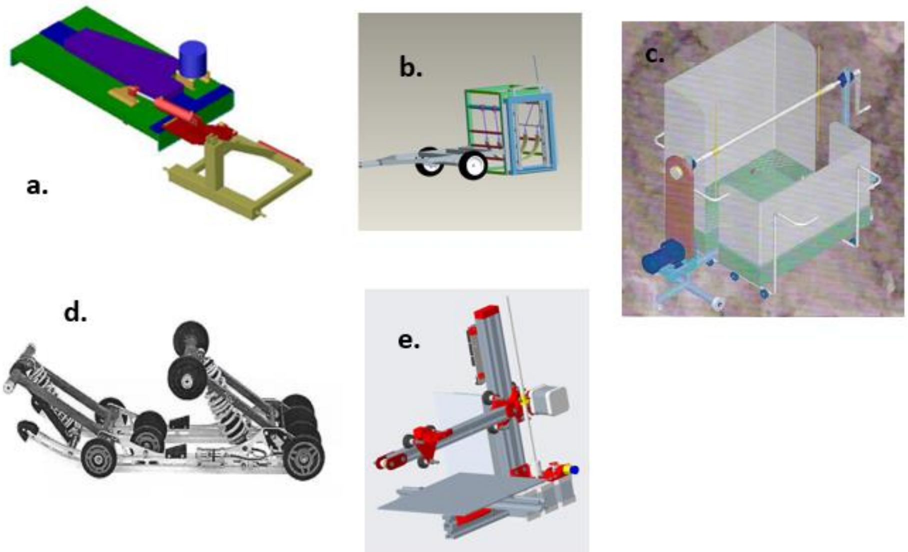

Figure 6. Examples of student-selected projects, a) bank mower for tractor, b) cow tipper, c) rotisserie grill roaster, d) snow-mobile suspension, e) 3D printer

3. Grading

Grading may very a bit year-to-year and from design project 1 to design project 2, but the basic format is as follows:

- Organization of bound report (20 pts)
  - Problem definition
  - Design function/requirements, well defined
  - Grammar and spelling
  - well organized and easy to follow
- Technical Content (50 pts)
  - Detailed calculations correct, appropriate, easy to follow,
  - Summary table with stress, deformation and factor of safety
  - Material specified
  - Multiple iterations shown/ brainstorming sketches
- CAD work (25 pts)
  - Assembly model
  - Assembly drawing with BOM
  - Detailed drawings for ALL critical components
- Design Aesthetics and appeal (5 pts)
  - Is it a good design and would you buy it, sales pitch

4. Assessment

A 10-question survey was given to the class for assessment purposes. The survey was given for 2018 where design project 2 was the standard gearbox, and for 2020 where design project 2 was the student-selected project. The survey questions are listed below:

1. As a result of this project, I have a better understanding of CAD modeling
2. As a result of this project, I have a better understanding of creating detailed engineering drawings

3. As a result of this project, I have a better understanding of designing machine components
4. As a result of this project, I have a better understanding of tolerances and fits and how they impact assembled parts
5. As a result of this project, my ability to function effectively on a team has improved (ABET outcome 5)
6. As a result of this project, I have a better understanding of specking out standard machine components and hardware
7. As a result of this project, I have a better understanding of the amount of work involved to design a complex machine
8. As a result of this project, I have acquired and applied new knowledge (ABET outcome 7)
9. This project required a lot of creativity
10. I enjoyed working on design project 2

Students rated the questions on a scale from 1 – 5 where a 1 was *strongly disagree* and a 5 was *strongly agree*. Results from the assessment survey are shown in Fig. 7, below:

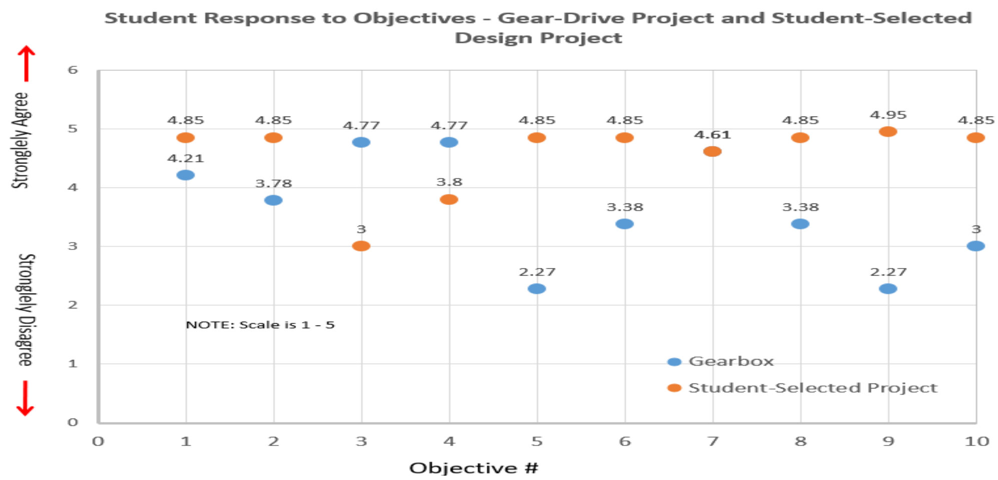

Figure 7. Course survey: Gearbox project (blue), student-selected project (orange).

The survey results support the following conclusions:

1. Without exception, students report an improvement in CAD related skills after completing the project (question 1 and 2).
2. Question 3, related to design of machine components, suggests students that did the gearbox feel they gained more experience designing actual machine elements (gears, shafts, bearings, etc.). This is entirely understandable since the gearbox project primarily involved machine elements. Students that did the gearbox project reported a better understanding of fits and tolerances as well (Question 4).
3. Question 5, related to ABET outcome 5, ability to function effectively on a team, showed a higher student rating for the student-selected project. Perhaps when students can select their own project, ownership is more prevalent. ABET outcome 7, acquired and applied new knowledge, scored higher for the student-selected project as well as shown in Question 8.
4. Finally, perhaps the most important takeaway comes from the final two Questions 9 & 10. Students seemed to think the student-selected project involved more creativity and they seemed to enjoy it more than designing gearboxes.

5. Conclusions

While both projects seem to satisfy the bulk of the outcomes defined above, students seemed to thoroughly enjoy the student-selected project more. The level of enthusiasm, creativity, and excitement was evident throughout the semester. Students seemed to ask more project-related questions when they were designing their own device. Students took the initiative to create animations and working prototypes when it was their own device they were designing. The downside seemed to be lack of the technical content related to machine elements. Many students designing their own devices were caught up in non-technical details. Students designing gearboxes were forced to use machine element methodologies; so the gearbox was more effective as a machine-design project. The challenge, therefore, is to come up with a project that gives students ownership, allows them to be creative, and at the same time requires the design of multiple machine elements.

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