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Implementing Open-ended Hands-on Design Projects throughout the Mechanical Engineering Curriculum

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Implementing Open-Ended Hands-on Design Projects throughout the Mechanical Engineering Curriculum

Introduction

Engineers engage in design activities on a daily basis and thus engineering design has been considered one of the most important topics in engineering education and one of the most important skills that engineering students should possess when they graduate. Most first-year introduction to engineering courses now emphasize on the engineering design process and most of these courses now contain "hands-on", team based design projects[1-5]. Benefits of such hands-on design projects implemented in the freshman year include, increased retention, student motivation, academic performance, etc. After the freshman year, most mechanical engineering students rarely have opportunities to engage in hands-on design projects until their senior year when the capstone design projects are implemented, where students apply their acquired knowledge to an open-ended problem and produce a working prototype of the design or a final product that has been manufactured. Within the Mechanical Engineering curriculum, some sophomore and junior level courses contain hands-on labs and others incorporate design projects. However, usually the hands-on labs are not design based and the design projects are not hands-on in nature. For example, for some upper level courses, design projects may be incorporated for which the final deliverable is a report which contains a final CAD model/drawing of the design, among other things like analysis, etc. but the design does not need to be physically created (no building or manufacturing is involved). Even though a few attempts have been made by a few authors in the past to implement hands-on design projects in sophomore and junior level mechanical engineering courses, for example, Al Hamidi, et al., discussed such efforts in the Mechanical Measurements course at Texas A&M University at Qatar[6]; Mascaro et al. at University of Utah implemented new laboratories which involve hands-on design in the first and second years of the mechanical engineering program[7-8]; Hodges and Sullivan discussed several projects in the Design or Mechanical Systems course, such as natural frequency analysis of a cantilever beam and a buckling analysis, for which students designs were fabricated in the machine shop[9]; there has not been a consistent effort to provide opportunities for students to tackle open-ended hands-on design problems throughout the mechanical engineering curriculum.

At Arizona State University, three open-ended hands-on design projects, one in each of the three mechanical engineering courses taught during the Spring 2015 semester have been implemented: a National Academy of Engineering (NAE)'s Grand Challenges hands-on design project in freshman Introduction to Engineering course; a truss bridge hands-on design project in sophomore Solid Mechanics course; a manual toy hands-on design project in junior/senior Mechanism Analysis and Design course. The goal was to provide students with hands-on design experiences throughout the mechanical engineering curriculum. In this paper, the implementation of these hands-on design projects will be described. Students' performances in these design projects will also be presented. Student perceptions of these hands-on design projects have been obtained through an end-of-semester survey and results will be discussed. Overall students felt very positively about these open-ended hands-on design projects and they agreed that there has been a lack of hands-on design experiences in the curriculum, and hands-on design projects would be invaluable to better prepare them for the job market. Students who participated in these design projects mastered the topics involved better than those who did not. Challenges of implementing these projects continuously for a long term, such as, budget, logistics, course workload, will be addressed as well and ways to run these projects in a sustainable way in the long run will be suggested.

Course and Hands-on Design Projects Description

Introduction to Engineering

The introduction to engineering course is a 2-credit multi-disciplinary required course for mechanical engineering students. During the Spring 2015 semester, the author taught one section of this course offered to 38 mechanical, aerospace, chemical, and electrical engineering students. The class met for a 50-min lecture and a 3-hr lab each week. A NAE Grand Challenges design project was implemented in this course which students worked on in teams of three or four during the second half of the semester in the labs. In this project, three open-ended design problems were formulated based on three of the fourteen NAE Grand Challenges for Engineering[10]: make solar energy economical; provide access to clean water; advance personalized learning, and student teams had the freedom to choose one out of these three design problems and design, build, and test a functional prototype to solve the design problem. There was a set of general requirements that applied to all the three problems, for example, all designs needed to be creative, aesthetically pleasing, well crafted, and the total cost should be as little as possible and it should not exceed $100. Each problem had some specific requirements in addition to the general requirements: in the first design problem, students were provided with a solar set-up, shown in Figure 1, which has a light bulb, simulating the “sun” that travels from “east” to “west” during a “day” at a constant rate. A solar power plant needed to be designed so that consistent and maximum power be generated throughout the day. Only two types of solar cells could be used and all of them must be placed within a 12in. by 12 in. area. The power plant must also not come in close contact with the “sun”. In the second design problem, students needed to help villagers living in a rural area of Uganda gain access to clean water. A bucket of contaminated water was provided to students and a light-weight and portable device must be designed to help the villagers carry water back home and purify it. The third design problem required students to design a fun and interactive educational toy or exhibit for a local science museum to teach a student-select scientific principle for a select age group. The details of this design project and its impact on students’ interest, motivation, value, and their perception of engineer’s role in the society can be found in Zhu and Trowbridge[11].

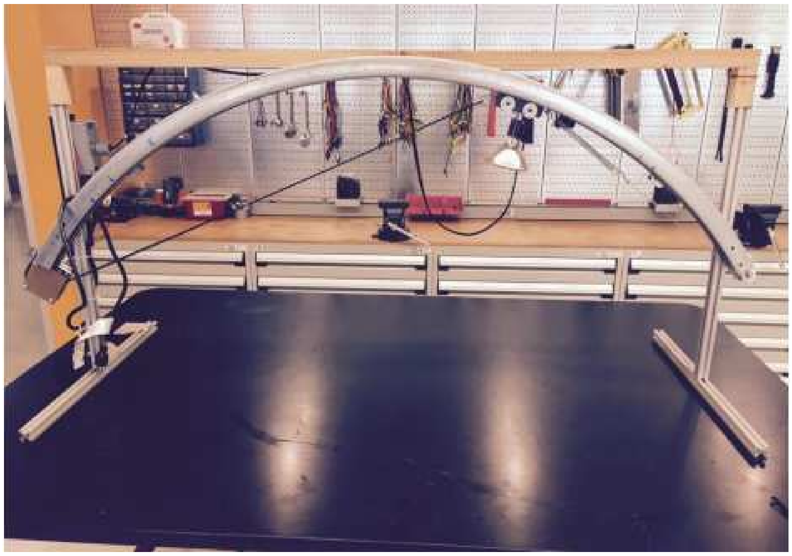


Figure 1.Solar Set-up for the Grand Challenges Design Project

Solid Mechanics

The solid mechanics course is a sophomore level required course for all mechanical engineering students. This 3-credit course introduces the concepts of stress and strain, the stress-strain relation, and applications of force transmission and deformations in axial, torsional, and bending of bars. During the Spring 2015 semester, 91 students were enrolled in the section of this course taught by the author. This course has been taught in a traditional way in previous semesters, where instructors lecture, students work on assignments outside of the class, and exams are used to assess the learning outcomes. During Spring 2015, the course has been completely restructured into a flipped classroom model (details of such an effort can be found in Zhu[12] and Lee et al. [13]), with a hands-on truss bridge design project. With the new flipped classroom model, students have already been assigned to groups and they worked on the truss design project in the same groups outside of the class.

Trusses have not been an explicit topic in this course and in previous semesters they were rarely discussed in this course. During the Spring 2015 semester, trusses were introduced and discussed through in-class activities, examples, and homework assignments as an application and an example of axially-loaded members. The hands-on truss bridge design project was then introduced at the end of week 4 after axially-loaded members were discussed. The goal of this project was to provide students with an opportunity to apply concepts of normal stress, factor of safety, yield stress, etc. in a real world setting and in a fun and interactive way. This project was adapted from balsa wood truss bridge design challenges. Requirements of this project included:

- the bridge must span an 18in. gap;
- the bridge must be in 2D;
- truss members must be made of ¼ in. by ¼ in. as well as $^{3}/_{16}$ in. by $^{3}/_{16}$ in. balsa wood;

- gusset plate made out of paper file folders must be used as joints;
- total cost (based on actual costs of the materials used) of the design must be minimum;
- maximum load efficiency, calculated as the ratio of the maximum load supported to the weight of the bridge, must be achieved;
- the design must be well crafted and aesthetically pleasing.

Students were only asked to consider failure due to tensile or compressive stresses in the truss members as other modes of failure, such as buckling was out of the scope of this course. They were allowed to use any software or modeling tools that they had access to to model their trusses. For example, some teams used Autodesk® ForceEffect™ (an example is shown below in Figure 2), an open and free engineering app for simulating design concepts while others used ANSYS Workbench (an example is shown below in Figure 3) which was briefly introduced to students with a tutorial.

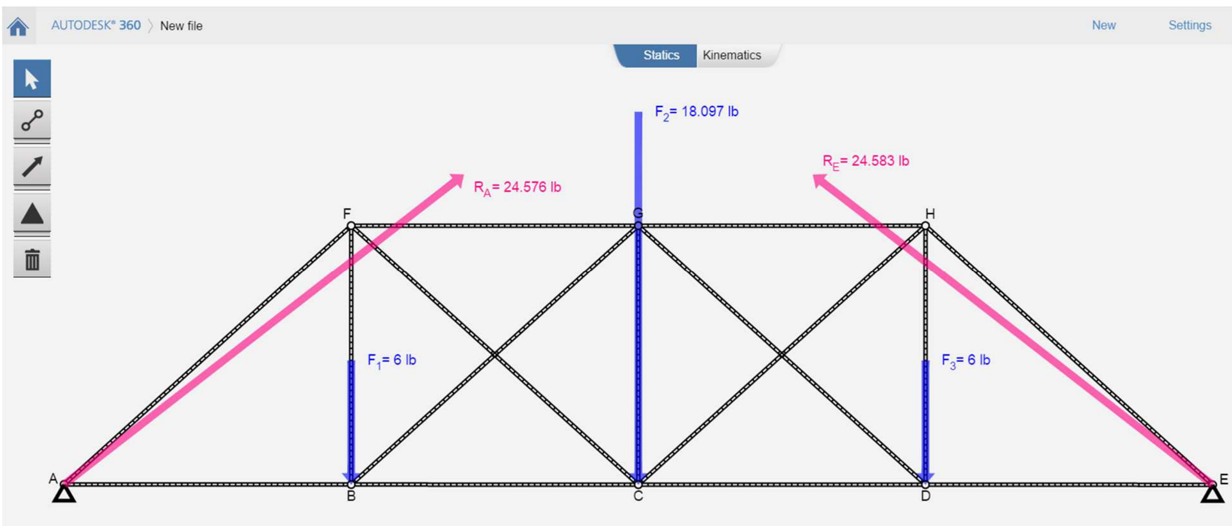


Figure 2. A truss design modeled in Autodesk® ForceEffect™

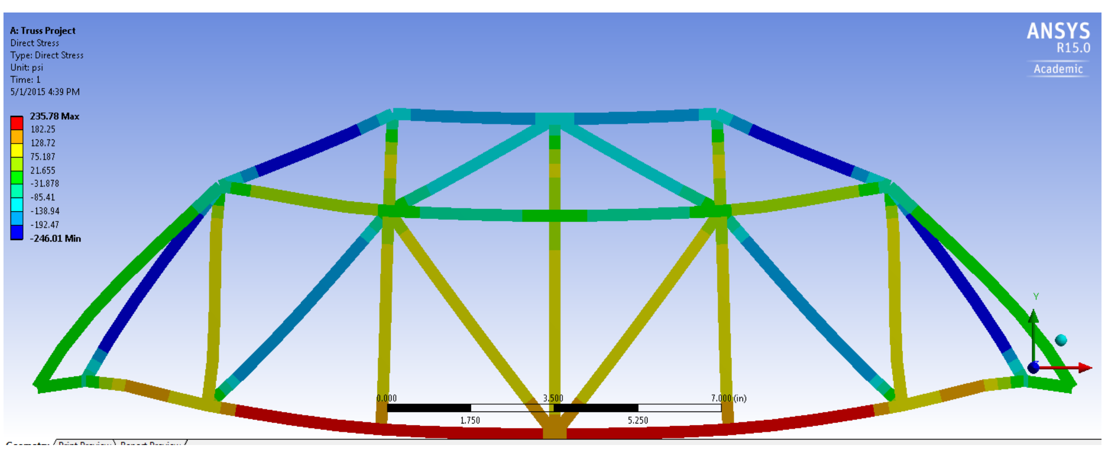


Figure 3. A truss design modeled in ANSYS Workbench

After the designs were built, they were all tested to failure.

Mechanism Analysis and Design

The Mechanism Analysis and Design course is a technical elective for mechanical engineering majors. It was offered to 91 students during the Spring 2015 semester. This 3-credit course introduces the fundamentals of planar mechanisms and the application of kinematics in the analysis and synthesis of mechanisms. It focuses on kinematic characteristic of planar mechanisms such as relative position, velocity and acceleration of moving links, and kinematic analysis and synthesis of specific link and joint combinations, such as cams and gears. In the past, this course was structured to equip students with a strong theoretical background in the analysis and synthesis of planar mechanisms. Students were able to perform mathematical analysis of the mechanisms and to design mechanisms. However, students often found it difficult to visualize how the mechanisms work in action. To remedy this, a manual toy group hands-on design project was implemented during the Spring 2015 semester, which allowed students to design, synthesize, and build 'machines' in a fun context. Students were able to learn about synthesizing mechanisms; transmitting motion through the different components; and design optimization through active engagement. They were also able to explore the functions of different mechanisms; and to visualize the mechanisms as they function in a real world application.

Specific requirements of this project included:

- the total cost (based on actual cost of materials) should be less than $50 and the design should cost as little as possible;
- the design should be fun and interactive, and be appropriate for a select age group;
- the design should incorporate at least four different planar mechanisms;
- either gears or cams-followers, or both should be represented in the design;
- to keep the budget a minimum, no electronics were allowed and the design must be manually operated;
- the design should be aesthetically pleasing and be well crafted.

Students were encouraged to use wood as the primary material of construction but they were allowed to use any materials as well as tools that they had access to, for example, 3D printers, CNC machines, laser cutters, etc.

Project Assessment and Student Performance

Introduction to Engineering NAE Grand Challenges Design Project

To help students work through the engineering design process, various deliverables were used throughout the project such as: problem definition and list of requirements; project schedule; project proposal; progress report memos; final presentation; and final design report. Students were also asked to keep a detailed design notebook to document the entire design process. Their project grades were determined based on the following distribution and the total accounted for 45% of their final course grade.

Table 1. Project Grades Distribution

Assessment Item	% of Total Project Grades
Problem Definition and Requirements	3.33%
Project Schedule	3.33%
Project Proposal	17.78%
Progress Report Memos	4.44%
Final Presentation	5.56%
Design Prototype	30.00%
Final Report	30.00%
Design Notebook	5.56%

The design prototype grade was determined based on the cost of the design, its creativity, aesthetics, craftsmanship, and quantitative test results, etc. Out of the ten teams, five chose to work on the first problem (solar power plant), out of which four had a successful working prototype; and the other five chose to work on the second problem (water purification and transportation), all of which were able to solve the problem successfully. The figures below show examples of final student designs.

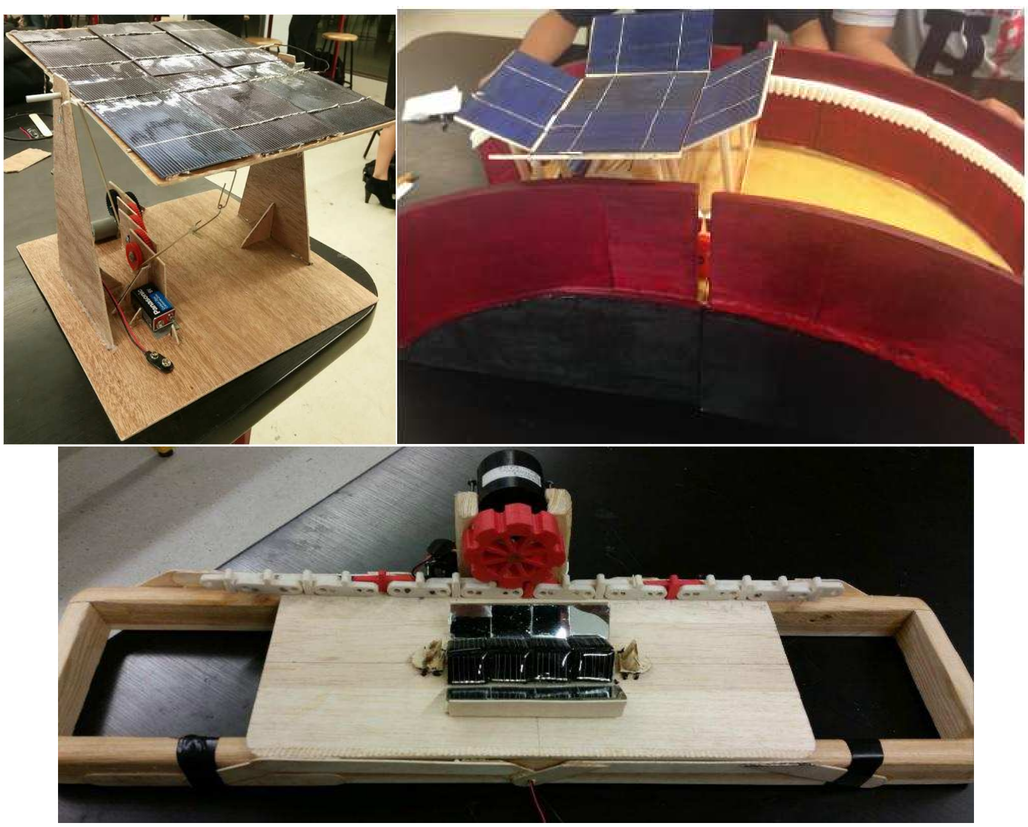


Figure 4(a). Three examples of solar power plants designed and built by student teams

Figure 4(b). Three examples of water purification and transportation devices designed and built by student teams

Solid Mechanics Truss Bridge Design Project

Deliverables of this project included a functional prototype (30% of the project grade) and a project report (70% of the project grade). The prototype was tested and evaluated based on cost, load efficiency, aesthetics, and craftsmanship. Figure 5 below shows the testing setup of the project. Sand was used as the load and the load was applied to the middle bottom three joints of the truss bridge. Each cup of sand shown in Figure 5 weighed 1 lb and one of the cups was added to the bucket at a time until failure occurred. To avoid warping of the trusses, two pieces of hard plastics were used to keep the truss in 2D.

Figure 5. Truss bridge design project testing setup

The minimum load efficiency in the class was 1805.56 and the minimum cost in the class was $0.87. Figure 6 shows examples of student designs.

Figure 6. Examples of truss bridge designs

Mechanism Analysis and Design Manual Toy Design Project

Student teams were required to create posters to showcase their final designs and participate in the final project poster session. At the poster session, all students in the class were asked to play with the toys. All designs as well as posters were evaluated by peers based on a set of criteria. More specifically, the design prototypes were evaluated based on cost, ability to meet requirements, creativity, aesthetics, craftsmanship, ease to play with, and whether it is fun to play or not. In addition to the functional prototype (34% of total project grade) and the poster (12% of the total project grade), a final report was required for this project (54% of the project grade).

Student designs for this project ranged from a game world to a circus train, from a dancing man to a duck hunt, from a flying dragon to a horse, from a bowling game to a soccer game, etc. All but 2 out of the 25 teams had functional prototypes. Below are examples of student designs and animated versions of the toys can be found at: https://www.youtube.com/playlist?list=PLCB-m5DR61mazJUp4K32wE1LKn-Ch3Fyt

Figure 7. A duck hunt game for the manual toy design project

Figure 8. Hey diddle diddle toy for the manual toy design project

Figure 9. Surfing super Mario toy for the manual toy design project

Figure 10. Pokémon game for the manual toy design project

Assessment and Student Perceptions of these Open-Ended Hands-on Design Projects

A survey was administered after the end of the semester to all students in all three courses to determine students' perceptions of these open-ended hands-on design projects. The survey was voluntary and 2 participated from the Introduction to Engineering class (participation rate 5.26%); 15 from the Solid Mechanics class (participation rate 16.48%); and 18 from the Mechanism Analysis and Design class (participation rate 19.78%). The very low participation rate for Introduction to Engineering is probably due to the multidisciplinary nature of the class and most students who were not mechanical engineering majors thought this research study was not relevant to them. Another possible reason for the low participation rates for all three courses was that the survey was administered after the finals week so students probably lacked the motivation to participate.

In the Introduction to Engineering class, participants were both freshmen; in the Solid Mechanics class most of the participants were sophomore but there were a few junior students; in Mechanism Analysis and Design, most of them were seniors.

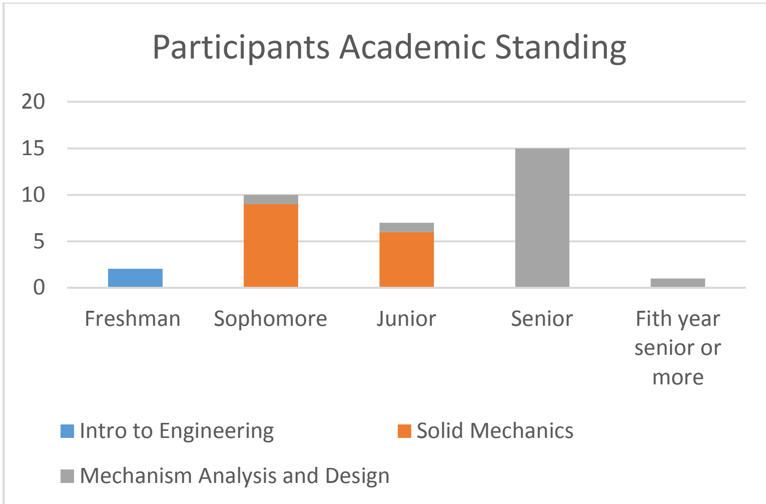


Figure 11. Academic standing of survey participants in all three classes

Most of the participants were mechanical engineering majors, as can be seen from Figure 12.

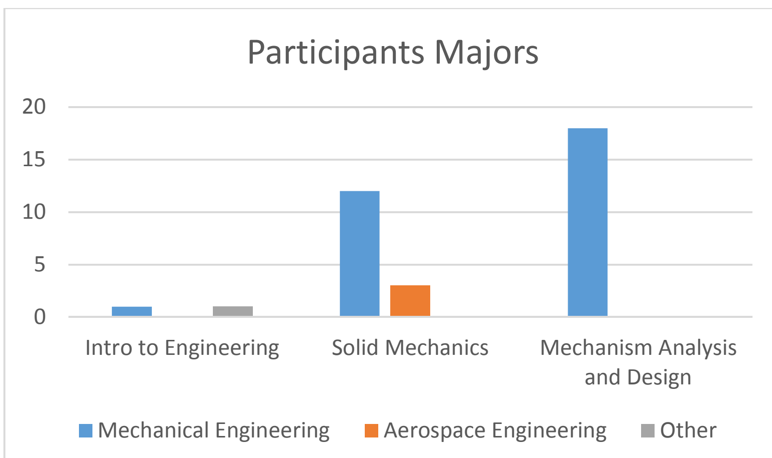
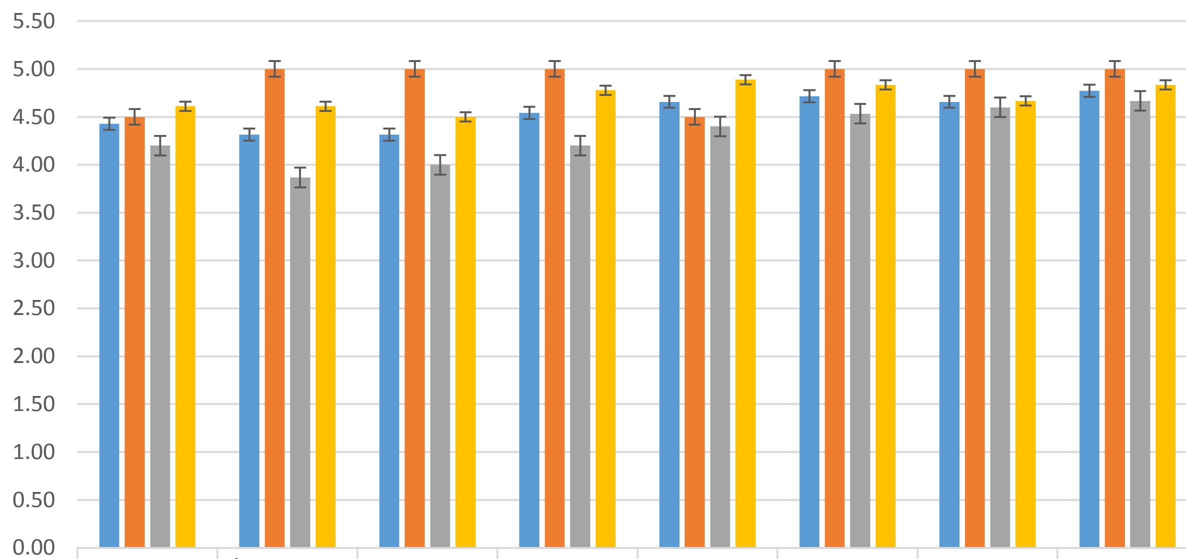


Figure 12. Majors of survey participants in all three classes

The survey consisted of 8 rating questions on a Likert scale of 1-5 with 1 being strongly disagree and 5 being strongly agree; as well as an open ended question "what comments do you have?" for general comments.

The survey results show that overall students in all three courses felt positively about these open-ended hands-on design projects as the mean scores for all questions were close to or above 4.5 out of 5. Introduction to Engineering participants really enjoyed the project and felt that it helped them learn engineering design and other course topics; it better motivated them to learn the concepts; and it better prepared them for open-ended design challenges in the future. Mechanism Analysis and Design participants felt that the toy hands-on design project allowed them to be more creative in their solutions; it helped reinforce engineering design and it helped with learning the course materials. Participants from all three courses felt that they would be better prepared to tackle design challenges after they graduate if they had more opportunities to work on hands-on design projects in the curriculum and that they would like or would have liked to do more hands-on work in courses. Solid Mechanics participants did not seem to feel more motivated to learn course concepts by doing the project nor felt as positively about this project in general and possible reasons will be discussed in the Instructor Insights section.



	The hands-on design project made me more enthusiastic about the concepts involved	I was more motivated to learn the concepts by doing the hands-on design project compared to other class activities (traditional lectures; traditional assignments; etc.)	The hands-on design project was helpful in learning the course materials	The hands-on design project helped me learn/reinforce how to approach engineering design	The open-ended hands-on design project allowed me to be more creative in my solutions	I enjoyed the hands-on design project	I will be better prepared to tackle open-ended design challenges after I graduate if more hands-on design projects are included in the curriculum	I would like to do more hands-on work in future courses (or for graduating seniors: I would have liked to do more hands-on work in previous courses)
Overall	4.43	4.31	4.31	4.54	4.66	4.71	4.66	4.77
Intro to Engineering	4.50	5.00	5.00	5.00	4.50	5.00	5.00	5.00
Solid Mechanics	4.20	3.87	4.00	4.20	4.40	4.53	4.60	4.67
Mechanism Analysis and Design	4.61	4.61	4.50	4.78	4.89	4.83	4.67	4.83

Figure 13. Survey results

The comments from the open-ended question in the survey also provided insights about student perceptions of these hands-on design projects. For example, some Solid Mechanics participants thought the project was a good refresh of the engineering design process that they learned during their freshman year in the Introduction to Engineering course and that it was a better way to engage students in the topics learned:

"I really enjoyed the project, it was probably the only time this year that I spent more time than I needed to on schoolwork"

"I thought it was a great way to refresh the design process."

Comments from Mechanism Analysis and Design participants who were mostly seniors that had completed all coursework in the mechanical engineering curriculum and had interviewed for full time jobs in the field indicated that students also felt that there was a lack of hands-on design experiences in the curriculum which were invaluable to them in the job market. For example, some of them mentioned:

"Many of the employers that I have interviewed with have asked about hands-on projects that I have been involved in. There have not been many that have been school related unfortunately. Most, if not all the projects that I have worked hands-on, have been outside of school affiliated with others. I strongly encourage and support the use of hands-on projects to help facilitate, reinforce, and engage students in the design process related to engineering. It truly brings in many of the facets that exist in the workplace, such as time constraints, budgets (which is a big one), and the ability to learn the concepts that are needed in order to make something actually work."

"There really isn't much hands on experience between freshman and senior year. Understanding and learning the basic concepts of engineering is really crucial because we continuously build off of it. How can we say we fully master anything if we can't even apply the basics in the real world? Though it takes more time out of class, I think it's important to fully understand the subject were we understand how and where it can be applicable to the world. Though the MAE341 project was stressful through out the process of building the toy mechanism the end results was truly rewarding to see how the theoretical concepts comes to real life with something so simple as a kids toy."

These senior students also learned through working on the toy design project that being able to design on paper and being able to implement the design in action were two different things and the hands-on design experiences helped close the gap between the two:

"I think the experience of designing is invaluable. I learned that just because a design might work great in Solidworks, that there are many other issues to consider that are a cause of reality. The quickest way to learn is by making mistakes. It is also great in that it teaches individuals the issues of working in a team, and the various struggles within, which is something that isn't discussed much in classes. It was great experience."

"It was a welcome change of pace to be able to build something. I am used to working with my hands as I do woodworking and auto repair in my spare time. Working hands on is a skill not a lot of engineers have and I believe they should. I could see in some of the projects mistakes in materials and dimensions that would have been avoided if the students had more experience working hands on."

In addition to the survey, performances of students in these classes were compared to those in a control group for Solid Mechanics and Mechanism Analysis and Design, and the results are discussed below.

Students that were enrolled in Solid Mechanics during Spring 2015 who had done the truss design projects were considered the experimental group and those who were enrolled in this course taught by the same instructor during Spring 2014 that did not work on this project were considered the control group. Since the truss design project was related to one of the core outcomes of the course: students will apply concepts of strain and stress to the analysis of statically-determinate and indeterminate bars under axial loading, students' performances on the second preliminary exam which was used to assess this core learning outcome were compared in both groups. Very similar problems were given to both the experimental and the control groups for this exam. It can be seen that students in the experimental group mastered this core learning outcome which the truss design project was related to much better ($p<0.0001$). However, it is unclear whether or not there is a direct correlation between the better performance and implementation of the truss design project, as the experimental group was also taught in a different way, using a flipped classroom model.

Table 2. Students' performances on preliminary exam II of Solid Mechanics

	Control Group	Experimental Group
Number of students	76	91
Mean score	77.38%	86.91%
Standard deviation	30.39	10.69

For Mechanism Analysis and Design, the experimental group consisted of students who were enrolled in the class during Spring 2015 that participated in the toy design project. The control group was the class taught by the same instructor during Spring 2014, which did not have this design project. The DFW rates (percentage of students who earned a grade of D (between 60% and 69%), F (below 60%), and those who withdrew from the course) as well as the final grades of students in both groups were compared. There is not a significant difference between performances ($p>0.05$) but the experimental group had a slightly lower DFW rates. Teaching and course evaluation results were also compared for both groups. There is not a significant difference between the two groups for all categories ($p>0.05$) and thus, implementing the toy design project has not changed students' evaluations of the course.

Table 3. DFW rates and students' final course grades in Mechanism Analysis and Design

	Control Group	Experimental Group
Number of students	73	91
DFW rates	18.75%	16.16%
Mean score	80.73%	82.50%
Standard deviation	13.78	11.83
% of A's (>=90%)	23.29%	31.87%
% of B's (between 80% and 89%)	46.58%	37.36%
% of C's (between 70% and 79%)	19.17%	21.98%
% of D's (between 60% and 69%)	5.48%	3.30%
% of F's (below 60%)	5.48%	5.49%

Table 4. Instructor and course evaluation results for Mechanism Analysis and Design

	Control Group (N=32)	Experimental Group (N=26)
Course	4.46	4.47
Instructor	4.58	4.68
Overall	4.31	4.65

Instructor Insights

Implementing open-ended hands-on design projects in various courses within the mechanical engineering curriculum is not a trivial task. The instructor feels that three of the biggest challenges are budget, logistics, and course workload.

In terms of budget, for Introduction to Engineering, there was a course fee of $50 for each student enrolled in the course and the course fee was used to purchase materials that students needed for the hands-on design project. For this course, on average the solar teams spent a lot more than the water teams did. The total cost for all materials used by students (10 teams) for the design as well as those used by the instructor for project setups was less than $1,000 and the course fee was more than enough to implement the NAE Grand Challenges design project. For Solid Mechanics and Mechanism Analysis and Design, a total funding of $1,500 was obtained from the school to run both the truss bridge and the manual toy design projects. For the truss bridge design project in Solid Mechanics, all materials were purchased by the instructor and then distributed to student teams whereas for the manual toy design project in Mechanism Analysis and Design since it was difficult to predict the kind of materials students would use, students were asked to purchase materials on their own and submit receipts for reimbursements. For Solid Mechanics, there were 23 teams and the average cost of materials across these teams was $2.65. The total cost of materials used for the testing setup as well as all wood glue was $140. For Mechanism Analysis and Design, there were 23 teams and the average cost of materials across these teams was $24.52 per team. Out of the 23 teams in this class, only one team submitted receipts for reimbursements. From a long-term point of view, overall all three projects could be run in a sustainable way. The course fee approach worked very well for Introduction to Engineering and for the truss project in Solid Mechanics once the testing setup is complete, it could be used multiple times in the future and it would cost each student less than $1 to purchase materials for the project on their own. The toy project requires higher budget but the instructor feels that it is OK for students to purchase materials on their own, as either they can find recycled materials at home or elsewhere or they would not care about the amount of money spent on the project. This was indicated by the fact that even though they were required to, only one team out of 23 asked for reimbursement.

For logistics, at Arizona State University, there are lab spaces dedicated to the freshman Introduction to Engineering class and thus Introduction to Engineering students were able to use the lab spaces as well as the tools these spaces were equipped with to work on their projects. For Solid Mechanics, the instructor purchased all of the materials and stored the materials in the office and students had to come to the instructor's office to obtain materials. This is not the most desired way to handle course materials. However, it is very challenging to require a lab space or a dedicated space to store the materials. Students worked on this project outside of the class using tools such as scissors and box cutters which most of them had easy access to. For Mechanism Analysis and Design, since students purchased materials on their own, purchasing and storing materials was not an issue. However, some students complained about the lack of access or training to appropriate tools to work on the project. This is an area that needs to be addressed for future implementation of this project.

As for course workload, Introduction to Engineering students completed the project completely during scheduled lab times for the class thus course workload has not been an issue for this class. For Solid Mechanics, some students complained about having to work in teams on the project and having to work on the project outside of the class. The instructor feels that the time that was required for students to spend on the project was very reasonable. In the future, the importance of teamwork skills probably should be addressed more and a better system should be implemented to support teamwork in the class. For Mechanism Analysis and Design, some students complained about the workload involved due to the project. Some of them mentioned that as seniors, they were busy working on the capstone design projects as well as looking for jobs and thus the time it took to work on the toy project seemed too much. The instructor agrees that the project required a lot more time and efforts from students compared to using traditional assignments for this 3-credit course. In the future, students will be encouraged to take this course during their junior year rather than their senior year. In addition, the project will be simplified and introduced at the very beginning of the semester in order to help reduce student workload.

Conclusions and Future Work

An attempt has been made at Arizona State University to implement open-ended hands-on design projects throughout the mechanical engineering curriculum. More specifically, a NAE Grand Challenges design project was implemented in the required freshman Introduction to Engineering course, a truss bridge design project was implemented in the required sophomore Solid Mechanics course, and a manual toy design project was implemented in the technical elective junior/senior Mechanism Analysis and Design course. These projects have been shown to be a both fun and educational way to motivate students and to help students learn/reinforce engineering design, as well as other topics. Overall, students in all three courses felt very positively about the project and in particular senior students felt that more hands-on design experiences should be provided throughout the curriculum to better prepare students for their future career. In the future, budget, logistics, and course workload issues will be addressed in order to implement these projects again. In addition, more open-ended hands-on design projects will be implemented in other core and elective mechanical engineering courses to provide students with a consistent experience throughout their four years of college.

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