Journal of Engineering Education Transformations,
Volume No 35, January 2022, Special issue, eISSN 2394-1707

Promoting Technology-Enhanced Project-Based Learning through Application of 3D Printing Technology for Mechanical Engineering Education

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***Abstract*—**3D printing is a progressively developing technology under umbrella of industrial revolution 4.0 for rapid prototyping and end-use applications. 3D printing technology is nowadays used in all sectors including automotive, civil, agriculture, medical, aerospace, art and jewelry, and education too. In this work, 3D printing technology is employed as a technology-enhanced tool in engineering education in combination with project-based learning for third-year undergraduates. The combined technology-enhanced project-based learning strategy was used to 3D print components of internal combustion engines to enhance students' comprehension of the fundamentals of internal combustion engines. The activity resulted in improvement in the performance of students in the examination (5.15% improvement in CO attainment and more than 10% improvement in all modes of written examination) as well as professional skill development promoting multidisciplinary learning opportunities and lifelong learning.

***Keywords*—**3D printing; engineering education; IR4.0; project-based learning; technology-enhanced active learning.

***JEET Category*—**Choose one: Research, Practice, or Op-Ed. (Please note, Op-Eds are by invite only. Refer to the Paper Submission and Review Guidelines for more details.)

I. INTRODUCTION

CONVENTIONAL teaching-learning (TL) practice includes chalk and talk, classroom lectures, class tests, homework, and textbooks, etc (AbdelSattar and Labib, 2019). It creates a passive learning environment that does not offer experimentation opportunities and is considered to be inadequate and inappropriate for engineering students (Prado da Silva et. al. 2015; AbdelSattar and Labib, 2019). Conventional TL practice brings dejection and loss of interest in students as it reduces the chances to offer multiple solutions to the problem presented by the facilitator (Prado da Silva et. al. 2015; Felder and Silvermann, 1988). (Meksophawannagul M., 2015) have reported a gap between employer's needs and learner's workability identified by various researchers. Owing to the 'pass the exam to get the certificate' attitude of the Thai students, students are not performing well at work despite scoring good marks in exams (Simpson, 2011). There is a need to change the overall academic curriculum and pedagogy for

engineering education to prepare industry-ready graduates, promote innovation and sustainable development and, increase employment opportunities (Edstrom and Kolmos, 2014). The same is reported by various organizations, councils, associations, and researchers (Besterfield-Sacre et. al., 2014).

To provide a solution to the problems through the application of scientific principles is the ultimate aim of studying engineering (Jia et. al., 2019). Thus, a proper grasp of a scientific/engineering principle and concept is vital for an engineering student. Modern TL methods employing students engagement improves comprehension of concepts for engineering students as compared to conventional TL practices (Montgomery and Fogler, 1996; Olinger and Hermanson, 2002). Active learning (AL) is one of the modern TL methods being practiced in engineering education for the last two and half decades. AL is a course-related activity/task that promotes active participation/engagement of students in the TL process (Felder and Brent, 2016; Lucke et. al., 2017). The use of the AL strategy in engineering education improves the active engagement of students and helps students to develop interpersonal and critical thinking skills (Lucke et. al., 2017; AbdelSattar and Labib, 2019). In addition to this, it also improves the overall performance of the students and retention of learning outcomes on a long-term basis beyond the semester time frame (Savage et. al. 2008; Freeman et. al. 2014).

The internal combustion engines (ICE) course is one of the key courses for the undergraduate mechanical engineering (ME) curriculum. It primarily includes the construction and working of various configurations of the engines, fuel supply systems, combustion, pollution, and its control techniques. In this work, third-year undergraduate ME students have operated on a project employing three-dimensional (3D) printing technology. The activity conducted combines the technology-enhanced active learning (TEAL) approach with project-based learning (PBL) to bring a novel technology-enhanced project-based learning (TEPBL) approach.

II. EDUCATION 4.0 AND TEAL

Education 4.0 (E4.0) is nowadays a popular buzzword amongst academicians and educational researchers around the globe. To get acquitted with the E4.0 concept, (Hussin, 2018) related E4.0 to the industrial revolution (IR) 4.0. (Shwab, 2017) presented a technological upgrade for each IR from IR1.0 to IR4.0 to showcase the way industrial revolutions took place across time as shown in Table I

TABLE I
IR1.0 TO IR4.0 TECHNOLOGICAL ADVANCEMENTS

IR	TIME	Technology Advancements
IR1.0	1760 to 1840	Construction of railroads, the invention of the steam engine, mechanical production
IR2.0	Late 19th Century to Early 20th Century	Use of electricity and assembly line for mass production
IR3.0	1960 to 1990	Digital revolution, development of semiconductors, mainframe computing, personal computing and the internet
IR4.0	Began at 2011	Smart systems, nano-technology, digitalization

In IR4.0 various new technologies have emerged at an exponential pace and are called disruptive technologies. The technological advancements under IR4.0 include artificial intelligence (AI), machine learning (ML), 3D printing, nanotechnology, autonomous vehicles, robotic, the internet of things (IoT), and energy storage (Diwan, 2017). The emerging new technologies under IR4.0 have affected all sectors including business, banking, television, media, transportation, manufacturing, agriculture, and education too.

The role of engineering education institutes is to create competent engineers who will contribute to the digitalized future world (Coskun et. al., 2019). To cater to the industry requirements nowadays, there is a need to implement the IR4.0 concept in the curriculum of various engineering disciplines (Coskun et. al., 2019). The resulting engineering education system implementing IR4.0 is thus called E4.0.

For the current generation of techno-savvy students with mixed learning styles, technology can serve as a supportive educational tool (Daniela et. al., 2018). Interactive and technology-enhanced learning strategies seem to be promising learning strategies for such students (Johnson et. al., 2013; McCoy et. al., 2015; Educause Center for Applied Research Study, 2013). TEAL employs digital tools, information and communications technology (ICT) tools, electronic media, multimedia, and machine tools in the TL process (Hassan et. al., 2018). TEAL helps students in skill development by triggering critical thinking, teamwork, self-analysis, and potential judgment (Daniela et. al., 2018).

III. PBL AND TEPBL

Project-Based Learning (PBL) is a TL strategy in which a problem/s is presented to a class or a group and students work collaboratively to present a solution to that problem. The PBL enables students to work in teams, use innovative skills, gather information, trigger thinking ability, and nourish problem-solving skills (Chiang and Lee, 2016). Employers demand fresh engineering graduates who have professional skills along with technical skills. The PBL helps students to develop professional skills together with the core technical skills (Warnock and Aragh, 2016). PBL is comprehensively used in STEM (Science, Technology, Engineering and Mathematics) pedagogy to enhance the undergraduates' comprehension of core concepts (Chiang and Lee, 2016; Warnock and Aragh, 2016).

3D printing technology creates 3D solid objects from a 3D computer-aided design (CAD) drawing through layer by layer addition of polymer material. Thus, referred to as the additive manufacturing process. 3D printing is a rapidly growing emerging technology under IR4.0 advancements and is progressively increasing in the last decade with the potential to transform the industry (Shahrubudin et. al., 2019). 3D printing has increasing applications in aerospace, automobile, healthcare, food, fashion, electrical, and electronics industry (Shahrubudin et. al., 2019). 3D printing has its applications in the education sector too.

3D printing technology is being used as a supportive educational tool right from primary school to higher education including art, biology, medical, chemical, engineering, etc. (Leinonen et. al. 2020) used 3D printing for fourth, fifth, and sixth-grade children of elementary school and concluded that 3D printing activity helps students to enhance the technical skill. 3D printing technology is now being extensively used in chemistry education. (Lohning et. al., 2019) used 3D printing to enhance comprehension of protein biochemistry, (Vangunten et. al., 2019) employed 3D printing to fabricate microfluidic devices to promote hands-on education in chemical education, (Linger et. al., 2019) utilized 3D printing technology to enhance visualization of chemical phenomena in the chemistry lab, (Jones and Spencer, 2018) fabricated 3D printed molecular models to enhance comprehension of students. (Hansen et. al., 2020) studied the potential for 3D printing technology to support biology education and concluded that there is a scope to have significant use of 3D printing in biology education. (Bilen et. al., 2015) fabricated 3D printed rocket as a part of an undergraduate engineering design project where students designed, analyzed, built, and launched the 3D printed rocket. (Menano et. al., 2019) presented case studies of the use of 3D printers by various artists in the art industry and also concluded that art education can be combined with various multidisciplinary technologies like 3D printing to promote student artistry, imagination, and 21st-century skills.

3D printing also finds its application as a technology-enhanced pedagogical tool in engineering education. (Hsiao et. al., 2018) conducted a series of experiments for 10th-grade pre-engineering students for 11 weeks by combining 3D printing with an experiential learning strategy which demonstrated improvement in hands-on skills and a better grasp of basic scientific concepts. (Ghotbi, 2017) designed an activity for mechanical engineering undergraduates to 3D print the mechanical linkages and mechanisms to study the working of a mechanical mechanism, its analysis and synthesis for kinematic and dynamics of machine course.

The work presented in subsequent sections combines PBL with TEAL through the use of 3D printing technology as a technology-enhanced tool to accomplish the activity.

IV. Methodology

The proposed learning activity is planned for undergraduate third-year mechanical engineering students. The total number of students was 141 including division A (69 students) and division B (72 students). The activity was conducted simultaneously for division A and division B through collaboration between course instructors for both divisions. The proposed TEPBL activity involves the following important stages as demonstrated in figure 1.

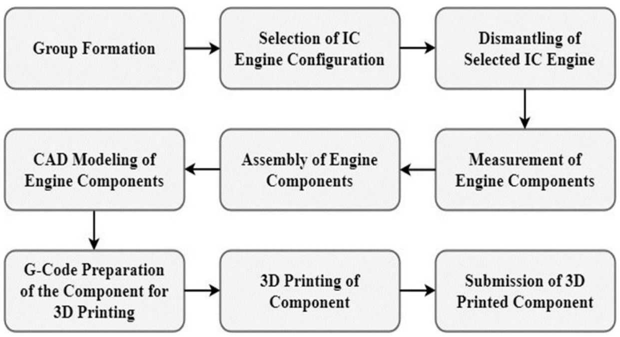

Fig. 1. Stages of TEPBL Activity.

Group Formation

Students groups were formed with each group consisting of 5-6 students. Students had the freedom to form their groups.

Selection of IC Engine Configuration

A variety of engines with different configurations are available in the IC Engine lab at RIT. Each student group selected a separate engine configuration for the activity undertaken.

Dismantling of Selected IC Engine

During lab hours, a separate session was allotted for dismantling and assembly of the IC engine. Each student group dismantled the engine selected by the respective group using the top to bottom approach i.e. starting from cylinder head to the crankcase. While dismantling, students carefully observed the assembly of different parts and their relative positions.

Measurement of Engine Components

After engine dismantling, the dimensions of different engine components were measured and noted by students. All necessary dimensions required to prepare the CAD model of the component were recorded by the students.

Assembly of Engine Components

Followed by the quantification of the dimensions of each component, the engine was reassembled.

CAD Modeling of Engine Components

The CAD models of the components were prepared by the students using commercial CAD software packages like CATIA. The CAD models were then uploaded on a learning management platform employed in RIT called MOODLE on a deadline basis. Figures 2(a) and 2(b) displays screen images of CAD model of connecting rod and piston submitted by students.

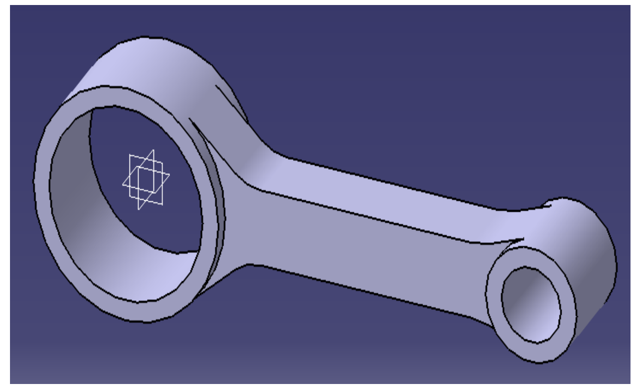

Fig. 2(a). CAD Model of Connecting Rod

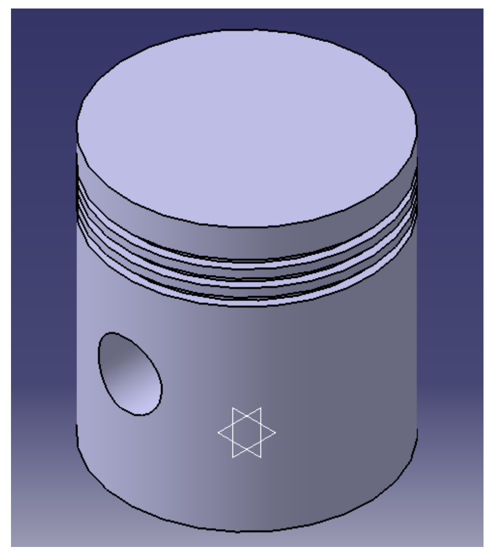

Fig. 2(b). CAD model of Piston

G-Code Preparation

A 3D printer reads a file input in G-Code format for printing. For this purpose, a CAD file prepared earlier is converted to STL (Stereo Lithography) file format using inbuilt capabilities in CAD software. The STL file is then imported to the Ultimaker Cura application (Open source slicing application for 3D printing) where a G-code is prepared from the STL file. Necessary settings like filament material, printing temperature, bed temperature, in-fill density, print speed, etc. are specified in the application for slicing (G-code preparation). Figure 3 illustrates a part of the G-code file specifying various machine settings provided in the slicing application as a demonstrative example.

```
;START_OF_HEADER
;HEADER_VERSION:0.1
;FLAVOR:Griffin
;GENERATOR.NAME:Cura_SteamEngine
;GENERATOR.VERSION:3.6.0
;GENERATOR.BUILD_DATE:2018-11-12
;TARGET_MACHINE.NAME:Ultimaker S5
;EXTRUDER_TRAIN.0.INITIAL_TEMPERATURE:200
;EXTRUDER_TRAIN.0.MATERIAL.VOLUME_USED:19106
;EXTRUDER_TRAIN.0.MATERIAL.GUID:506c9f0d-e3aa-4bd4-b2d2-23e2425b1aa9
;EXTRUDER_TRAIN.0.NOZZLE.DIAMETER:0.4
;EXTRUDER_TRAIN.0.NOZZLE.NAME:AA 0.4
;BUILD_PLATE.TYPE:glass
;BUILD_PLATE.INITIAL_TEMPERATURE:60
;PRINT.TIME:10551
;PRINT.SIZE.MIN.X:83.232
;PRINT.SIZE.MIN.Y:85.417
;PRINT.SIZE.MIN.Z:0.2
;PRINT.SIZE.MAX.X:239.675
;PRINT.SIZE.MAX.Y:154.583
;PRINT.SIZE.MAX.Z:20
;END_OF_HEADER
```

Fig. 3. Print Settings from G-Code File

3D Printing of Components

G-code file prepared using the Ultimaker Cura application was imported to the 3D printer available in the laboratory. In addition to the construction and assembly of IC engines, students also had hands-on experience with the 3D printer in this phase. Figures 4(a) and 4(b) presents 3D printed connecting rod and piston by students.

Fig. 4(a). 3D Printed Connecting Rod

Fig. 4(b). 3D Printed Piston

Submission of 3D Printed Components

Each students group submitted 3D printed IC engine component to the course instructor and also uploaded a photograph of a 3D printed component on MOODLE.

V. STUDENT SURVEY

To quantify the effect of any active learning method, in addition to the academic performance of the students it is vital to analyze student feedback through a student survey. To do so, at the end of the activity a student survey was conducted by sharing a questionnaire consisting of 7 questions with students. Table II presents a summary of responses given by 139 students.

TABLE II
IR1.0 TO IR4.0 TECHNOLOGICAL ADVANCEMENTS

	Questionnaire	**Student Responses**	
		Yes	**No**
1	Did you enjoy the activity of 3D printing of ICE components activity?	136	03
2	Do you have prior experience with 3D printing?	12	127
3	Were you actively engaged throughout the conduct of this activity?	131	08
4	Did you gain knowledge about the construction and working of ICE?	129	10
5	Did you gain hands-on experience on how to use a 3D printer machine?	122	17
6	Are you confident enough to retain the knowledge gained through this activity beyond the semester time frame?	116	23
7	Are you willing to use 3D printing for your mini project and or capstone project?	104	35

Collectively for divisions A and B, 91.36% of students are first-time users of a 3D printer machine. The rest of the students have used a 3D printer machine as a part of an environmental project or mini-project. More than 97% of students enjoyed fabricating ICE components with 3D printers while more than 94% of students declared active engagement in the activity. Responses were also taken for gain in knowledge of students for ICE and hands-on skills with 3D printers. Around 92% of students declared sound knowledge gain about ICE components, their construction, and working while 87% of students recorded hands-on skills enhancement with 3D printers. More than 83% of students are confident to retain the knowledge gained through this activity beyond the semester time frame. During the activity, it was observed that students enjoy being operating a 3D printer machine as it enhances the 3D visualization of ICE components. As a result of this, around 74% of students are interested to use 3D printer technology in mini-project and or capstone projects which are a part of the mechanical engineering undergraduate curriculum.

VI. COURSE OUTCOMES AND EVALUATION METHOD

To make the engineers graduating competent at the national as well as global level Rajarambapu Institute of Technology (RIT) has instrumented outcome-based education (OBE) system. In OBE culture, the learning outcomes of each course are clearly stated in the form of course outcomes (CO). At the end of every academic cycle, COs for each course are computed.

The internal combustion engines course is a part of the undergraduate mechanical engineering program. The course predominantly includes fundamentals of ICEs like introduction engine and engine cycle, fuel supply systems for spark-ignition

(SI) and compression-ignition (CI) engines, combustion in SI and CI engines, alternative fuels, pollution, and its control techniques and performance parameters. The expected learning outcomes from students for ICE course are exhibited in the form of the CO statement in Table III. All this content is arranged in six chapters with equal weightage of marks to each chapter.

TABLE III
LIST OF COS FOR INTERNAL COMBUSTION ENGINES COURSE

CO Code	CO Statement
	After completion of the course, students will be able to;
CO1	Differentiate between various configurations of the engine and draw valve timing and port timing diagram
CO2	Analyze and differentiate between theoretical air standard, theoretical fuel-air and actual cycles.
CO3	Calculate the design and operating parameters of the fuel-supply system of SI engine and analyze mixture requirements at different loads and speeds
CO4	Compare different types of injection systems and calculate the quantity of fuel and size of the nozzle orifice
CO5	Explain the stages of combustion in si and ci engines and the effect of various operating parameters on combustion
CO6	Explain methods of measurement of different performance parameters and prepare a heat balance sheet
CO7	Recognize alternative fuels for ICEs with properties and compare different pollution norms

ICE course is evaluated for 100 marks which consists of activity-based evaluation (20 marks) and written examination (80 marks). In-semester examination (ISE) evaluates students through an activity-based evaluation method while unit test 1 (UT1), unit test 2 (UT2), and end-semester examination (ESE) evaluate students through written examination. Table IV depicts the evaluation scheme adopted for the ICE course with weightage and course content.

TABLE IV
EVALUATION SHCEME WITH WEIGHTAGE

	Evaluation	Mode of Conduct	Marks	Weightage	Course Content with Weightage
Activity-based Evaluation	ISE	Online quiz, experiential learning activity	20	0.2	All chapters
Written Examination	UT1	Written Test	25	0.15	Chapter 1 (0.5), Chapter 2 (0.5)
	UT2	Written Test	25	0.15	Chapter 3 (0.5), Chapter 4 (0.5)
	ESE	Written Test	50	0.5	Chapter 1 to 4 (0.15 each), Chapter 5 to 6 (0.2 each)

The TEPBL activity explained in this paper is conducted as a part of ISE under activity-based evaluation. For the evaluation of the activity, a five-scale rubric is used based on four criteria as depicted in table V.

TABLE V
RUBRICS FOR THE EVALUATION OF TEPBL ACTIVITY

Criteria	Proficient (4 to 5)	Adequate (2 to 3)	Substandard (0 to 1)
Active Participation	The student was actively participated with enthusiasm in all the stages of the activity conducted. The student participated in all hands-on activities and performed all the tasks.	The student was involved in all the stages of activity conducted.	The student participated in the activities but does not involve hands-on activities along with the group members.
Quality of Work Accomplished	Maintained excellent quality in the work in each phase of the task undertaken, meets the deadline, accurate and neat on routine	Maintained a good quality in the work with minimum errors. Meets the deadline for most of the time.	Mediocre quality of the work accomplished. Struggled to meet the deadline and errors in each phase of the work.
Thinking and problem-solving skills (The ability to learn, to reason, to think creatively, to make decisions, and to solve problems)	Exhibits excellent problem-solving and decision-making skills through critical thinking and brainstorming	Exhibits good problem-solving abilities through critical thinking	Exhibits average problem-solving abilities
Interpersonal Effectiveness-(Ability to get along with others, use courtesy, and contributes to a team)	Exhibits outstanding interpersonal skills even in difficult situations. Accelerates performance when performed in the team.	Consistently courteous and helpful. Functions effectively as a member of the team.	Cooperative and courteous most of the time. Gets along well with others. Willing to support the team effort.

VII. RESULT AND DISCUSSION

Improvement in Attainment of COs

Attainment of CO for the ongoing academic year (OAY) is compared with the preceding academic year (PAY) is depicted in figure 5. Attainment of COs for OAY as well as PAY is finalized by employing an OBE platform named IonCUDOS.

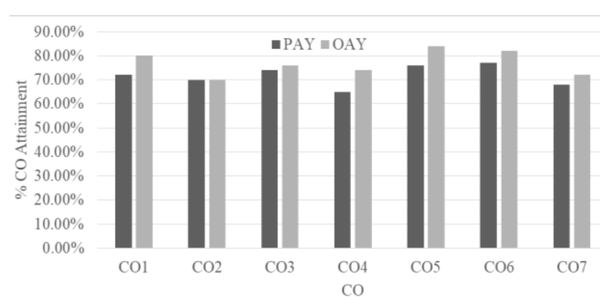

Fig. 5. Attainment of COs for OAY and PAY

TEPBL activity conducted has revamped attainment for all COs in PAY. The average attainment of COs is 76.86% for OAY as compared to 71.71% for PAY, thus an improvement of 5.15% is witnessed.

Improvement in Students Average Marks:

Students' average marks for the OAY as well as PAY for all modes of evaluation are differentiated employing a bar plot as demonstrated in figure 6.

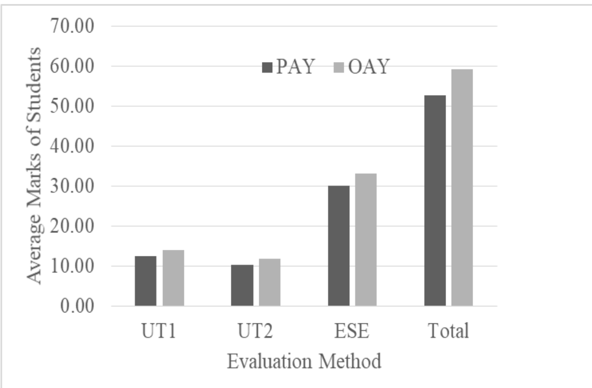

Fig. 6. Students' Average Marks Comparison

Practicing TEPBL has shown a positive impact on the performance of students for all modes of evaluation. Students' average marks for UT1, UT2 as well as ESE escalated by 13.62%, 15.75%, and 10.44% respectively. Students' comprehension of ICE construction and working resulted in improvement in the performance of students for the UT1 exam. Improved comprehension of the fundamentals of ICEs has also reflected improved performance for UT2 and ESE examinations.

VIII. Conclusion

For an educational researcher, it is very tough the efficacy of the active learning strategy employed quantitatively. Improvement in the academic performance of students in written exams is not the only measure of the efficacy of active learning strategy. In this work, PBL was combined with the TEAL strategy to bring novel TEPBL to the mechanical engineering students. The activity was conducted in various stages and at the end of the activity, the performance of students was compared with that of PAY. The results indicates that the use of TEPBL reflects in:

• Improvement in the academic performance of the students reflected through enhancement in the attainment of Cos (5.15% improvement in COs) and improvement in average marks (13.62%, 15.75%, and 10.44% in UT1, UT2, and ESE).

• Retention of the knowledge gained through the TEPBL beyond the semester time frame

• Multidisciplinary learning opportunities to the students along with the core subject knowledge gain

• The willingness of students to employ 3D printing for subsequent project work promotes lifelong learning.

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