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Designing a Big Machine: A Description and Assessment of a Mechanical Engineering Design Project

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Designing a Big Machine: A Description and Assessment of a Mechanical Engineering Design Project

The Introduction to Mechanical Engineering Design course at the University of Pittsburgh piloted a design project in which students in the two course sections designed and built what the instructors referred to as a "big machine", which is similar to a Rube Goldberg machine. In past years, students in this design course completed a design project that emphasized user-centered design. Beginning in the fall 2015 semester, the big machine was incorporated as a second design project so that students would also get experience designing with the goal of fitting into a larger system. With this project, the emphasis was no longer solely on the end user, but also on making sure that their designs met the constraints and requirements of the system.

In the big machine project, each team of 4-5 students (a total of 58 teams) was assigned a section of the machine of about 10 feet long and was asked to communicate with the adjacent teams to coordinate input and output requirements. Teams had to use the design process to design their segments such that their inputs and outputs would align with the preceding and the following teams' segments, thus creating the big machine. Teams also had to demonstrate creativity with the design of their segments, and follow additional constraints outlined by the instructional team.

The purpose of our study is to describe the project and assess how well it worked, both in terms of implementation and in terms of student outcomes. Specifically, this paper will: (1) describe the process of creating and implementing this project, (2) describe what worked well with this project, and identify areas for improvement for future semesters, and (3) summarize students' perceptions of the activity, as well as their perceptions of the knowledge and professional skills developed, based on their responses to a survey.

Introduction

The Introduction to Mechanical Engineering Design course at the University of Pittsburgh piloted a design project in which students in the two course sections designed and built what we, the instructional team, referred to as a "big machine". The big machine is similar to a Rube Goldberg machine: it consisted of many parts and components working together to ultimately complete a task.

The use of Rube Goldberg design projects has been documented in the literature, in many different contexts, including:

- In the context of a K-12 extracurricular program[1] and a K-12 distance learning experience[2]
- In the context of extracurricular Rube Goldberg competitions[3]
- In the context of a pilot Introduction to Mechanical Engineering Design course with 16 students the first year[4] and 21 students the second year[5]
- In the context of a junior-level electrical laboratory class with number of students ranging from 8 to 26 over the years[6]

- In the context of an engineering dynamics course with 47 students[7]

The literature documents the many benefits of using Rube Goldberg projects. For example, the use of these projects requires that students use creativity[6,7]; develop teamwork skills, both within their teams and with other teams[4-6]; strengthen their knowledge of technical and course-related topics[5-7]; do hands-on work[7]; and even learn about operating under a budget and creating a bill of materials[5].

This paper describes the use of a Rube Goldberg machine at a much larger scale than typically found in the literature: in the context of a required mechanical engineering course with 286 students (58 groups). The purpose of this paper is to describe the project and assess how well it worked, both in terms of implementation and in terms of student outcomes. Specifically, this paper will: (1) describe the process of creating and implementing this project, (2) describe what worked well with this project, and identify areas for improvement for future semesters, and (3) summarize students' perceptions of the project, as well as their perceptions of the knowledge and professional skills developed, based on their responses to a survey.

Description of the course

The Introduction to Mechanical Engineering Design course at the University of Pittsburgh is a three-credit, sophomore-level course in which students learn about the design process, technical drawing, and computer-aided design (SolidWorks); it is mechanical engineering students' first exposure to design, as the first-year engineering courses focus on problem solving and programming, not on design. It is a required course for students in the Mechanical Engineering and Materials Science programs, and also for students from other departments who receive a minor in Mechanical Engineering. In the fall 2015 semester, there were 286 students, divided between two sections taught by two instructors. Both instructors followed the same syllabus and used the same assignments. Students from both sections worked on the same big machine project: all 286 students worked on creating one big machine.

In previous semesters, students in this course completed a design project that emphasized user-centered design. Using the design process and user discovery, they designed a product that would directly meet users' needs. This user-centered design project is still part of the course, but in the fall 2015 semester, a new project was incorporated, to be completed in addition to this one. The user-centered design project was completed during the first nine weeks of the semester, followed by the new project. The new project that was piloted was a design project in which students in the two course sections designed and built a big machine. With the big machine project, students got experience designing with the goal of fitting into a larger system. With this project, the emphasis was no longer solely on the end user, but also on making sure that their designs met the constraints and requirements of the system.

Description of the big machine project

The instructional team that worked on developing and implementing this project consisted of the two faculty members who taught the course and an undergraduate teaching assistant – a senior in mechanical engineering. In designing this project, we began by identifying the design skills the project was aiming to develop. These skills included: defining engineering requirements, designing with incomplete information, designing for engineering requirements, designing against constraints, considering tolerances in design, and designing as part of a complex system. Additional skills the project aimed to develop were creativity, communication, and teamwork skills.

We then outlined the path the machine would follow, encompassing three floors of the engineering building. The machine would start on the third floor, then follow its path down to the second floor, and end on the first floor. Appendix 1 includes maps of the building and the machine's path. The path was divided into sections of approximately 10 feet each, and each student team of 4-5 students (a total of 58 teams) was assigned a section. Some teams were made up of students from a single course section and some teams had members from both sections.

The big machine project began approximately halfway into the semester and was divided into three parts, so students had three deliverables. These deliverables are described below. All the deliverables were completed by the teams outside of class. No in-class time was provided for students to work on the project, but the instructors did use class time to provide instructions and clarifications about the project, and to connect course material to the project, when applicable.

<u>Part 1: Propose the task for the big machine</u>

A Rube Goldberg machine includes multiple, complex steps to ultimately complete a (usually simple) task. Our big machine therefore needed a task that it would complete at the end of its run. The first deliverable for the big machine project was an individual assignment in which students proposed a task for the big machine; the students were given three days to complete this assignment. The original intention of this assignment was for us to compile a list of the more feasible and interesting tasks from all the students' proposed ideas, and then ask students to vote on their preferred task.

Examples of tasks proposed by students included: wake a sleeping student, hammer a nail, submit an assignment, water a plant, pop a balloon, and return library books, among others. Some proposed ideas were not appropriate due to safety concerns, such as lighting a candle and launching fireworks. An idea that we noticed was very prominent was showcasing the University and/or the University engineering programs. Because this idea was so prominent, we decided to skip the voting process that was originally intended and select this idea. The task of the big machine therefore became to highlight the University along its path, ending with unfurling a University banner and shooting confetti.

<u>Part 2: Submit preliminary design and log book</u>

The second deliverable was a group deliverable consisting of two steps: (a) defining and communicating requirements for the preceding team (the team that is adjacent to and preceding them along the machine's path), and (b) documenting the team's preliminary design in their design log book. Regarding (a), each student team had to begin to think of ideas for how their segment would operate and to identify what mechanical action they wanted to use to cause their segment to start. Because their segment would be initiated by the preceding team's segment, they needed to define those input requirements (in other words, what input from the preceding segment of the machine will initiate action on their segment of the machine?) and communicate those requirements to the preceding team by email. Those stated requirements were to be used by the preceding team to design the output of that team's machine segment. Student teams were encouraged to be as clear and specific as possible (describing position, location, size, motion, weight, etc., as needed) so that their instructions would be interpreted correctly. At this point, the student teams necessarily had begun designing their segments with incomplete information, as they had not yet received the requirements for what their output should be.

Regarding (b), once student teams had identified their input requirements and received instructions on what their output should be, they then had all the information to design their entire segment. As they designed their segment, they were required to document their idea generation process and their preliminary designs in a design log book, which was submitted for instructor grading and feedback.

In addition to the requirements specified by the student teams as part of the input requirements, students had to follow these requirements and constraints:

- In keeping with the machine's University-centered task, teams were required to incorporate either some aspect of the University (University programs, culture, student life, …) or some aspect of the city of Pittsburgh into their design.
- Their University theme could not be duplicated – each segment had to have a unique theme. To avoid duplication, a Google document was set up so that as student teams identified their themes, they would write it in the document, and other teams would know they could no longer choose those ideas.
- Safety constraints needed to be followed. These included: not impeding ingress and egress to hallways and classrooms, not creating obstacles to walking or wheelchairs, not impeding access to fire extinguishers, and not obstructing stairways.
- Neither explosives nor flames could be used.
- No residues (paints, oils, etc.) could be left behind.
- Liquids were not allowed to escape containers.
- Nothing could be mounted to walls or adhered to floors.
- A safety mechanism was required in each segment to prevent the machine from being triggered accidentally by others (which could result in a catastrophic cascade of the machine at an inopportune time).

Student teams were also informed that they needed to keep tolerances in mind – the machine still had to work even if neighboring segments didn't align perfectly.

Students had approximately one month to complete all of Part 2. As we reviewed the submitted log books, we either approved designs or asked students to make changes, depending on how well they met the above requirements and constraints. Shortly after this initial feedback was provided, student teams were required to briefly meet with us at the locations of their machine segments to verbally describe their designs and receive the necessary feedback.

Part 3: Build final design and submit log book

We determined a “Build Day” for students to build and integrate their segments into one machine, and a time was specified when the machine would be tested and a video recorded. Although a Build Day was specified, student teams were encouraged to work with the adjacent teams prior to that so that they could test and modify their segments.

As the Build Day approached, we decided to require a few test runs, for several reasons:

- Although student teams were strongly encouraged to build and test, it was evident they were not doing this. Requiring a test run meant that students would have to build and test their designs prior to the official run day, giving them extra time to make changes to their design, if needed.
- We were interested in documenting this project and planned on recording the machine in action during the official run day. However, only recording on the run day meant that there was a possibility of not getting a good video and/or not getting good footage of certain segments. Having these test runs would mean that we would be able to record each individual segment.
- As part of their final submission, student teams were required to submit a video of their segment working, and these test runs would allow the students to record their segment in a calmer and less crowded setting than if they recorded on the official run day. In addition, this setting allowed students to record their segments in the context of adjacent segments.

For these test runs, the 58 student teams were divided into three groups and were assigned a day to test and record: groups 1-21 on day 1, groups 21-42 on day 2, and groups 42-58 on day 3. Each day, the student teams would set up and test their segments, and two TAs, led by the head TA, would record the segments and help the students when necessary.

Students then submitted their team’s log books with a description and picture or sketch of their final designs, as well as a video of their segment of the machine in operation. This submission was due approximately one month after Part 2 was due.

Although we had a small budget to purchase materials for the students, only a small subset (around 12) requested materials; for the most part, students used materials and objects that they brought themselves (cardboard, toy cars, etc.).

The official run day

The goal of the official run day was to start the machine and have it run through its entire path. The student team whose segment initiated the machine reached out to the University’s Chancellor (this was their way of meeting the requirement of having a University theme) to see if he would be willing to start the machine by shooting a basketball into a bucket. The Chancellor agreed, so at the official run day, he initiated the machine and, with the instructional team, followed the machine as it ran.

Because of the length of the machine, we had decided that should one segment fail, the head TA would simply initiate the next segment so that the machine would continue running (instead of re-starting the entire machine each time one segment failed). During the run, approximately 10/58 segments required the intervention of the TA. It took 10-15 minutes for the machine to complete its run.

The big machine project: what worked and what needs improvement

The instructional team's perspective

Throughout the project, we met weekly to determine next steps and to assess how the project was going. At the end of the project, we had one final meeting to debrief and make recommendations for next year.

From our perspective, many things worked well: the project was challenging, required creativity, required hands-on work, and required teamwork. The project provided students with an opportunity to develop skills such as defining engineering requirements, designing with incomplete information, designing for engineering requirements, considering tolerances in design, designing as part of a complex system, and developing creativity, teamwork, and communication skills. Table 1 below summarizes the project's main tasks and what skills each task aimed to develop. An unexpected benefit was found that, given that this project was the first build experience for many of the students, they were surprised to learn that the machine segment did not work as expected because of unexpected factors, such as friction in moving elements or deflection of structural members.

Table 1: Main tasks and the skills they aimed to develop

Skill / Task	Define input requirements	Write input requirements to preceding team	Use other team's input requirements to design output	Design and build full segment	Follow constraints and requirements
Define engineering requirements	X	X			
Design with incomplete information	X				
Design for engineering requirements			X	X	X
Consider tolerances in design	X		X	X	X
Design as part of a complex system			X	X	X
Creativity	X		X	X	X
Communication	X	X	X	X	X
Teamwork	X	X	X	X	X

In addition, it was great to see the students engaged and motivated. Seeing the students take the initiative of contacting the Chancellor, seeing their excitement as they built and tested, and hearing them cheer when their segment worked indicated to us that the students enjoyed the project and took pride in their work.

We did identify areas for improvement. Some of the changes being considered for next year include:

- Require students to create a SolidWorks model to communicate their input requirements. This would ensure that student teams provide more details and dimensions in their input requirements. This change is being considered in order to address the issue of many teams who provided very vague requirements to adjacent teams, which resulted in some parts not connecting when the segments were built.
- Require a maximum reset time for each machine segment. During the test runs, it was noticed that certain segments of the machine required a long time to set up and prepare for operation, primarily if they had many small parts (for example, a series of dominoes). This was an issue anytime the segment had to be restarted, because setting up all the small parts took significant time, thus slowing down the test runs and videotaping. To address this, students could be required a maximum reset time (for example: "Upon failure or after a successful run, your segment must be able to be reset in less than one minute").
- Require students to use materials that will ensure their segment is structurally sound. Many of the segments that had issues had complex structures built with cardboard. Although the cardboard worked for some designs, it was not appropriate for certain designs that needed to be more structurally sound.
- Require students to create a bill of materials. We noticed that students did not think about designing for available materials or cost. For example, when they purchased lumber, they would waste much of it, or those who did request materials often requested non-standard dimensions and quantities; this would not happen if they simply modified the lengths of the lumber they bought. In future implementations of the project, students will be required to create a bill of materials, consider cost, and minimize wasted materials.
- Consider starting the project earlier in the semester. The big machine project started approximately halfway into the semester, which resulted in student comments regarding not having enough time to develop and build a good design. Starting the project earlier in the semester could be a way to address this.

While in an ideal scenario, the big machine would run without any segments failing and needing to be restarted, we did not very strongly emphasize this during this first implementation of the project because with 58 groups, a successful run would require significantly more time and testing than was available in the semester, especially considering the course required that students complete another project in addition to this one. In future implementations, we would like the machine to run without needing to be restarted, and are currently considering how to address this – for example, should points be taken off for segments that don't run on the official run day?

We had certainly underestimated how much the students expected that they would build their design and it would run successfully without the need for iteration. They learned the hard way that physics (friction, bending, humidity, etc.) is real, and that it takes frequent testing and iterating to get a segment that works. Their feedback (below) shows that they did indeed learn this lesson.

<u>The students' perspective</u>

To learn about the students' perceptions of the big machine project, a short survey was administered at the end of the project, after the official run day. The survey was created specifically to assess the big machine project and learn about the students' perceptions of the project and the skills they developed. Students were sent a link to an online anonymous survey, in which they were asked to rate which skills were developed as a result of the project. In addition, they were asked to provide information on what worked well about the project and how they would improve it. The survey can be found in Appendix 2.

A total of 163 out of 286 students completed the survey, for a response rate of 57%. Table 2 provides the means for each item.

Table 2: Means for survey items[1]

The big machine project helped me develop the following skills:	Mean[1]
Understand the need for testing of a design	4.35
Creativity	4.23
Work with my team	4.18
Building/creating	4.17
Obeying constraints	4.06
Design as part of a complex system	4.04
Planning	4.03
Work with multiple teams	4.01
Design with incomplete information	4.00
Follow engineering requirements	3.93
Consider tolerances in design	3.91
Oral communication	3.89
Clearly define engineering requirements	3.83
Organizational skills	3.79
Written communication	3.45

[1]Response options were 1=Strongly disagree, 2=Disagree, 3=Neither agree nor disagree, 4=Agree, and 5=Strongly agree

In response to the question "What did you like about the big machine project?", students wrote that they enjoyed the hands-on work and the creativity it required. They also enjoyed seeing their segments work together. In addition, they learned about the nature of engineering work –

for example, they mentioned learning how difficult it is to go from conceptualizing something to actually creating it. Representative student comments are below:

> "It was really awesome seeing how the whole thing was put together and how complex it was."

> "I really liked the ability to do whatever we wanted with the task. The freedom allowed for creativity which was really nice. I enjoyed the project as a [whole] because it was a hands on project, it was a little less rigid than other project/classes that allowed it to become more of a fun activity, and it was rewarding! Seeing everyone's parts set-up [on Build Day] was impressive and seeing it go off made all of the group meetings and work so absolutely worth it! This is something that I know I will be talking about for years to come because it was awesome!"

> "The duality between making sure all of our internal parts of the machine worked and then having to make sure it interacted with other machines correctly."

> "I liked that the whole class was involved with the project. I have never worked on a project where everyone in the class contributed to the same goal."

> "I thought it was a great way to make the leap from planning to reality. I think it's interesting how much harder it is to make something a reality after conceptualizing it."

> "It was an assignment that was actually fun, but taught us important aspects of engineering at the same time. Also helped to connect with peers."

> "I loved everything about it. It made me feel like a real engineer! I loved working with the groups ahead and behind me, and it was such a great feeling [of] accomplishment when our sections worked!"

Student comments regarding how their individual segments fit as part of one complex machine, regarding the need to make sure their designs worked independently and as part of the machine, and regarding the challenges involved in turning an idea or design into reality highlight the unique aspects of the big machine project.

In response to the question "How would you improve the big machine project?", many students mentioned the difficulty in communicating with the adjacent teams, and believed the project would be improved if clearer guidelines on communication expectations and/or required meetings among the groups were incorporated. In addition, there were some comments on the amount of time the project took and the poor timing of the test runs and Build Day (the week before final exams). Finally, students commented on the need for more required testing to ensure that the segments worked well together. Representative student comments are below:

> "I would recommend that you take into account the fact that this week (the last week of the semester) involves a lot of tests and projects being due for some students… so you should probably let the students have some input on when would be a good time for them to set up their project/have it taped/etc..."

> "Give us more time with it. Start it earlier on in the semester"

> "It took a little bit longer [than] expected to build it. It was in the midst of a lot of other projects being due and coming back from Thanksgiving break. I think the timing was a little off. Possibly get started on it sooner than later."

> "I think that I would like this to be a semester long project. In my opinion, not enough time was given to properly flesh out an amazing product. Everything seemed rushed and I wish I could have had more time to properly test things (although my segment did work as intended). It would be nice if we had a scheduled three days in the middle of the semester (sort of like we had) where everyone has to test their segments and make sure that they work with the subsequent group. THEN have another scheduled three days towards the Big Machine Day to film and finalize all of the details."

> "A bigger emphasis needs to be placed on communication between groups. Too often we tried to contact the group ahead of us and got no response. If the point of this project was more focused on that, I think it would be more likely to be successful and would create a different atmosphere altogether, where the key to success is communication."

> "Group to group communication was not that great"

> "I don't think the project represented the inter-team communication and working together it was meant to be. Some teams were relatively un-receptive to answering additional questions and I think it would have been better if teams were supposed to meet in small groups for testing along the way…"

Student comments regarding the need to better structure communication among teams and the need to build and test sooner and more often in the process highlight some of the unique challenges of the big machine project.

It is important to note that we relied on students' self-assessments of the skills involved in the big machine project. A consideration for future semesters is the incorporation of instructor assessments to determine whether and to what degree these skills actually are developed in students as a result of the big machine project.

<u>Advantages and disadvantages of incorporating the big machine project</u>

Based on our experience with the project, as well as what we learned from the students' feedback, we identified some advantages and disadvantages of incorporating the big machine project. Some of the advantages were: it was a project the students were excited about, students had a hands-on project to work on, it was a first-time building experience for many students, the students were required to further develop their creativity and communication skills, and the students worked together towards a common goal – one shared by all students taking the course. The main disadvantages were the difficulties that arose within and among teams, as well as the extra coordination required to organize and lead such a large group of students.

Conclusions

Overall, the big machine project was an enjoyable one for both the students and the instructional team. In addition, based on students' responses to the survey, it is evident they developed many of the skills the project intended to develop. The skills they developed will be useful to them not only in the context of design, but in their future engineering careers. As pointed out by the National Academy of Engineering[8], the engineer of 2020 will need creativity, teamwork, and communication skills. The students' survey responses indicated that teamwork and creativity in particular were developed as a result of this project.

The student surveys also indicated that they learned about the need to test designs. In their comments, they emphasized that they realized how difficult it is to take something from the conceptual stage to a final product, and that they would have liked more time to continue to test and iterate their designs. This indicates that students are becoming familiar with the "essence" of engineering – "the iterative process of designing, predicting performance, building, and testing", and this is happening early in their program, as recommended by the NAE[9].

The students enjoyed the hands-on component of the project, which was expected, as this has been the case at other institutions (see Berg[7]). While many institutions incorporate hands-on design projects as part of the first-year curriculum, it is not as common in the middle years of the curriculum. This project gave the students the opportunity to engage in hands-on work at a point in their studies when there tend to be few, if any, courses with hands-on components.

Two challenges that students mentioned included working with other teams and the timing of and time required for the project. Similar findings were mentioned in Berg[7]. Regarding the latter, when to start the project and how much time to give students is something we will likely revise for the next implementation of the project. Regarding the former, per students' suggestions, we are also considering ways that would encourage and facilitate team interactions, so that teams would more effectively work with each other. The engineer of 2020 needs strong teamwork skills[8]; indeed, engineering work is characterized by teamwork, not just within a team but with other teams, so developing this skill will be a key requirement for their future careers.

Our experience leads us to agree with Berg's[7] statement that when this type of design project "is incorporated into the engineering classroom it allows for a unique blend of creativity and challenge that is often hard to accommodate in introductory engineering curriculum". While the first implementation of the project was by no means perfect, we look forward to improving and re-implementing the project, both because of the valuable skills it develops in the students and because of the enthusiasm, excitement, and engagement that was evident in the students.

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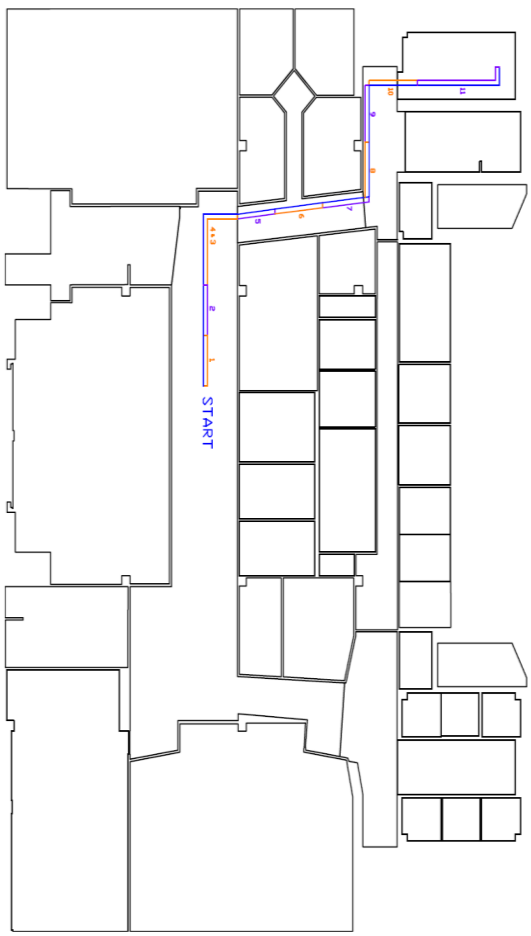
Appendix 1: Map of machine path

Third floor:



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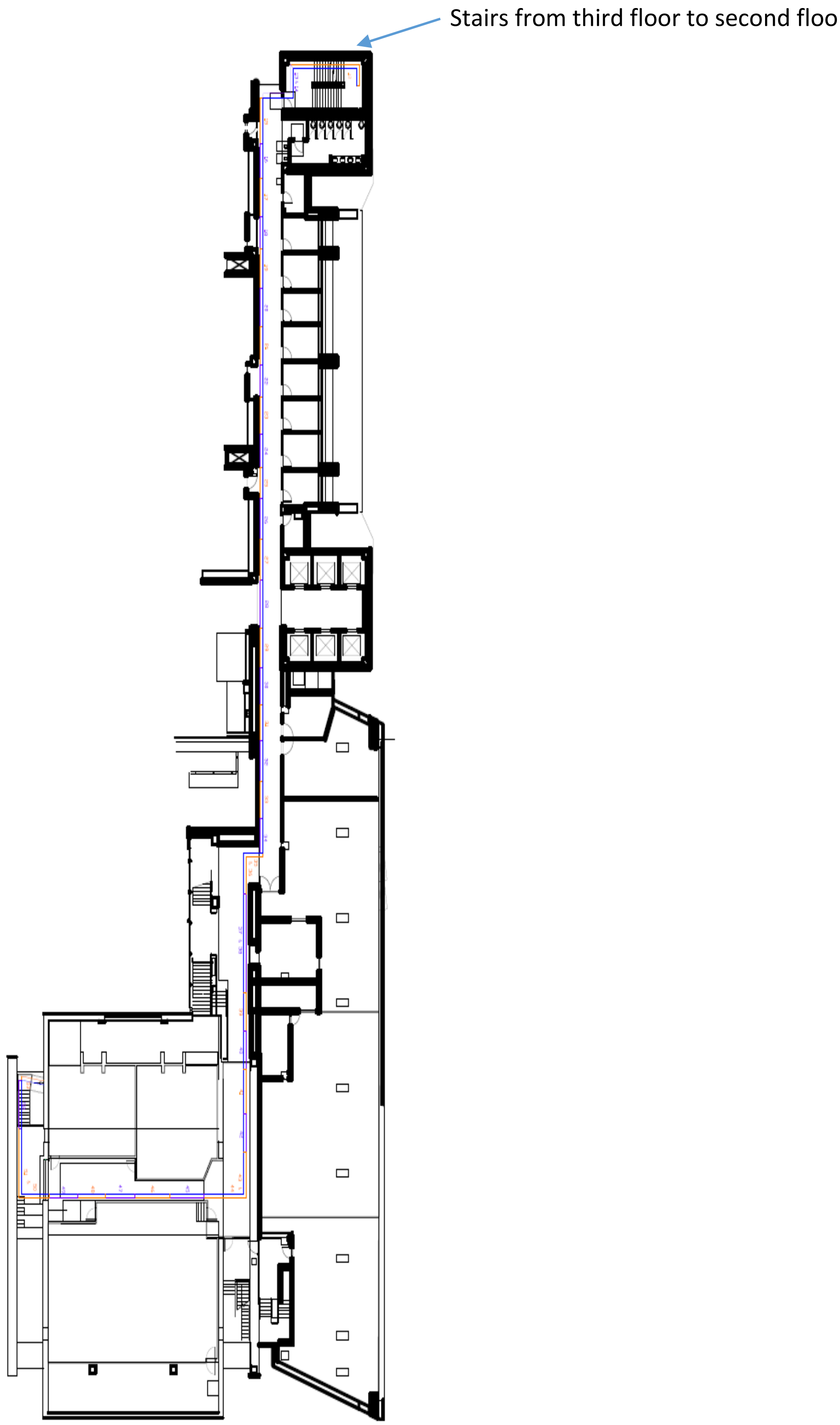
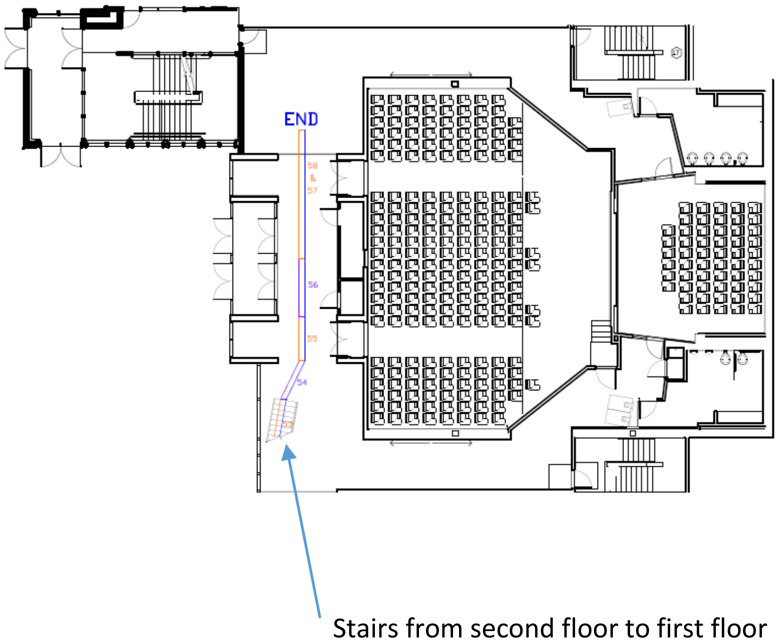


First floor:



Appendix 2: Survey

1. Select your gender: Male   Female
2. Respond whether you strongly disagree, disagree, neither agree nor disagree, agree, or strongly agree: The big machine project help me develop the following skills:

- Clearly define engineering requirements
- Follow engineering requirements
- Consider tolerances in design
- Design as part of a complex system
- Work with my team
- Work with multiple teams
- Oral communication
- Written communication
- Creativity
- Obeying constraints
- Building/creating
- Planning
- Organizational skills
- Design with incomplete information
- Understand the need for testing of a design

3. What did you like about the big machine project?
4. How would you improve the big machine project?