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Closed-loop mechanical engineering design teaching to electrical and computer engineering students using CAD, CAE, and 3D printing

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Closed-loop mechanical engineering design teaching to electrical and computer engineering students using CAD, CAE, and 3D Printing

Abdullah Umair Bajwa[1,2]

Abstract: A computer aided design and engineering (CAD, CAE) course was designed to train senior electrical and computer engineering students in the mechanical engineering design process and introduce them to selected relevant topics from machine elements, material science, mechanics, and manufacturing to emphasize practical design considerations like manufacturability, mechanical integrity, and functionality. The course served as a 'learning through doing and making' based pedagogical experiment that leveraged the ease-of-use, manufacturing briskness, affordability, and portability of fusion deposition modeling-based 3D printing to teach these topics in an integrated manner within the time constraints of a three-credit-hour course. Couplings between CAD and CAE tools (motion simulation and analysis) and 3D printing were leveraged to reinforce student learnings on topics from machine elements and mechanics, and provide opportunities through project-based assessments to reflect on their design choices and use economically-available design performance results to introduce design refinements.

The course was very well-received by the students who reported that they found it motivating and stimulating, and that it enhanced their knowledge, skills and confidence. The paper presents an overview of the course and summarises experiences, challenges, lessons, recommendations and outcomes from two semesters of its teaching. Integrated and synergistic deployment of suitable pedagogical approaches is found to be very important for the execution of the course; and its resource-intense nature and high student workload requirements appear as potential challenges.

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Introduction

Experiential, hands-on minds-on, active learning approaches like learning through making and doing, and project-based learning have been known to benefit student learning as they promote creativity, engagement, critical thinking, and collaboration by making students active producers of knowledge rather than passive consumers [1, 2]. By providing on-demand, self-directed, and interest-driven learning, and promoting the development of practical solutions, experiential learning opportunities make students responsible for their own learning and provide "a sense of empowerment" [3]. Additional benefits in the form of improved student attitudes towards STEM majors and increased instructor interest and engagement have also been reported [4, 5]. The following quote from the American polymath, Benjamin Franklin succinctly reflects the ethos of experiential learning pedagogies, "*Tell me and I forget, teach me and I may remember, involve me and I learn.*"

This is not to undervalue traditional (lecture based) pedagogical practices as they have an important role to play in imparting factual knowledge [6]. By smartly curating learning experiences to provide students opportunities to practice different learning styles, both lower (understanding and remembering) and higher order (analysing, applying, evaluating, and creating) cognitive faculties from Bloom's taxonomy can be developed in a well-rounded manner [7]. The teaching of engineering design in particular, because of the unstructured and open-ended nature of its subject problems, requires a smart balance of various traditional and non-traditional pedagogical approaches. A case study of one such attempt is presented in this paper. A course designed to teach mechanical engineering design concepts to third and fourth year electrical and computer engineering students to help bridge gaps identified in their design learnings is discussed.

Design is "considered to be the central or distinguishing activity of engineering" [8, 9] and is thus an integral part of the engineering curriculum. Engineering design is a systematic, intelligent, problem-solving process through which engineers develop solutions that achieve desired objectives of form and function within bounds imposed by constraints [10]. In their seminal paper on the challenges in teaching engineering design, *Dym et al.* [9] recommended that "enhanced design pedagogy" should be made the highest priority by engineers in academe to curtail the loss of "human design potential."

Over the past few decades, 'project-based learning', which has been described as "problem-oriented, project-organized" learning has become a common design pedagogy [11]. Its benefits, ranging from improved teamwork to communication, have been well documented [2, 9, 10] and numerous case-study examples of project-based engineering courses can be found in the literature [12, 13]. Another, in some ways overlapping, pedagogical approach which has become increasingly popular in university design instruction is learning through making [2, 14, 15, 16, 17]. Making can be described as the use of materials for idea creation and expression [1]. Making-centered learning approaches are based on constructionist and constructivist pedagogies and promote the practice and development of high-level cognitive traits [1, 18]. 3D Printing (3DP), taken to be synonymous with additive manufacturing (AM) herein, is an important part of learning through making engineering design courses. The short turn-around time of 3DP allows students to understand and appreciate the iterative nature of the design process. The ready availability of cost-effective desktop 3D printers has been a strong enabler of making based pedagogies. Both learning through making and project-based learning put into practice Kolb's Experiential Learning Cycle theory [19] by providing opportunities for concrete experiences, reflective observation, abstract conceptualization, and active experimentation; which makes them natural choices for teaching engineering design [14, 20].

Compared to other engineering disciplines, university programs in mechanical engineering, because of their targeted learning outcomes, focus more on engineering design and provide more opportunities for students to apply the design process. This is done through courses in the ‘design stream’ like product and machine design; and computer aided design, engineering, and manufacturing (CAD, CAE, CAM), with additional support from courses in solid mechanics, material science, and manufacturing (see ref [21] for an example). Consequently, mechanical engineering and other mechanical-centered programs like aerospace, mechatronics, civil, and manufacturing engineering have more frequently adopted making-based design pedagogies [4, 14].

Context and Motivation:

The course was taught at Habib University - a small liberal arts university located in Pakistan’s largest city Karachi, which is home to over 16 million people [22]. Habib University was set up in 2014 with the aim to impart a world-class, yet contextually grounded (in the South Asian setting) liberal arts education to train interdisciplinary and transdisciplinary problem solvers who aspire to improve their society [23, 24]. Hence, there is a strong emphasis on teaching students design frameworks that can be leveraged to generate high quality solutions to real-world problems. The university is an undergraduate-only institute and has a student population of around 1000 who are affiliated with either the ‘School of Arts, Humanities and Social Sciences’ or the ‘School of Science and Engineering.’ The engineering program offers degrees in electrical engineering and computer engineering. Students in the electrical and computer engineering (ECE) program have the following courses in the design track:

- Engineering Workshop and Design (1st year): A 1 credit hour (CH) course that introduces concepts of engineering design (a cornerstone design course [12])
- Engineering Design and Innovation (3rd year): The course discusses design thinking and systems thinking, and provides an avenue for the students to practice them through a semester-long project around a local societal concern
- Capstone Project (4th year): 3+3 CH course in which students develop solutions for external or internal design clients

In addition to these mandatory courses, students can optionally enrol in non-engineering design courses from the Communication and Design program like ‘Design, Technology and Society’ or ‘Systematic Design’. Even though there were plentiful opportunities for students to be trained in important tenets of design, some gaps in the ECE students’ design learning were identified, which presented opportunities for teaching mechanical engineering design. A listing of these gaps/opportunities is as follows:

- ECE students typically encountered design in the context of circuit design or design of electronics systems wherein, unlike for design of mechanical systems, design choices are not visible as tangible artifacts. Rather, they appear as less tangible changes, e.g. differences in circuit topology or different amplifier choices, etc.

- A design inertia was observed amongst ECE students that impeded the transformation of ideas into prototypes. A mechanical engineering design course could help change student attitudes towards prototyping through skills development and provision of low-risk opportunities for making. Many mechanical systems also involve motion, and therefore their output is a source of pleasure for students and positive feedback to iterate upon.
- A need for improving the quality of student designed and manufactured prototypes was felt. Moreover, a number of ECE students regularly engaged with mechatronics projects, e.g., robotics, electric vehicles, solar panel systems, etc, and they needed the knowledge of mechanical system design. An enhanced grasp of mechanical aspects of design could promote the production of high-quality prototypes.
- Teaching mechanical design also aligns with liberal arts model of a broad education, and the engineering degree being a more general engineering degree.

It was in this context a gap-bridging computer aided mechanical engineering design course was envisioned. It was first offered, completely remotely, in Fall 2020 and then in Fall 2021 when it was taught mostly in-person. 31 students were enrolled in the first offering and enrolment was capped at 15 in the second offering to allow increased opportunities for and to manage the logistics of experiential learning. The majority (50-70%) of the enrolled students hailed from Karachi but there was a healthy representation of students from other regions of Pakistan, including from rural (e.g. interior Sindh) and remote (e.g. Gilgit-Baltistan) parts. The course had a higher proportion of male to female students (26:5 in Fall 2020 and 15:0 in Fall 2021). An overview of the course and lessons learned from the two offerings are presented here, in case they could be useful for other non-mechanical engineering or even non-engineering programs.

Course Design

Accelerating the Design Process:

The course was designed to maximize opportunities for design reflection, quality check (i.e. design requirements compliance) and iteration. Lead time in the conceptual design (preliminary + detailed design) and communication stages was significantly reduced through the use of CAD modeling, CAE analysis, and 3DP respectively. A few examples of how these tools could accelerate the engineering design process implementation are:

i. Quick transformation of design concepts into virtual models using CAD, and thus, allowing for the selection of promising concepts or combination of desirable features of various concepts (i.e. decomposition) into one concept; and refining the design further in the virtual space without needing to make physical prototypes or models.
ii. Expeditious concept selection, evaluation, and testing can be made possible through the virtual prototypes, e.g. by assessing the dynamic (motion-related) performance of the designs.
iii. 3D printed parts could be used both as models and prototypes in projects. The two are being distinguished based on their intended use – models are used in the conceptual and preliminary design stages to test certain performance aspects of the design under controlled setting, whereas, prototypes refer to the first fully functional physical artifact

that can meet all design requirements and perform satisfactorily under 'real world' conditions [25].

A schematic overview of the accelerating and reflection opportunities from these tools at various stages of the design process is shown in Figure 1.

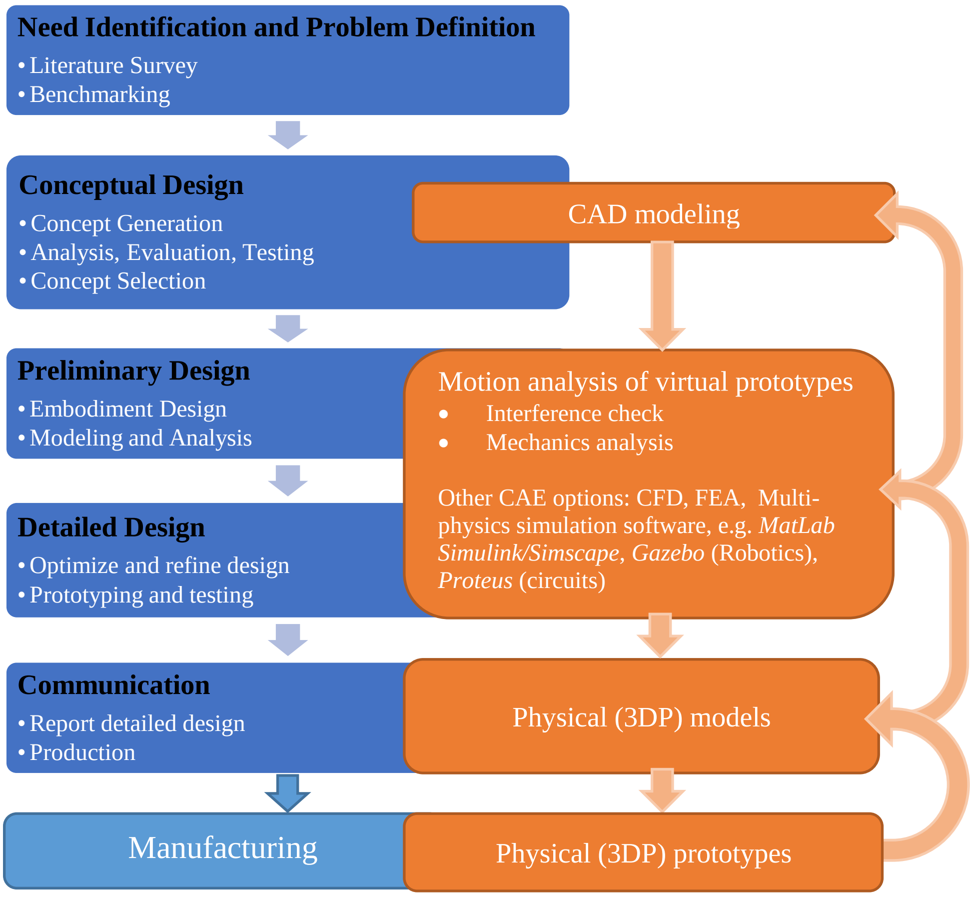


Figure 1: Influence of CAD, CAE and 3DP on the traditional engineering design process.

Course Structure:

Relevant topics and skills were selected to be taught in the course within the time constraints of a 3 CH (15 weeks) course and resource constraints of the ECE program at a small, private liberal arts university in Pakistan (Table 1). These topics are briefly discussed next. A weekly breakdown of the course containing a list of the topics covered (Table 2) as well as the various assessments used in the course (Table 3) are provided in the appendix.

The course had the following stated learning objectives:

i. Discuss the engineering design process from a mechanical engineering lens to make students cognizant of practical considerations like manufacturability, mechanical integrity, and functionality.

ii. Make students adequately competent in CAD modeling, 3D printing, and kinematic analysis to use these skills in design undertakings during their academic and professional careers.

iii. Train students to effectively communicate their design concepts through oral presentations, technical reports, graphics, and prototypes.

Resources Available: • Two FDM 3D printers • Learning management and lecture video recording systems • 3DP student workers • 3D printed teaching props **Constraints:** • 15 week semester, 3 credit hour course • 3^{rd} and 4^{th} year ECE students with minimal prior knowledge of course topics • Printing material (~15 g of PLA per student) and 3D printing supervision (TA available for 5 days) • CAD and CAE suite with free licenses that could run on typical student laptops

Table 1: Summary of available resources and constraints for course design.

Mechanical Engineering Topics:

A selective offering of mechanical engineering topics, mostly sourced from textbooks by *Budynas and Nibett* [26], *Norton* [27], *Dieter and Schmidt* [28], and *Dym et al.* [10] were covered. Topics were selected to help bridge gaps in mechanical design and prototyping that had been identified, and to prepare students for future ECE courses in design and robotics. The topics covered included:

- Mechanical Engineering Design Process
- Mechanical Design Considerations (e.g. material selection, mechanical properties of materials, failure modes)
- Machine Elements (e.g. shafts and shaft components, screws and fasteners, gears, springs)
- Mechanism Design (introduction to topics in mobility and mechanics - static, kinematic, and dynamic - analysis)

Around 4 weeks (26.5%) of the course was dedicated to teaching these topics with more emphasis on application than on theory, making the lessons breadth, not depth, imparting in nature; which is also true in general for the entire course.

CAD and CAE Topics:

The student version of the CAD/CAE platform *PTC Creo* was used to teach selected topics. The platform was selected because the student version was available free of cost and contained all important CAD and CAE features needed within the same suite. CAD modeling topics covered included: part modeling, assembly modeling, and engineering drawing. CAE topics were limited to mechanics analysis and included: making movable assemblies using appropriate degrees-of-freedom joints, imposing body, surface, and external forces (dynamic/static analysis), applying actuators to prescribe motion (kinematic analysis), and analysing and reporting results using graphical tools like motion envelopes and trajectories. Around 3.5 (24.5%) and 3 (20%) weeks were spent teaching CAD and CAE topics, respectively.

3D Printing:
There was no expectation from the students to be familiar with 3DP beforehand and it was hoped that by the end of the course, students would be able to design for and execute 3DP. Around 1.5 weeks (10%) of the course were dedicated to teaching introductory concepts in 3D printing. An additional 3 weeks (20%) were dedicated for project work in which students 3D printed and refined their designs for a major course project (discussed later). These topics introduced students to different forms of AM and then focused on the particular technology used in the course, fusion deposition modeling (FDM). Of the typically available plastic 3DP technologies, FDM printers are considered to be the most economical [14], both in terms of capital and operating costs. Students were taught practical aspects of FDM based 3DP (resolution, printing time, infill density, orientation, mechanical properties, material waste, etc.) to encourage them to be mindful of these aspects while making their CAD models, i.e. design for additive manufacturing (DfAM) [29]. The open-source slicing program *Ultimaker Cura* was used because of its ease of use, versatility, and informative/interactive graphical interface.

Two FDM printers were used in the course with polylactic acid (PLA) filament. One was an imported *Ultimaker* (a Dutch company) model *S3* printer and the other one was from a local Karachi-based manufacturer. Specifications for both are provided in the appendix (Table *4*). Even though the local printer had relatively limited capabilities, it performed acceptably well for the purposes of the course - a finding which can be helpful for other universities in similar settings. Another option could have been the use of open-source, so-called Rep-Rap printers that can be assembled in-house [3]. It has been reported that printer technology choice can affect cognitive and content learning outcomes [30].

Pedagogy
Important pedagogical approaches and tools that were used to teach the non-traditional, applied, breadth-based course are discussed below and relevant examples from student assignments are presented as needed.

Lectures:
Traditional hour-long lectures were delivered to impart foundational knowledge on mechanical engineering design and design considerations, machine elements and motion analysis. Most of these lectures took place towards the start of the course (weeks 1 and 2). The sequencing was deemed important as these topics served as examples in CAD topics later (e.g. designing machine elements) and students had to be mindful of engineering design considerations (e.g. mechanical strength, cost, quality) in design assignments. Moreover, it was thought that having traditional, in-person sessions that required moderate engagement and were predictable in their flow at the start of the semester would allow the students and the instructor to ‘settle in’, develop a sense of community, and understand the norms and expectations of the course. In subsequent weeks, the less traditional pedagogical approaches discussed next were deployed.

Flipped Teaching:

It was inadvertently discovered during the first (online-only) iteration of the course that students preferred asynchronous (recorded) lectures over synchronous ones for learning CAD topics. Recorded videos allowed them to pause the lectures to implement the modeling steps discussed. Therefore, during the second (in-person) course iteration, tutorial styled, short (5-15 minute) instructional videos for various CAD topics were prepared. The videos were shared with the students beforehand and the class time, which was made optional, served as an opportunity for them to practice modeling by discussing amongst themselves or with the instructor. Each week students had to submit a CAD modeling task assigned to them, which were often machine elements (Figure 2). Springs and threaded fasteners were used to teach helical sweep modeling in week 7, and a ball bearing task was assigned in week 9 to demonstrate assembly modeling and exploded views. The CAD tasks accounted for 12% of the course grade in the first course iteration but their weightage was doubled in the second offering to better reflect the student efforts required for their successful completion.

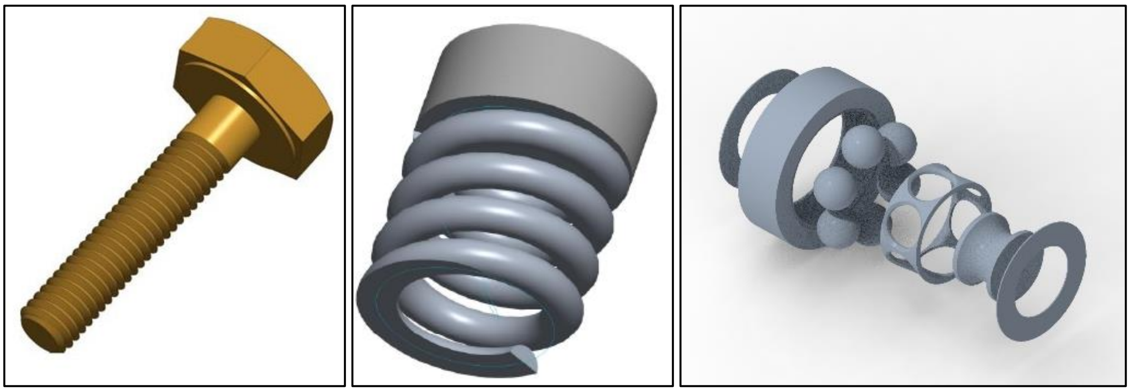


Figure 2: Sample machine element-based CAD modeling tasks (left to right: a hex bolt, spring with ground end, exploded view of ball bearing).

Using 3D Printed Teaching Aids:

As noted by *Ford et al.* [4] in their extensive review on the use of 3D printing in education, 3D printed purpose-built teaching props are one of the most common uses of 3DP in teaching as they enrichen the student learning experience. In preparation for the second iteration of the course, a month long ‘making summer school’ program was organized in which four first year students were recruited to: (i) test the capabilities of the 3D printers available and (ii) make 3D printed props to help teach the CAE course. The first-year students were able to quickly develop adequate modeling and 3DP capabilities; after which, they independently designed and printed parts, and refined their designs based on the printed parts’ performance. The summer program was a pedagogical experiment to evolve suitable practices for teaching the envisioned CAD-CAE-3DP course. Examples from it are also included herein. Some teaching aids developed are shown below: nut and bolt, spur gear-stepped shaft-ball bearing-lock nut assembly, demonstration of various tessellation resolutions (Figure 3), and a 3-link mechanism capable of being configured in revolute-revolute and revolute-spherical joint configurations (Figure 4).

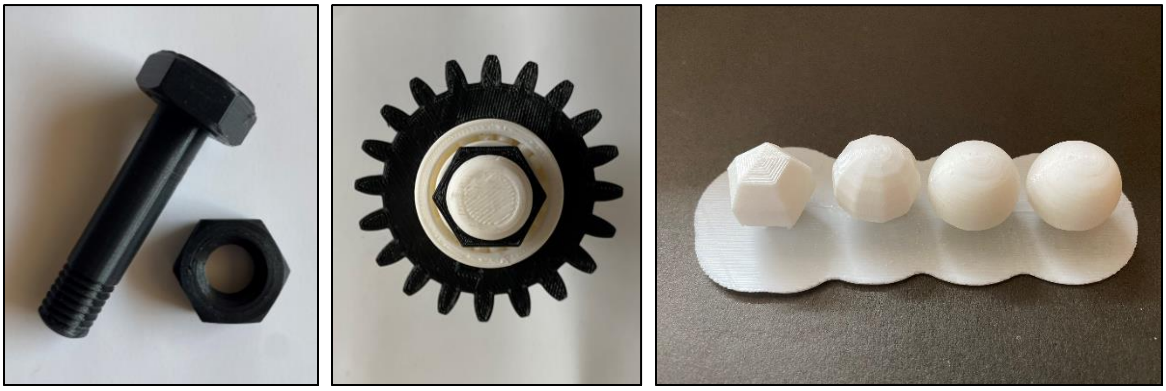
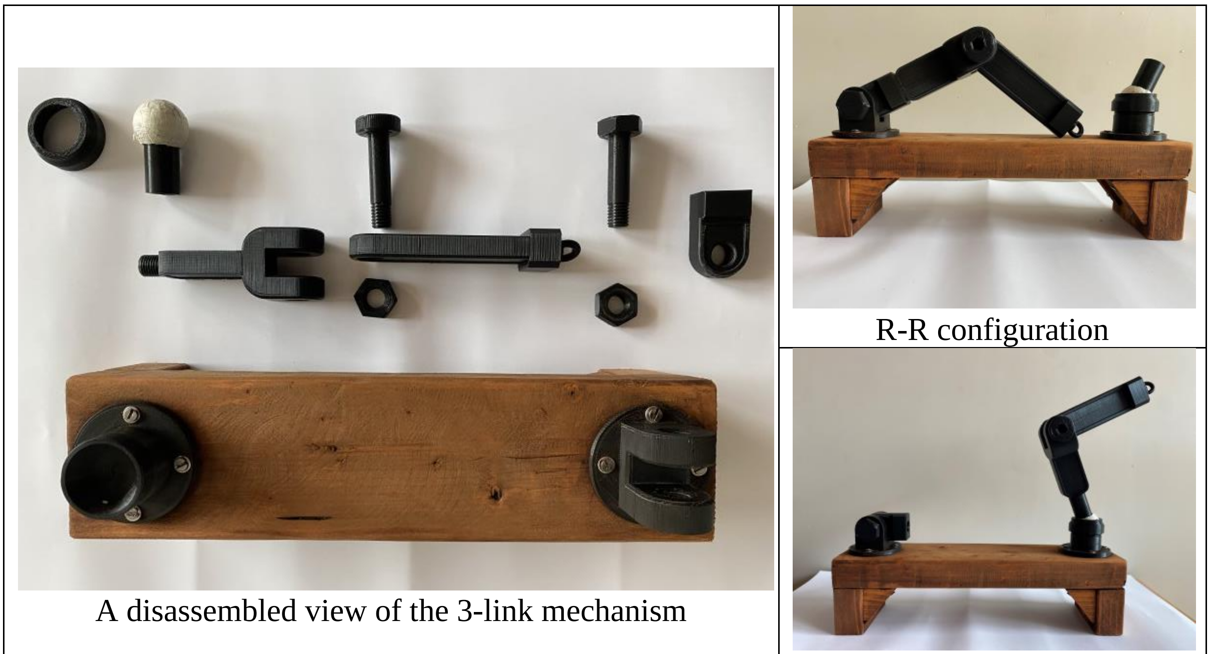


Figure 3: 3D printed teaching aids made for the course.



A disassembled view of the 3-link mechanism

R-R configuration

S-R configuration

Figure 4: 3D printed three-link mechanism to demonstrate revolute (R) and spherical (S) joints.

These tools were used in the teaching of concepts related to DfAM, mobility and degrees of freedom, CAD (movable assemblies), and 3DP considerations in general. Additionally, they (particularly the three-link mechanism) were used for reverse engineering and mechanism modeling CAE assignments. In one assignment, students had to make a CAD model of the 3D printed parts and then recreate and analyze a prescribed motion task - model the reciprocating motion of the R-R 3-link mechanism and the effect of joint friction as it is released from a non-equilibrium position. Students had to 'tune' joint friction to recreate a recorded video (Figure 5) provided to them (static analysis). Future projects could require addition of actuators at the joints to perform kinematic or dynamic analyses.

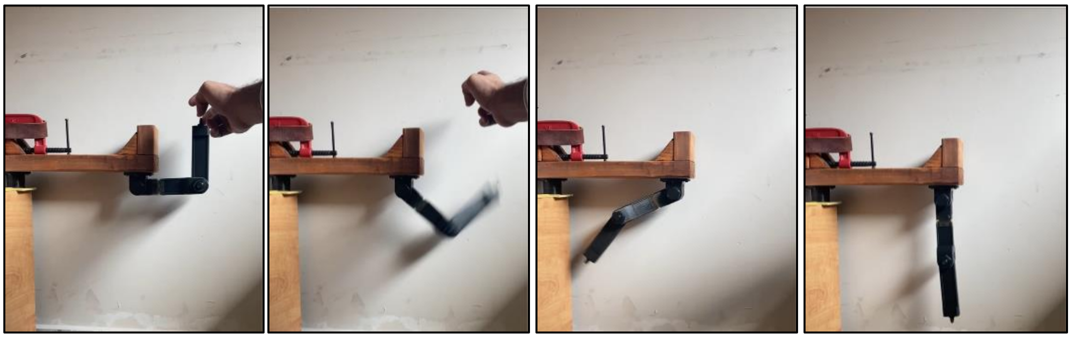


Figure 5: Screen grabs from the video recording of compound pendulum's reciprocating motion.

Project-Based Learning:

Project-based pedagogy was used to encourage students to learn and internalize important concepts in engineering design and mechanism analysis, and to develop CAD modeling skills. A course project, accounting for 40% of the total grade in the first virtual-only offering and then 20% after being simplified in the in-person offering, required the students to virtually design an internal combustion engine and then analyze its motion. This proved to be a fruitful learning exercise as it provided students a chance to assemble different machine elements (e.g. springs, crank shafts, bearings), albeit virtually, in a moving assembly and observe the effects of different design choices on its motion. The project was semi-open-ended where it constrained the design of certain components by prescribing dimensions but allowed students some room to iteratively refine their designs to meet performance targets, e.g. crankshaft should be balanced, compression ratio should be equal to a prescribed value. The students then had to discuss the effects of changing design (crankshaft offset) or operating (engine speed) parameters on the piston's motion. The projects were completed in teams of four. Half of the members were self-selected and half assigned by the instructor. Sample student submissions are copied in Figure 6.

The semi-open ended project was complemented by a more open-ended mini-project (assignment) in which students had to identify design objectives and constraints from a need statement given to them. It accounted for 10% of the course grade, and the need statement was from an instructor looking for a 'document reader' to assist his online teaching during the COVID-19 pandemic. The students had more freedom to explore the design space within the cost and packaging constraints provided, and were asked to use tools like pairwise comparison chart, performance metrics, and decision matrix to design a suitable product. Examples of some preliminary and final designs are shown in Figure *7*. The project was performed in teams of two.

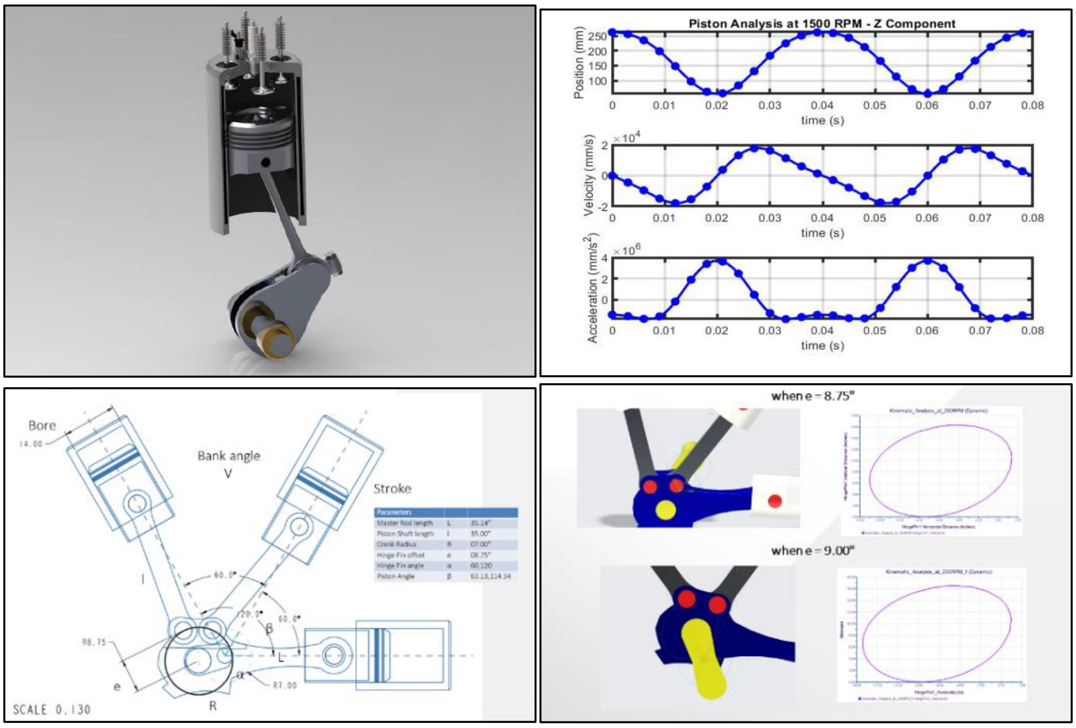


Figure 6: Engine project design and analysis examples from (top) first and (bottom) second course offering.

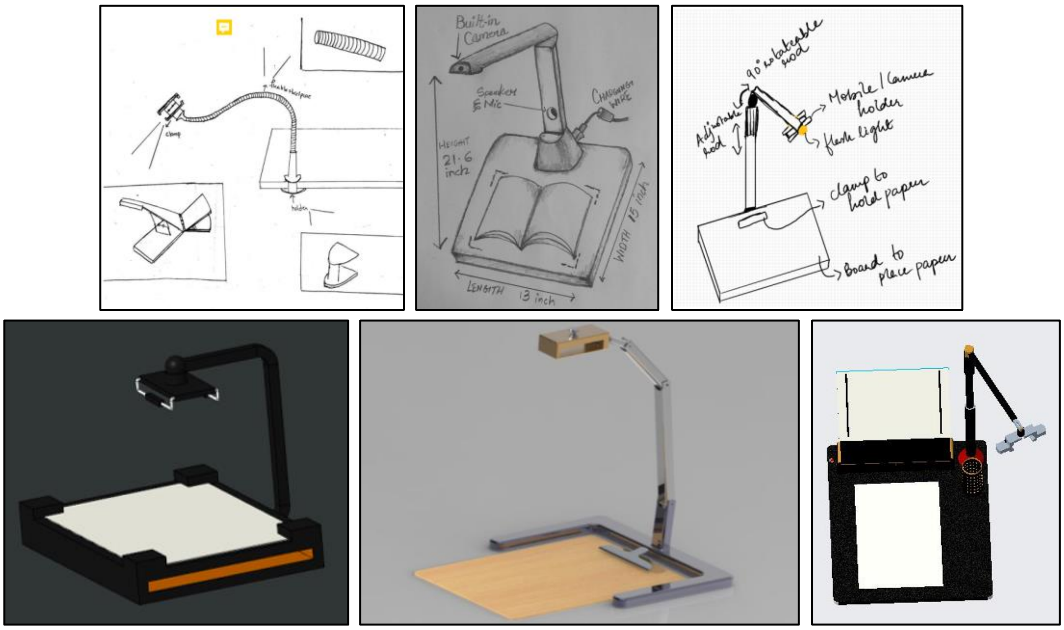


Figure 7: Student submissions for document reader design project.

Learning Through Making:

Learning through making pedagogy was used in the in-person offering of the course to take advantage of the rapid prototyping opportunities made available by 3DP. This permitted students to practice iterative design by using printed parts to test and improve their designs. The major learning through making assignment required students to design, print, and analyze a spinning fidget toy. The design requirements were entertainment value maximization (spins the longest), and having a 'cool' aesthetic. Students performed the project in teams of three, and each team was provided a ball bearing to work with. The following 3DP constraints were imposed: total material usage < 12.5 g (PLA only), total print time < 75 minutes, infill density < 30%. This made students experience the economic decisions that engineers have to make to efficiently use time and material resources during manufacturing, e.g. make:

- design changes to reduce material consumption and printing time to comply with constraints even though the design meets all design requirements,
- trade-off decisions regarding printing settings (e.g. layer thickness, orientation, infill density) based on factors like time and material consumption, criticality of the part, desired surface finish, and its functional requirements.

Students demonstrated their final designs (an example shown in Figure 8) in front of faculty judges who scored them on their design quality, product quality, performance, and presentation. Two students from the summer school were engaged as 3DP consultants, with whom students could discuss DfAM aspects of their designs, and a TA was available to oversee the 3DP.

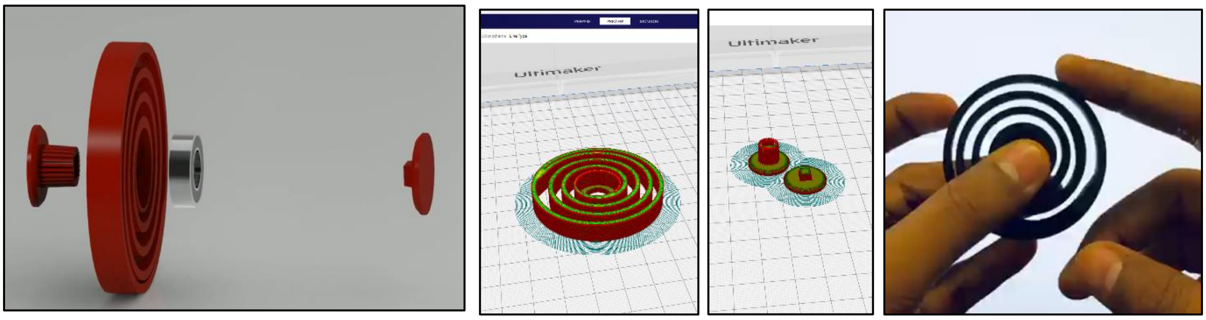


Figure 8: CAD design, 3DP set-up and printed spinning toy for learning through making project (student submission).

Though not a part of the course itself, the student interns in the making summer program also learnt concepts of mechanics and DfAM while designing and manufacturing teaching props. Some examples of the concepts learned, through making, by the students in the fidget toy assignment and summer program are:

- The concept of different kinds of fits, dimensional tolerances, and need for clearances in joints and threaded parts.
- Understanding various features of threads (e.g. major and minor diameters, pitch, handedness, thread profile) by making a threaded cap for a bottle shown in Figure 9.
- Practical challenges associated with implementing various types of joints and the limits of their motion, e.g. cantilever vs straddle mounted implementation of pin joints, and cone of mobility for spherical joints (Figure 4).

Another beneficial aspect of the accelerated design process noticed was an appreciation for the value of 'designing quality' into the product, as the cost of improving quality increases the later in the process, design changes are made; and shoots up precipitously if design changes are made in the manufacturing stage. An example of this is the fit-test cylinders from Figure 9 that were made to avoid spending time and material in making a large part just to discover that it was useless because the threads did not mate properly.

Team based learning was also promoted by the project and making based learning assignments, which by their nature require effective collaboration with others to produce acceptable products and solutions.

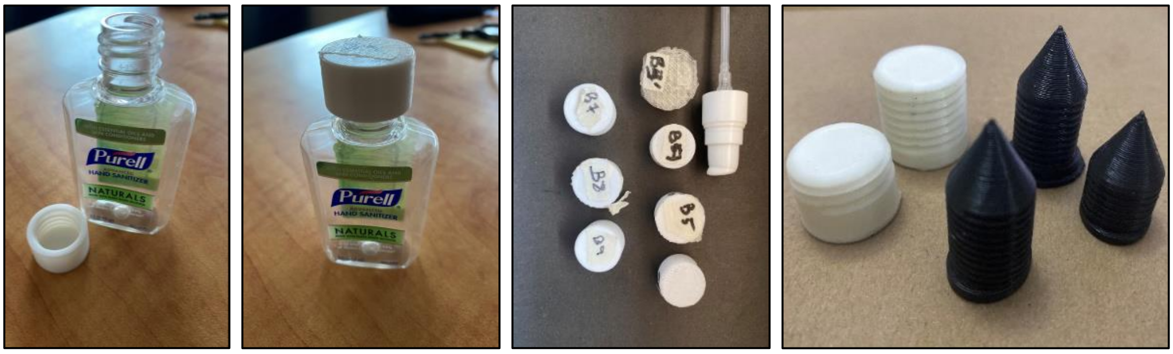


Figure 9: Threaded cap designed and manufactured for a sanitizer bottle. Right figures show test thread prints with sub-optimal thread clearance and/or pitch.

Integrated Course Flow:

Integral to the successful execution of the course, which covered a diverse list of topics, was the exploitation of opportunities for complementarity across the various topics using the pedagogical tools listed above. This required the distribution of course topics, assessments and activities across the semester to be integrated and intertwined (as opposed to a topic-based series flow). After refinements based on the first course offering and lessons from the summer 3DP program, the course flow shown in Figure 10 was followed in the second course offering. This proved to be an effective structure as it not only ensured that course contents were covered in a timely manner but also that the students developed the necessary skills needed for various assignments at different stages of the course.

CAD models of machine elements downloaded from online databases were found very useful in executing the integrated course flow. They helped demonstrate the design and specifications of different elements during lessons, and also supported CAE assessments in which mechanisms had to be designed. Instead of making intricate CAD models for machine elements from scratch, students could download models with the correct specifications (e.g. diametral pitch and contact angle of a spur gear) from online libraries. This also helped develop an appreciation for not ‘reinventing the wheel’ but instead using ‘off the shelf’ standard components wherever possible. CAD models from the online hardware store *McMaster-Carr* were found to be well suited for the engineering course.

Content Curation:

It was critical for the smooth and timely flow of the organizationally demanding course that course content, which not only included traditional media like reading material but also video recordings, CAD files and 3DP resources, was easily accessible to the students. Similarly, student assessment submissions, which included non-traditional media, and their grading had to take place smoothly while ensuring confidentiality. This was made possible by curating the course exclusively through an online Learning Management System (LMS) based portal. At Habib University the commercial LMS *Canvas* was used. Course material was shared on the LMS portal based on topics instead of chronology, which prevented organisational difficulties that could have arisen from the non-serial nature of the course. Moreover, lectures were posted as ‘discussions’ that permitted students to comment on them, which created a lively community where peer-to-peer and peer-to-instructor discussions led to a richer and more interactive learning experience.

The LMS also provided opportunities for increased transparency and objectivity in assessments through easy design and application of performance rubrics. The rubrics were shared with the students beforehand to guide them in their work by providing performance benchmarks. Special attention was given while designing rubrics for open-ended assignments to ensure that they were not overly rigid and restrictive so as not to curtail creativity. From a practical point of view, the rubrics also made the grading process more efficient.

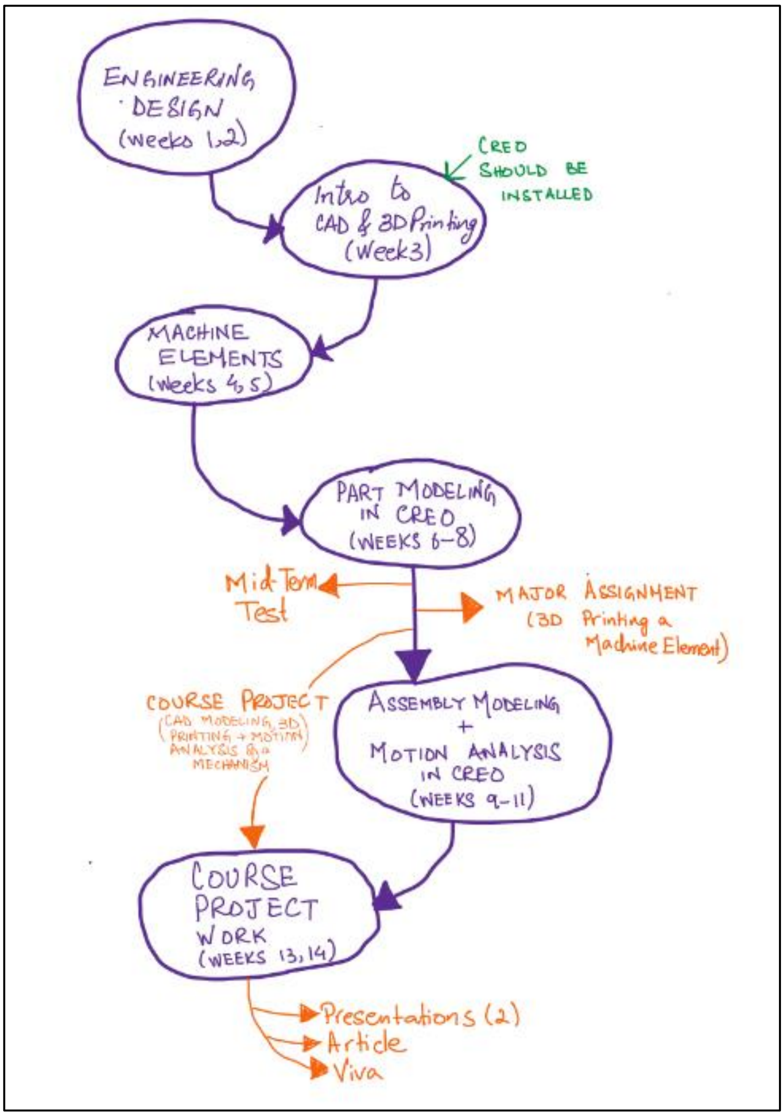


Figure 10: Course flow followed for the integrated teaching of various topics (copied from the syllabus).

Observations and Recommendations

Student Feedback:

The course received excellent feedback during both the offerings with an average score of 4.9/5 as per the official university course surveys by the Office of Institutional Research. The surveys had a response rate of 73%. The students were asked if they found course resources helpful in learning new topics, course content motivating and stimulating, and assessments helpful in increasing their knowledge/skills and confidence. In their feedback, students noted that the maker-based learning activities “played an important role in learning the skill-set” they needed to do well in the course, and also helped them apply their learnings to “practical scenarios.” Some students did report that they found the course demanding in terms of time commitment, and the motion analysis topics challenging. Students also reported that after the course, they felt more comfortable in using the university’s 3DP resources for other course projects.

Lessons Learned and Recommendations:

Overall, the students performed very well in the course. Except for 3 students across the two offerings, all students scored a “B” grade (75%) or higher, and around 15% of the students scored over 95%. Some important lessons learned from formal and informal student feedback and experiences of the instructor are listed below, along with recommendations for course design:

Managing Student Workload:

Given the nature of the course which covered a wide range of topics, at times, it was found challenging to ensure that students were not being overburdened.

Even though skills development topics like CAD can benefit greatly from asynchronous teaching, it is important to be mindful of the friction that exists as students implement and practice the taught topics. In a synchronous class, these implementation delays would be sensed by the instructor but in the asynchronous setting, special attention should be given so as not to go beyond the expected student contact time. Anecdotally, a 20-30% implementation time reduction was found reasonable for teaching CAD topics.

Intertwining different course topics to exploit synergies across them helped in the timely execution of the course by providing experiential learning opportunities. The nature of such synergies and their effectiveness would vary depending on the course topics and learning outcomes, available resources (3D printers, support staff, etc.), class size and other practical considerations; and might require some experimentation before arriving at an efficient arrangement. Such experiments can make for insightful scholarship of teaching and learning (SoTL) studies, e.g. by implementing changes in different sections and monitoring student learning outcomes.

Another system-level option to allay some of the contact hour challenges can be to integrate learning through making and project-based learning assignments to other courses, e.g. students can choose to work on their capstone projects or other projects of interest to them. A broad curriculum design exercise to identify and maximise such synergies across the undergraduate curriculum can be helpful in this regard.

In team projects, individual participation surveys conducted periodically were found to be very useful in ensuring that all team members had even workloads.

Skills Development via Doing:
Students found open ended design assessments exciting and enjoyable, and engaged in them passionately. Appending open-ended assessments to closed-ended, skills development ones provided students a chance to creatively experiment with their newly acquired skills in an unrestrained setting. This helped them internalize the taught topics and gain confidence in their skills. The inclusion of open-ended experimentation opportunities without diluting the need for skills development assessments can thus help reinforce learning and develop a design thinking mindset.

Promoting Practical Making:
Students were very quick in learning important 3DP and DfAM aspects and quickly became independent in designing and executing prints. The scaffolded approach to incrementally increase exposure to 3DP via sequenced course assessments and the advanced classification level of the students are believed to have contributed to these outcomes.

The course was designed to be a breath based, skills and mindset development course. It was thus very important to clearly convey the scope of the course so as not to over-sell the utility of the analysis skills taught, and to underscore the importance of understanding the theory of CAE analyses through further education. Simulation topics were restricted to motion analysis, for which students had some foundational understanding from previous courses in mechanics. There was interest among the students in learning fluid mechanics (CFD) and stress analysis (FEA) topics as well. If such topics are to be taught, maybe in an advanced version of the course, it should be ensured that students have a sound understanding of the underlying physics to prevent the unintentional misuse of these analysis tools and drawing of incorrect conclusions. Most commercial CAE suites have elementary CFD and FEA capabilities built-in.

It was also important not to inadvertently promote a ‘3D print everything’ mindset given the ease of designing and manufacturing bespoke, non-standard parts using the CAD and AM skills taught. DfAM and design consideration topics taught during the course and encouragement to use standard ‘off the shelf’ machine element CAD models helped achieve this to a certain extent. In future course offerings, further reinforcement can be provided by including traditionally manufactured parts in making assignments by imposing suitable constraints and/or making the choice of manufacturing technology an assessment criterion. Other (subtractive) rapid prototyping technologies like computer numerical control (CNC) machines can also be considered.

Course Execution:
A course of this sort is resource intensive - in terms of preparation, instructor involvement, equipment needed, as well as support needed for making the equipment available to the students with appropriate supervision. The summer 3DP program to prepare course content and teaching props, and develop an understanding of the limitations of the printing infrastructure, along with the availability of a TA to oversee 3DP were instrumental in the successful execution of the course. Advance planning and resource arrangement are thus important for such courses. Also, the capital and operating cost of 3DP, especially for smaller

universities, has to be considered during course design and to the extent possible, redundancy should be added.

Pedagogical Choices:
The selected pedagogical approaches generally worked well during the course. The lectures provided an opportunity for students to settle in and develop the requisite knowledge-base for future course activities; short tutorial styled CAD/CAE videos, coupled with practice sessions, proved to be useful in encouraging students to build required modelling and analysis skills, and project and making based learning tasks provided opportunities for the simultaneous use of all the knowledge acquired and skills developed in the course. That said, refinements can be made to further enhance experiential learning and design process deployment opportunities, e.g. using flipped learning approaches instead of lectures to teach foundational mechanical engineering design concepts, increasing the level of integration between CAD, CAE, and 3DP assessments by having a modular, cumulative course project. Furthermore, if some of the constraints from Table 1 can be relaxed, 3DP could be used more liberally to further bolster experiential learning opportunities. The course presented can serve as an initial blueprint for the design of a gap-filling mechanical engineering design course but pedagogical and course content choices would vary depending on the particular teaching context (constraints, resources, and priorities).

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Nomenclature

AM	Additive manufacturing
CAD	Computer aided design
CAE	Computer aided engineering
CAM	Computer aided manufacturing
CFD	Computational fluid dynamics
CH	Credit hour(s)
DfAM	Design for additive manufacturing
ECE	Electrical and computer engineering
FDM	Fusion deposition modeling
FEA	Finite element analysis
LMS	Learning management system
PLA	Polylactic acid
R	Revolute
S	Spherical
SoTL	Scholarship of teaching and learning
STEM	Science, technology, engineering, and mathematics
TA	Teaching assistant
3DP	3D printing

References

[1] T. Trust, R. W. Maloy and S. Edwards, "Learning through making: Emerging and expanding designs for college classes," *TechTrends,* vol. 62, pp. 19-28, 2018.

[2] K. L. Meyers, A. S. Morgan and B. P. Conner., "3D printing to introduce design in a cornerstone project," *Global Journal of Engineering Education,* p. 18.1, 2016.

[3] C. Schelly, G. Anzalone, B. Wijnen and J. M. Pearce, "Open-source 3-D printing technologies for education: Bringing additive manufacturing to the classroom," *Journal of Visual Languages & Computing,* vol. 28, pp. 226-237, 2015.

[4] S. Ford and T. Minshall, " Invited review article: Where and how 3D printing is used in teaching and education," *Additive Manufacturing,* vol. 25, pp. 131-150, 2019.

[5] S. S. Horowitz and P. H. Schultz, "Printing space: Using 3D printing of digital terrain models in geosciences education and research," *Journal of Geoscience Education,* vol. 62, pp. 138-145, 2014.

[6] M. Carrió, P. Larramona, J. E. Baños and J. Pérez, "The effectiveness of the hybrid problem-based learning approach in the teaching of biology: a comparison with lecture-based learning," *Journal of Biological Education,* vol. 45, no. 4, pp. 229-235, 2011.

[7] R. Kay, T. MacDonald and M. DiGiuseppe, "A comparison of lecture-based, active, and flipped classroom teaching approaches in higher education," *Journal of Computing in Higher Education,* pp. 449-471, 2019.

[8] H. Simon, The Sciences of the Artificial, Cambridge: MIT Press, 1996.

[9] C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey and L. J. Leifer, "Engineering design thinking, teaching, and learning," *Journal of engineering education,* vol. 94, no. 1, pp. 103-120, 2005.

[10] C. L. Dym, P. Little and E. J. Orwin, Engineering Design - A Project Based Introduction, 4 ed., John Wiley and Sons, 2014.

[11] J. T. Luxhøsj and P. H. Hansen, "Engineering curriculum reform at Aalborg University," *Journal of Engineering Education,* vol. 85, no. 3, 1996.

[12] C. L. Dym, M. M. Gilkeson and J. R. Phillips, "Engineering design at Harvey Mudd College: Innovation institutionalized, lessons learned.," *ASME Journal of Mechanical Design* , 2012.

[13] C. B. Williams and C. C. Seepersad, "Design for additive manufacturing curriculum: A problem-and project-based approach," in *International Solid Freeform Fabrication Symposium,* Austin, 2012.

[14] N. I. Jaksic, "New Inexpensive 3-D Printers Open Doors to Novel Experiential Learning Practices in Engineering Education," in *ASEE Annual Conference & Exposition,* 2014.

[15] A. M. Paudel and D. K. Kalla, "Direct digital manufacturing course into mechanical engineering technology curriculum.," in *ASEE Annual Conference & Exposition,* New Orleans, 2015.

[16] R. Radharamanan, "Additive manufacturing in manufacturing education: a new course development and implementation," in *ASEE Annual Conference & Exposition,* 2017.

[17] J. Baleshta, P. Teertstra and B. Luo, "Closing the loop: integrating 3D printing with engineering design graphics for large class sizes," in *Proceedings of the Canadian Engineering Education Association (CEEA),* McMaster University, 2015.

[18] K. M. Oliver, “Professional development considerations for makerspace leaders, part one: Addressing “what?” and “why?,” *TechTrends,* vol. 60, pp. 160-166, 2016.

[19] D. A. Kolb, Experiential learning: Experience as the source of learning and development, FT press, 2014.

[20] M. &. M. P. Muscat, “Using Kolb's learning cycle to enhance the teaching and learning of mechanics of materials,” *International Journal of Mechanical Engineering Education,* vol. 40, no. 1, pp. 66-78, 2012.

[21] “Mechanical Engineering - BS (Program Requirements),” Texas A&M University , [Online]. Available: https://catalog.tamu.edu/undergraduate/engineering/mechanical/bs/#programrequirementstext. [Accessed Jan 2022].

[22] A. Hasan, D. Alvi and A. Hashim, “What the census tells us about Karachi,” Dawn, July 2022. [Online]. Available: https://www.dawn.com/news/1702463. [Accessed Jan 2023].

[23] G. Khan, A. Khaliq and B. Memon, “Making In A Liberal Arts Institution, In The Global South,” in *International Symposium on Environmental Makerspaces*, Cleveland, Ohio, 2017.

[24] “Vision, Mission, Values and Learning Goals (Habib University),” [Online]. Available: https://habib.edu.pk/about-us/vision-values/. [Accessed Jan 2023].

[25] L. S. Jensen, A. G. Özkil and N. H. Mortensen, “Prototypes in engineering design: Definitions and strategies,” in *Proceedings of the 14th international design conference*, Dubrovnik, 2016.

[26] R. G. Budynas and J. K. Nisbett, Shigley's Mechanical Engineering Design, 9 ed., McGraw-Hill, 2011.

[27] R. L. Norton, Design of Machinery, 3 ed., McGraw-Hill, 2004.

[28] G. E. Dieter and L. C. Schmidt, Engineering Design, 4 ed., McGraw-Hill, 2009.

[29] Ultimaker, *How to design for FFF 3D printing,* 2019.

[30] S. Greenhalgh, “The effects of 3D printing in design thinking and design education,” *Journal of Engineering, Design and Technology,* 2016.

Appendix

Week	Topic(s)	Reading(s)	Assessments	
			Released	Due
Week 1 Aug-30	• Intro to mechanical engineering design	Shigley – Ch # 1 Dym – Ch # 1-2	--	
Week 2 Sept-6	• Mechanical design considerations (e.g. material selection, mechanical integrity)	Shigley – Ch # 1, 2, 3 Dym – App-A	Assignment 1 (T/2): design process implementation T/2 teams announced	
Week 3 Sept-13	• Intro to CAD modeling in PTC Creo (extrude and sketching) • Intro to FDM printing	3D Printing Manual (ENGR-291)	CAD Task 1 Quiz 1 reading on DFAM	
Week 4 Sept-20	• Shafts and shaft components • Screws, and fasteners	Shigley Ch # 7, 8	Quiz 2: Reflection article on an assigned topic	Quiz 1 Assignment 1
Week 5 Sept-27	• Springs and bearings (types, and design basics) • Gears (types, and design basics)	Shigley Ch # 10 - 15		CAD Task 1
Week 6 Oct-4	• Creating parts in Creo (revolve, and sweep)	Lecture notes	CAD Task 2	Quiz 3 on machine elements T teams to be shared with the instructor
Week 7 Oct-11	• Creating parts in Creo (helical sweep) • Mid-semester test	Lecture notes	Major Assignment (T/2): Designing and printing a machine element Course Project (T) CAD Task 3	CAD Task 2 Mid-semester test (Oct 13)
Week 8 Oct-18	• 3D printing practice	Lecture notes		CAD Task 3
Week 9 Oct-25	• Assembly in Creo • Intro to mechanisms in Creo	Lecture notes	CAD Task 4	Major Assignment
Week 10 Nov-1	• Making movable assemblies	Norton Ch # 2 Lecture notes	CAD Task 5 Assignment 2: Mobility analysis of a mechanism (T/2)	CAD Task 4 Quiz 2
Week 11 Nov-8	• Motion analysis (Kinematic)	Lecture notes	CAD Task 6	CAD Task 5
Week 12 Nov-15	• Drawings in Creo • Buffer	Lecture notes		CAD Task 6 Assignment 2
Week 13 Nov-22	• Course project work			Course Project Update Presentations (Nov 22)
Week 14 Nov-29	• Course project work			
Dec 5-6	Reading Days			
Dec 7 – 11 & 13 – 15,	Course Project Presentations + Viva (Time TBD)			Course Project Paper (Dec 15, 6 pm)

Table 2: Week-wise course breakdown (copied from Fall 2021 syllabus)

(a)

Assessment Type	Quantity	% of Final Grade
Assignments	3	15
Major assignment (mini project)	1	10
CAD tasks	6	12
Reflection articles	2	8
Mid-semester exam	1	10
Course project	1	42.5
Progress presentation	*1*	*5*
Final report	*1*	*17.5*
Final presentation	*1*	*15*
Peer review	*1*	*5*
Class participation	-	2.5

(b)

Assessment Type	Quantity	% of Final Grade
Assignments	2	10
Major assignment (mini project)	1	10
Quizzes	3	12
CAD tasks	7	30
Mid-semester test	1	8
Course project	1	20
Progress presentation	*1*	*4*
Final paper	*1*	*6*
Final presentation	*1*	*7*
Individual participation surveys	*2*	*3*
Final viva voce exam	1	5
Class participation and punctuality	-	5

Table 3: List of course assessments for (a) Fall 2020 and (b) Fall 2021 course offering.

	Local 3DP	**Ultimaker S3**
Technology	Fused Deposition Modeling (FDM)	
Print head	Single Nozzle	Two Nozzles
Resolution	300 to 75 µm	200 to 20 µm
Nozzle Size	0.4 mm	0.4 mm (0.25 to 0.8 mm can be bought)
Build Volume	Open (8 liters)	Enclosed (8.83 liters)
Build Plate	Metal (unheated)	Glass (heated)
Extruder type	Direct drive	Indirect via Bowden tubes
Filament Material	PLA, PLA composites, TPU	PLA, Tough PLA, ABS, PVA (water soluble support material), TPU, more

Table 4: Specifications of 3D printers used in the course.