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DEVELOPMENT AND EVALUATION OF A SOPHOMORE MECHANICAL ENGINEERING DESIGN COURSE INFUSED WITH CDIO SKILLS

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ABSTRACT

The Mechanical Engineering Department at the California State University at Northridge has adopted the Conceive-Design-Implement-Operate (CDIO) framework as the overall guiding philosophy in reforming its undergraduate education. An important standard to achieve in this adoption is to have several design-build project experiences in the curriculum. To spearhead this effort, one of two sessions of a sophomore design course that teaches mechanical design for manufacturing was chosen as an experimental session and was redesigned to teach a project involving designing and building yoyos, along with CDIO, personal, and interpersonal skills. Student teams go through the complete product development cycle (i.e., four phases of CDIO): conceiving innovative ideas and concepts; designing and reiterating concepts of yoyos to meet requirements; implementing the concepts and manufacturing yoyos; and operating the yoyos in the context of safety and a yoyo-trick contest at the end of the semester. Engaging in the project helps students become proficient in using Computer Aided design/Manufacturing tools and machines (e.g., SolidWorks, Esprit, Rapid Prototyping, Injection Molding, and Computer Numeric Control machines); internalize the role of key manufacturing metrics in modern manufacturing systems; and learn personal, interpersonal, and professional skills. Results obtained through self-reporting surveys and performances on a design problem given to students in both sessions show that teaching the design-build project significantly improves students' ability to conceive and design a product and to work in a team-based environment. The improvement in the students' learning has resulted in adopting a design build project in all future sessions of this course. A plan for integrating this course with other core design courses, and into the Department overall plan for adopting CDIO is also discussed.

I INTRODUCTION

The present Mechanical Engineering (ME) curriculum at the California State University at Northridge has evolved from a set of senior electives in a general engineering degree program to a formal BS in Mechanical Engineering (BSME) in 1993. In response to comments received during the Department's first accreditation under Accreditation Board for Engineering and Technology (ABET) 2000 engineering criteria, the assessment-based guidelines of the ABET, the Department sought to improve its curriculum by introducing design courses in the freshman and sophomore years. The goal of these changes was to introduce design concepts and related computational tools at the lower division to improve students' preparation for the senior design capstone course and their future careers. These changes resulted in a "design stem" of courses: the freshman orientation course ME101, a one-year sophomore design sequence ME286AB, the junior-level machine design course ME330, and a year of senior design capstone course (ME486AB).

However, implementing the new courses has revealed the need for a more comprehensive approach to the engineering design cycle—beginning before the senior course—in which students would be exposed to several design-analyze-build cycles during their time at the university. To address this need, the Department has selected an education framework that has proven to be successful, widely accepted, and, most importantly, consistent with its vision. Extensive research identified the CDIO (Conceive-Design-Integrate-Operate) engineering education framework pioneered by MIT as the most appropriate systemic solution [1,2]. In June 2005, the Department was admitted as a collaborator of the CDIO consortium, and has been spearheading an effort to extend the framework to include minority institutions such as CSUN [3]. To spearhead this effort, one of two sessions of the sophomore design course (ME286A – Mechanical Design I) that teaches mechanical design for manufacturing was chosen as an experimental session and was redesigned to teach CDIO skills through a project involved designing and building yoyos.

In the remainder of this paper, the development and evaluation of this experimental ME286A session will be described in detail.

II COURSE DEVELOPMENT

Since its inception in Spring 2003, the existing ME286A teaches mechanical design, design methodology, design for manufacturing, graphical modeling, dimensioning and tolerances, materials, machining theory and practice. The lecture topics include:

1. The engineering design process: the design process, steps, design examples, drawings, standards, concurrent design
2. Design Methods -- problem solving, specifications, conceptual design, design principles, detail design
3. Mechanical properties of materials, stress, strain, hardness
4. Engineering materials: metals, ceramics, polymers, ferrous and non-ferrous metals, traditional ceramics, thermoplastic polymers, thermosetting polymers
5. Casting, molding, and related processes: sand and die casting, injection molding, permanent molding, powder metallurgy

6. Metal forming and sheet metal working: rolling, forging, extrusion, drawing, bending, cutting
7. Material removal processes: turning, drilling milling, grinding, non-traditional processes
8. Joining and assembly processes
9. Welding, brazing, soldering, bolts, rivets, inserts
10. Metrology Inspection, instruments and gages, surface measurement
11. Interaction of materials, processing, and design: design using castings, forgings, sheet metal, welding, heat treatment, assembly

The laboratory introduces students to the computer aided design software Solidworks. The main assignment involves obtaining the dimensions of a bicycle's parts, drawing the parts, and assembling the parts.

While this existing course meets the Department's goal in introducing design, design-for-manufacturing concepts and related computer-aided design tools at the lower division, it has also been clear this course needs to be redesigned and expanded significantly in order to expose students to one of several design-analyze-build cycles during their time at the university. Thus, starting Spring 2005, an experimental session was taught in parallel with this existing course. While covering the same topics as the existing course, the experimental session introduces several new elements. A design project to build yoyos was piloted. With this project, students work in teams and go through the complete product development cycle (i.e., four phases of CDIO): conceiving innovative ideas based on market research for yoyos; designing yoyos to meet technical requirements and manufacturing requirements; integrating the yoyo parts and materials selection; and operating the yoyos in the context of safety and entertainment. Students are exposed to Computer Aided Design and Computer Aided Manufacturing tools and machines (e.g., SolidWorks, Esprit, Injection Molding, Rapid Prototyping, and CNC machines). In addition, engaging in the project helps students internalize quality, cost, rate and flexibility as key manufacturing metrics; internalize the impact of manufacturing constraints on product design and process planning; internalize the role of key metrics in modern manufacturing systems and design methodologies for manufacturing and assembly; and learn personal and professional, teamwork, and communications skills.

The details of a creative design process, the yoyo design-build project, and the personal and interpersonal skills taught in this class are described in the next three sub-sections.

II.A CREATIVE DESIGN PROCESS WITH PEER EVALUATION

Departing from the conventional design process taught in the existing course, the experimental session adopted a creative design process pioneered by design researchers at MIT [4,5]. This design process is called Deterministic Design (DD) and has been used successfully in a number of design courses (e.g., 2.008 and 2.009 at MIT) and in a number of design projects [5]. Through systematic organizations of ideas and peer evaluation, the DD acts as a catalyst to funnel and distill creativity into a successful design. As illustrated in Figure 1, students follow the DD process to develop ideas in stages from course to fine. In each stage of funneling and distilling ideas, a table called FRDPRARRC (abbreviation for Functional Requirement, Design Parameter, Analysis, Risk, and Risk Countermeasures) is used to systematically organize ideas and perform the necessary analysis and experimentation to arrive at the final design selections (See Figure 2). To use the table, each student creates one table that becomes their development road map and typically one sheet of paper is dedicated to each FR/DP pair. Students then gather in a group and exchange their FRDPRARRC table(s) for peer evaluation. The evaluation consists of examining whether: the FRs are adequately synthesized, the DPs are properly chosen, appropriate references/equations are used, and all important risks and risk mitigations are identified. This evaluation process gives an individual credit for his ideas while allowing the team to exam all possible ideas that the group can come up with and select the best one. As described in the next section, the DD process allows students to come up with as many wild, crazy concepts in the design, but, at the same time provides students a rigorous method to channel their passion in a deterministic way to meet the deadline.

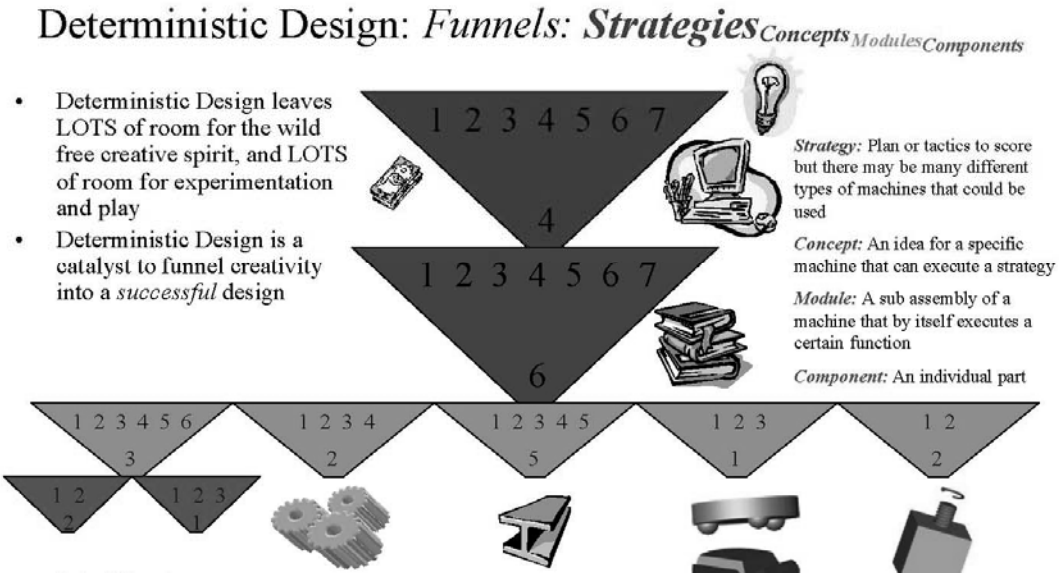


Figure 1: Deterministic Design (Adapted [5])

Systematic Organization of Ideas: *FRDPARRC*

Functional Requirements (Events) *Words*	***Design Parameters (Idea)*** *Words & Drawings*	***Analysis*** *Experiments, Words, FEA, Equations, Spreadsheets…*	***References*** *Historical documents, www…*	***Risk*** *Words, Drawings, Analysis…*	***Counter-measures*** *Words, Drawings, Analysis…*
A list of independent functions that the design is to accomplish. Series (1,2,3…) and Parallel (4a, 4b..) FRs (Events) can be listed to create the *Function Structure*	Ideally independent means to accomplish each FR. AN FR CAN HAVE SEVERAL POTENTIAL DPs. The "best one" ultimately must be selected	Economic (financial or maximizing score etc), time & motion, power, stress… EACH DP's FEASABILITY MUST BE PROVEN. **Analysis can be used to create DPs!**	Anything that can help develop the idea including personal contacts, articles, patents, web sites….	High, Medium, Low (explain why) risk of development assessment for each DP	Ideas or plan to mitigate each risk, including use of off-the-shelf known solutions

Figure 2: FRDPARRC Table (Adapted from [5])

II.B DESIGN-BUILD PROJECT

The design project implemented in the experimental session involved designing and building a yoyo. The design theme is to make a yoyo prototype that can be packaged with the McDonalds' Kid Happy Meal. Students in the class work in a team of about five members and use the DD process to continuously iterate their design throughout the CDIO phases. In the *Conceiving* phase, students conceive innovative yoyo ideas based on market research for yoyos and McDonalds' customer profiling. An important tradeoff analyzed in this phase is the attractiveness of the design versus the cost of designing and building. Typical analysis includes surveying and getting feedback from kids on ideas and estimating the fixed cost and incremental cost. An example of concepts conceived in this phase using Solidworks is shown in Figure 3.

15 DESIGN CONCEPTS

Figure 3: Students' yoyo concepts conceived

In the *Designing* phase, down-selecting concepts and designing yoyos to meet technical requirements and manufacturing requirements are facilitated by the DD process. The concepts down-selection process involves ranking the concepts using the "beauty pageant" technique, where the criteria are based on parameters such as cost, manufacturability, performance, attractiveness. An example of a FRDPARRC table is shown in Figure 4.

Functional Requirements	Design Parameters	Analysis	References	Risk	Counter Measure
Size	Should be sized to fit in a child's hand; ages five to ten	Surveys and customer profiling	Investigate typical yoyo sizes for kids	If too small, may be difficult to develop with the tools and time we have available	Come up with a compromised size to allow us to manufacture it in the time we have and yet fit most kids hands
Shape	Smooth surfaces; Rounded edges	Surveys and customer profiling	Investigate typical yoyo designs	The better the surface finish the more difficult it is to machine	Use a typical surface finish like 32 microns
Appearance	make it appealing to kids - glow in the dark; neat shapes…	Surveys and customer profiling	Research different types of yoyo designs	Mold becomes more complicated; harder to machine	Make the design as simple as possible; try various colors
Function	Must perform in a typical manner; Simple, standard design	$a = g / (I/mr^2 + 1)$ $\omega = [2gx / (I/m+r^2)]^{1/2}$ $t = (2L/g)^{1/2} (1+I/mr^2)^{1/2}$ $v = [2gx / (1+I/mr^2)]^{1/2}$	Experimental Investigation of Yoyo Design by Alma Bardon; Physics; Dynamics	improper application of equations; unbalanced design	Study references; Design a good symmetrical design
Assembly	Easy to assemble; Minimum number of parts; Minimum tool usage	BD manual charts to calculate assembly time	Fastener options	Makes design more complicated; snap fits are complicated to machine in mold	Compromise and allow the use of a fastener and one tool
Cost	Less than $1.00; must be able to be included in a McDonald's Happy Meal for under $5.00	Amortize the following into the cost of the yoyo: Cost of mold material = X; Cost of machining the mold = 0; Cost of thermoplastic material = Y; Cost of additional hardware = Z; Cost of producing injection molded part = P; Cost of assembly = 0; Total cost of yoyo = X+Y+Z+P	Engineering Economics	Must be a mass produced part to keep cost down below $1.00	Make design as cost effective as possible by reducing X,Y,Z and P
String Length	String length should be around six inches shorter for child	Typical yoyo string length is approximately 32 inches long	Measure several yoyo string lengths	None	None

Figure 4: Students' FRDPARRC table for yoyo project

In the *Implementing* phase, the students create a prototype of the best concept with the rapid prototype machine and examine its feasibility for manufacturing. The next step involves importing the Solidworks model into the computer-aided manufacturing software, Esprit, to generate a set of computer instructions, which are used by the Computer-Numeric-Control (CNC) machines to machine to mold. In the last step, yoyos are produced by feeding and melting plastic pellets in an injection molding machine with the designed mold. Future assignments in this phase will include making a large quantity of yoyos and collecting data to derive quality statistics and metrics.

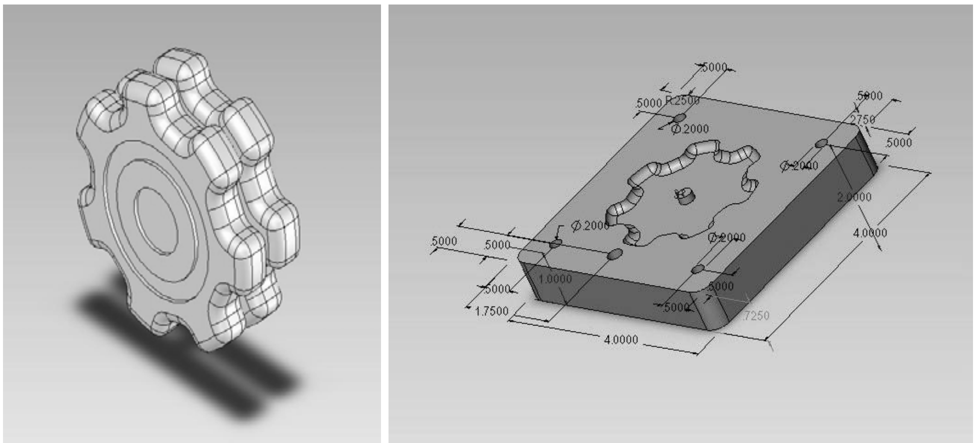


Figure 5: Students' yoyo and mold designed for injection molding

The Operating phase of the project involves playing with the yoyos and learning tricks to participate in a yoyo-trick competition held in the class at the end of the semester. Through the competition, the students reflect on their design, determining what works and what needs to be improved in the next generation of their design.

II.C INTERPERSONAL AND PERSONAL SKILLS

The experimental session requires student to write an interim report and make a 15-minute presentation of their progress with the design project half way through the semester. At the end of the semester, they are also required to submit a final report and make a final presentation of their design. Throughout the semester, regular meetings are held with the instructor to ensure that students properly manage resources (time, personnel, money). Teamwork is also taught with a "The Team Learning Assistant Workbook" by Deacon Carr (Carr 2004). Workbook exercises include writing a team contract, assessing team member performance qualitatively and quantitatively, and reflecting on the learning experience. To help the instructor determine a individual team member's contribution, students are also asked to divide 500 points (for a 5-member team) among themselves and rate their team members performance qualitatively.

III COURSE EVALUATION

Given that the differences in the makeup of the students in the experimental and existing courses are random, and that the lecture topics remain almost same in both courses, a self-reporting survey and a simple design-for-manufacturing problem were to use evaluate the effect of the changes in the experimental session on the ability of students to conceive, design, implement, and operate a system (product in this case) in a team-based environment.

III.A SELF-REPORTING SURVEY

A survey was administered at the end of the semester with 26 students in the existing session and 25 students in the experimental session. The survey statements along with the results are shown in Figure 6. A scale from 1 to 5 was used to rate each statement, where a rating of 1 corresponds to "not at all", a rating of 2 corresponds to "a little", a rating of 3 corresponds to "to a certain degree", a rating of 4 corresponds to "a lot", and a rating of 5 corresponds to "very much".

	Experimental Session		Existing Session	
Survey Description	Mean	Standard Deviation	Mean	Standard Deviation
1. "The class project has contributed towards reaching the course goals"	4.35	0.70	3.73	0.92
2. "The class taught me complete steps in a design-build experience of a product, from conception to production, in a teamwork environment"	4.18	0.81	3.02	0.86
3. "I find it stimulating to design when I knew that I was later going to build a model of what I had designed"	4.24	0.83	3.85	1.05
4. "The class project has made me learn more about the product development process than I would otherwise have done"	4.12	0.86	3.46	1.03
5. "There was a good connection in the course between the design and the build phases."	3.94	0.90	3.12	1.21
6. "I have learned to effectively work in a team through the class project"	3.94	0.97	3.31	1.16
7. "I have learned to effectively communicate your technical work through the class project"	3.59	0.87	3.54	1.03
8. "I like to work on design-build projects"	4.82	0.39	4.50	0.81
9. "I am competent in using Solidworks for design projects in other classes"	4.00	0.71	3.65	1.23

Figure 6: Survey question and results

These results show that qualitatively students find it stimulating to work on projects. Having a class project also enhances learning, teamwork, and communications skills. Comparison of the rating in both sessions shows that students in the experimental session rated their learning about the complete design build cycle of a product higher than students in the existing session. This is consistent with the high rating in both sessions that the students like to work on design-build projects and that the design-build project helps students make the connection between designing and building phases.

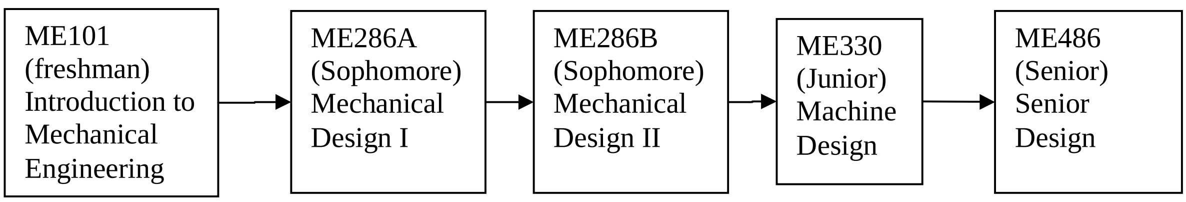
III.B DESIGN PROBLEM TEST

A design-for-manufacturing problem (See Figure 7) was also included with the survey. This problem probes the student ability to recognize that: 1) The geometry of the part as shown in the Figure a is such that it is hard to find standard fixtures to hold the work piece on the milling machine; 2) Drilling holes on inclined surfaces should be avoided. This will be hard to fixture and precisely align the holes; 3) The hole diameters, for example 11.385 mm and 11.4834 mm, are not close to any standard drill sizes, which will necessitate more tooling. It is good to use standard dimensions; and 4) Dimensions with three significant places are not required. This might be confusing. For a total of 8 points (2 points for each design-for-manufacturing issues), students in the experimental session score a mean of 5.92 while students in the existing session score a mean of 3.25. The hypothesis was that having the design-build experience improves the student ability to recognize design-for-manufacturing issues and the results seem to corroborate with this hypothesis.

IV DISCUSSION AND FUTURE DIRECTIONS

While the results of the self-reporting surveys and the mean score on the design-for-manufacturing problem were obtained from a limited sample of students, it is clear that teaching the design-build project significantly improves students' ability to conceive and design a product and to work in a team-based environment. The improvement confirms the fact that engineers are concrete operational learners, and, thus, learn the most by doing. The improvement in the students' learning has resulted in adopting a design build project in all future sessions of this course.

The Department is also planning to integrate this course with other core design courses, and into the Department overall plan for adopting CDIO. Since implementing its BSME degree program in 1993, the Department has offered its first lower-division courses. The most recent curriculum changes, made in response to input from faculty, ABET, industry, alumni, graduating seniors, and other stakeholders, have sought to impart design concepts and related computational tools at the lower division to improve students' preparation for the senior design capstone course and their future careers. These changes resulted in a "design stem" of courses (see diagram below): the freshman orientation course ME101, the one-year sophomore design sequence ME286AB, the junior-level machine design course ME330, and a year of senior design.



While this development has improved the Department's offerings, it also resulted in a patchwork curriculum. The adoption of CDIO will help the Department systematically unify the curriculum to improve students' learning and retention. Furthermore, this effort will also provides a cornerstone for the Department to take the leading role in addressing the projected U.S. engineering workforce needs for increased representation of underrepresented minorities, which is challenging due to the poor retention and academic performance of too many minority engineering students. As a response, the Department has proposed a three-year project to build upon CDIO, while making the key success-enabling principle of the Minority Engineering Program model--collaborative learning--an explicit and integrated part of a reformed mechanical engineering design curriculum. The first goal of the project is to establish a model framework for adapting and implementing CDIO so that it can be generalized for and have programmatic impact at other predominantly minority institutions similar to CSUN; can contribute to an evolving community of interaction, development and ongoing improvements in the education of minority engineering students; and can significantly increase the number of minority students able to Conceive-Design-Implement-Operate new products and systems. To achieve this goal, the new framework addresses the specific needs of minority institutions and comprises of a set of principles designed to overcome the barriers to success for minority students. To evaluate the effectiveness of this framework, the project's second goal is to apply it to the CSUN Mechanical Engineering design curriculum, and then compare the relative performance in the follow-on design course of students who complete the CDIO program and those in the traditional program, as well as the two groups' performances on specific tasks in a simulated industry work setting. The anticipated outcome is that the percentage of students retained in the CDIO program will be 35% higher than the percentage for students retained in the traditional program. We will accomplish this through the benchmarking of the ME Department's curriculum; the design and construction of a Student Design Center (SDC); the redesigning of core lower-division design classes; enhancing the competence of participating faculty members in teaching CDIO skills and in using active experiential learning methods; and developing a system of CDIO skills assessment and CDIO program evaluation.

Assume that one of your friends comes up with the solid model and three corresponding drawings and tells you that he wants to machine this part out of an aluminum stock. Explain briefly the DFM issues in trying to manufacture this part on a milling machine.

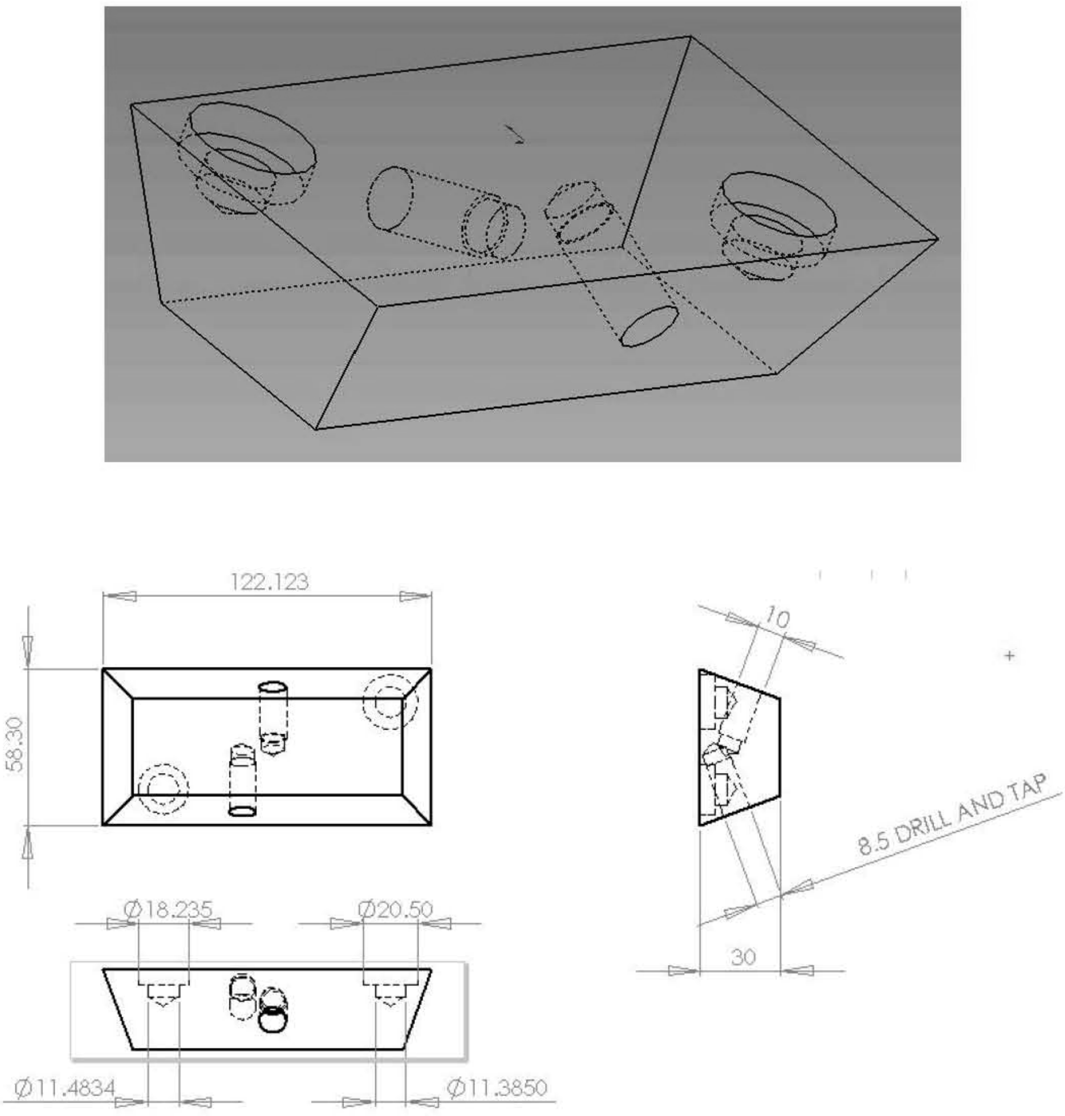


Figure 7: Design-for manufacturing problem (adapted [6])

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