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Incorporating an Open-Ended Project to Address Complexity Solution of Engineer's Problem in Undergraduate Laboratory Course

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Introduction

The role of an accreditation body on an engineering curriculum is to ensure the program is built on a knowledge base and attributes that enable graduates to continue life-long learning, adaptability to changes in technology and economy, and development of competences required for independent practice. The emphasis to address complexity of solution of engineer's problem in accreditation criteria on engineering graduate appears a challenging proposition for engineering educators to design and meet such outcomes-based criteria. Why is solving complex problems a skill that is essential for successful learning in relation to working and living in the 21st Century? How does this skill align with the teaching and assessment in an undergraduate laboratory course? What are the pedagogical implications of this skill? These questions can be answered in three steps. Firstly, this skill articulates the importance of problem-solving skills in the 21st century economy. Secondly, it views solving complex engineering problems attributes through the lens of accreditation and professional body. Thirdly, it discusses students' complex problem-solving process though modeling activities by undertaking a problem-based project.

Foremost among the challenges for the 21st Century engineering education, set forth by National Academy of Engineering, is to meet current and future demands for engineering skills and knowledge related to the nation's economy and society: the development of technology innovation to drive national competitiveness, long-term economic growth, solve societal change and quality of life [1]. Therefore, the success of rapid globally interconnected technological innovation depends on social, cultural, political, and economic factors. For example, solution of global issues related to poverty, inequality, climate change, environmental degradation, and peace depend on the intersections between technology and public policies and therefore innovation of technologies are becoming increasingly important. This further relates to the need for engineers of 2020 to have skills in using science and practical ingenuity to identify problems and find solutions [2]. In preparing for 'Industry 5.0', a team from UC College of Engineering and Applied Science has formed a research institution as part of UC new Digital Future initiative. The Digital Futures initiative is designed to foster sky-shot thinking, high risk-high reward applied research that are inclusive, innovative, impactful of up-to-state, collaborative and computational of advanced technology to solve societal, economic, and climate related issues caused by urbanization [3]. Hence, engineering education and global or societal goals are interrelated, that each one shapes the other.

According to Diana [4], although education policies has been focusing on the 21st century 4Cs' skills set of communication, collaboration, critical thinking, and creativity, more reformation work is seen in educating students to be successful in a complex and interconnected world. Feedback based on employers' interview regards engineering graduate skills as a necessity to compete in the 21st century economy, which is about innovations skill and improving services. A survey from undergraduate's alumni of a large public university in

Midwest on eleven engineering majors on the importance of ABET competencies in their professional experience rated teamwork, communication, data analysis, and problem solving as significantly top cluster of competencies [5]. Kivunja [6] defined 4C's super skills in the framework of the21st century skills: (i) critical thinking and problem solving, (ii) communicating, (iii) collaborating, and (iv) creating and innovating. These skills are essential for a graduate to be successful in the working world and life. The work utilizing Bruner's 5E instructional mode of engagement, exploration, explanation, elaboration and evaluation approach on curriculum development and assessment that engages the 4Cs supper skills. Hence, overall concluded that engineering curriculums must equip engineering graduates with the survival skills to think critically and be problem solvers in the 21st century economy.

Among the focus of accreditation criteria on graduate attributes is to develop competences required for successful practice in their field that put on high expectation of synergy energy from what they learned in classroom. The response from accreditation and professional bodies on the demand of engineering graduate skills such as solving complex problems has been substantially emphasized in their accreditation or professional criteria. ABET [7] defines complex engineering problems with one or more of the following characteristics: involving wide-ranging or conflicting technical issues, having no obvious solution, addressing problems not encompassed by current standards and codes, involving diverse groups of stakeholders, including many component parts or sub-problems, involving multiple disciplines, or having significant consequences in a range of contexts. The integration of solving complex problems into engineering curriculum is emphasized under ABET criterion 3 that a program must explicitly document student ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics [7]. This is synonymous with The International Engineering Alliance (IEA) of Washington Accord's Graduate Attribute Profile Criterion WA2, students need to: identify, formulate, research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences with holistic considerations for sustainable development [8]. The Institutions of Mechanical Engineers, UK [9] emphasize that individuals attending their professional interviews need to demonstrate competency in solving complex problems in their Professional Competence Profiles Criterion Section B: Design, development and solving engineering problems.

Many teachings and assessments utilize project-based learning methods to achieve ABET accreditation criteria 3. Project based learning model helps develop real world problem solvers or thinkers instead of rule followers [4], [10] – [12]. Ashby [10] mentioned that to incorporate concepts of sustainable development into engineering, materials and design programs, there are two ways of doing it: either by creating new courses or by embedding it in the existing program. However, both pedagogical approaches need to interface with problem-based learning methods. The author argues that successful students overcome task difficulties by using a layer proposal to address multidiscipline concerns ranging from stakeholder analysis, social and life cycle assessment, and big issues such as climate, resources, waste etc. The proposal effectively measures students' progress towards achieving their task.

Farrell and Cavanagh [11] describe a laboratory project on biodiesel production that integrates sustainability concepts into a first-year introductory engineering course at Rowan University. A student team of four was formed and the key success of student learning lies in the pre-lab as well as within lab notebook page reviews. The pre-lab session is an in-class discussion between students and an instructor to help students at the initial stage to organize their body of conceptual work. During this discussion, the instructor will be able to assess the accuracy and quality of the students pre-existing knowledge and subsequently be able to suggest relevant formative feedback to the students. The teamwork project involved multidiscipline knowledge ranges from performing stoichiometric calculations, identifying, and planning appropriate measures to mitigate risk, modifying a process to achieve a specific goal, identifying causes for a faulty process, and costing of test kits. The attainment of student learning outcomes on ABET criterion 3 were based on several pre-tests and post-tests. The attainment of learning outcome of greater than 70 percent on student learning objectives, indicates a high measure of effectiveness in ABET criterion 3.

Sharma and colleagues [12] explain how a team project of designing a new "Quad Bike" model helps students in acquiring problem solving skills and exposure to multidisciplinary education. Students involved in this project learn skills such as teamwork, selection of materials, vehicle dynamics concepts, application of theory of statics and strength of materials throughout the designing work. The “Quad Bike” frame structure is designed using computer aided (CAD) and stress–strain analysis using ANSYS software. The successful student-learning outcome of this project is accomplished by solving complex problem skills using modern tools, actively engaging in decision-making and time management.

Overall works concluded that the four key features are important in comprehend of addressing complex solution problems: (i) team-based framework; (ii) multidiscipline education including sustainability of a project or coursework-based learning; (iii) application of modern tools in complex engineering problem with an understanding of the limitations; and (iv) effective communication by means of oral presentation and technical report writing, or both on complex engineering activities. These features agree with Farrell and others work [13] that mention a progressive engineering education at Rowan University uses innovative methods of teaching and learning that embed these four key elements in pedagogical approaches to produce students who have competencies to operate successfully in a complex, dynamic, and competitive 21st century environment.

This work focusses on how students learn critical thinking skills by solving a complex problem in an open-ended project from a learning theory perspective. Specifically, the work discusses how the open-ended project incorporates the four key features of learning that helps comprehend the complex solutions of engineers’ problems in the undergraduate laboratory course and fulfillment of ABET criterion 3. The challenge of this work is as follows: Is the sequential structure of the undergraduate laboratory course with the four key features of learning still relevant to the 21st century classroom?

Course content framework

The open-ended project has been incorporated in a sophomore first semester laboratory course at a higher learning institution, with a program outcome (PO) that was developed based on Washington Accord framework through the International Engineering Alliance (IEA) network. The course outcome (CO) with performance descriptions that is mapped to PO are shown in Table I of CO-PO matrix. The CO-PO matrix has seven COs mapped to 7 POs. The PO define graduate attribute and relate to Washington Accord (WA) graduate attribute framework as shown in Table II, in which PO5bs defines the ability to create appropriate techniques, select resources, and apply or manipulate of modern tool to execute complex engineering activities. PO9b defines the ability to communicate effectively on complex engineering activities by means of report writing. PO4a defines students' attribute to conduct experiments, collect required data and identify related observation in investigating complex problems related to mechanical engineering. PO4b defines students' attribute to analyze and interpret data using engineering principles and appropriate techniques in investigating complex problems related to mechanical engineering.

Table I
LABORATORY COURSE OUTCOME (CO) - PROGRAM OUTCOME (PO) MATRIX

Course Outcomes	PO1			PO2		PO3			PO4			PO5		PO6		PO7	PO8	PO9			PO 10	PO 11	PO12	
	a	b	c	a	b	a	b	c	a	b	c	a	b	a	b			a	b	c			a	b
CO1: Conduct experiment, collect required data and identify related observation (PO4(a))									✓															
CO2: Analyze and interpret data to explain the behaviour of materials (PO4 (b))										✓														
CO3: Manipulation of proper tools to investigate and explain the selected material properties (PO5(b))													✓											
CO4: Apply reasoning in safety procedures related to laboratory activities (PO6(b))															✓									
CO5: Demonstrate commitment towards laboratory ethics (PO8)																	✓							
CO6: Communicate effectively by means of report writing (PO9(b))																			✓					
CO7: Work in a team effectively to complete the course work (PO10)																					✓			

Table II
PROGRAM OUTCOME (PO) MAPPING TO INTERNATIONAL ENGINEERING ALLIANCE (IEA) - WASHINGTON ACCORD GRADUATE ATTRIBUTE (WA)

Program Outcome			IEA – WA Graduate Attribute
PO Statement		Sub-Attribute	
PO4	Conduct investigations, interpret data and provide conclusions in investigating complex problems related to civil/computer and communication/electrical/mechanical engineering.	a) Use research methods for collecting data. b) Analyze and interpret data using engineering principles and appropriate techniques.	**WA4**
PO5	Create appropriate techniques, select resources, and apply modern engineering tools to execute complex engineering activities.	b) Manipulation of modern tool to execute complex engineering activities.	**WA5**
PO9	Communicate effectively on complex engineering activities	b) Communicate effectively by means of report writing.	**WA10**

The assessment-course outcome matrix shown in Table III offers a framework to identify, collect, and prepare data to evaluate the attainment of each PO. With reference to Table III, the assessment consists of a safety quiz, pre-lab, final report, open-ended project, project proposal, instructor evaluation, and peer evaluation which define relevant CO and strategies align to their respective PO. For example, each CO is tagged with respective PO as follows: CO1 tagged with PO4a, CO2 tagged with PO4b, CO3 tagged with PO5b, CO4 tagged with PO6(b), CO5 tagged with PO8, CO6 tagged with PO9b, and CO7 is tagged with PO10. The course level process flow as shown in Fig.1, highlights that all written reports contribute to the attainment of PO4a, PO4b and PO9b. The assessment of prelab contributes to PO4a attainment. PO5b attainment is related to CO3 that is assessed with a project proposal in advance of the open-ended project. Safety quizzes, instructor evaluation and peer evaluation assessment will contribute to the attainment of PO6b, PO8 and PO10 respectively. Further discussion on the PO attainment will focus on the open-ended project's PO that is PO4a, PO4b, PO5b and PO9b.

Table III

LABORATORY COURSE ASSESSMENT-COURSE OUTCOME (CO) MATRIX

	PO4(a)	PO4(b)	PO5(b)	PO6(b)	PO8	PO9(b)	PO10
Assessments	CO1	CO2	CO3	CO4	CO5	CO6	CO7
Pre Lab (PO4(a)) [10%]	✓						
Report (PO4(a), PO4(b) & PO9(b) [40%]	✓	✓				✓	
Safety Quizzes (PO6) [4%]				✓			
Open Ended Lab (PO4(a) and PO4(b)), (PO5(b)) & PO9(b) [40%]	✓	✓	✓			✓	
Peer Evaluation (PO(8)) [3%]					✓		
Instructor Evaluation (PO10) [3%]							✓

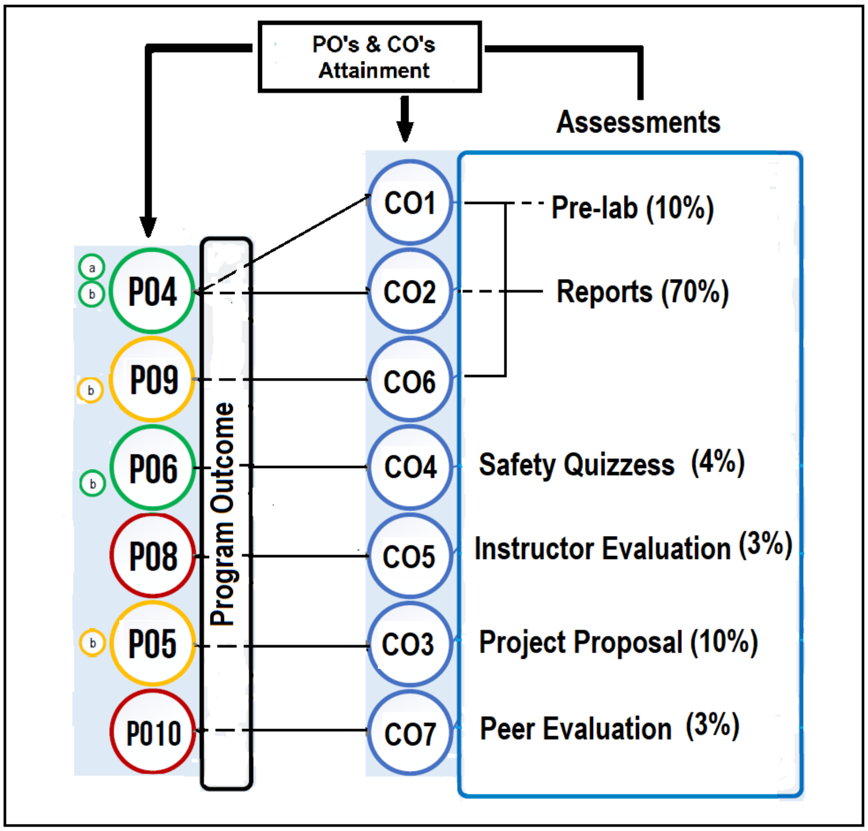

Fig.1. The course level process flow of mechanics and materials laboratory.

The following discussion on pedagogical framework and student attainment focus primarily on hands-on open-ended project with its instruction to achieve student-learning outcome based on the ability to create appropriate techniques, select resources, apply, and manipulate modern engineering tools to execute complex engineering activities (i.e., attainment of PO5b), and the ability to communicate effectively on complex engineering activities by means of report writing (i.e., PO4a, PO4b and PO9b).

Pedagogical framework

The laboratory course requires one laboratory meeting weekly for three hours over the course of fourteen weeks. Both instructor and laboratory technician are present during the laboratory meeting where experimental work is conducted. During the introduction weeks (Week2&3), learners are briefed on safety procedures, codes of conduct of laboratory activities and assessed on applied reasoning in safety procedures related to laboratory activities via safety quizzes. A team of four learners is formed with a maximum of six groups per class. The teams are exposed to five fundamental tests in continuous weeks, followed by a project proposal submission prior to commencing the open-ended project at weeks 11 and 12. The main intent of planning and conducting such instructional design is to embed three learning skills associated with behavioral, cognitive, and constructivist learning that lead to a successful execution of an open-ended project.

The demonstration of experimental procedures such as metallographic works, set-up a test sample, positions of data measurement such as gauge, and constraint such as force limitation associated with test equipment is conducted before each team commences their work. The five standard test observations provide behaviorism learning with an emphasis on mastering six standard testing procedures before progressing to a more complex level of performance associated with using the equipment. This learning approach is associated with an early conceptualized social learning theory [14] which reformulated into social cognitive theory [15] as a better description of how people learn from social experience that include attention, remembering their working procedures (retention), reproduction and being motivated to successfully perform the experimental work.

A laboratory manual and five pre-labs are provided in advance of the experimental work. Each pre-lab has between three to four short answers that range from definition of test principles to formulation, and analysis of test graphs i.e., stress on knowledge and comprehension of bloom’s taxonomy of lower cognitive level (i.e., C1 & C2). Following are examples of short answers: State the objectives of this experiment; Explain how to determine the Modulus of Shear, G through measurement of applied torque and angle of twist; Define elastic and plastic deformation; Label the plastic region, elastic region, ultimate tensile strength, and yield strength in the stress-strain diagram below; Explain the principle of impact testing; State one application using the concept of thin cylinder. Explain; Which engineering applications do you think that torsion test is vital? Give two examples: State one application using the concept of thin cylinder. Explain. This activity provides the learner with recalling facts, relationships, materials properties, formulation, and how to acquire and organize respective experimental knowledge. Overall, students have little trouble functioning at this comprehension knowledge level that is gauge by the attainment of PO4(a). The on-the-spot feedback on pre-lab work provides an active cognitive approach that results in an immediate response and acknowledges mental processing and planning.

At the end of experimental work, a written report will demonstrate student ability to: (i) transform raw data via formulation, (ii) tabulate data for analytical and graphical presentation, (iii) estimate errors in their results and, (iv) compute specific properties associated with respective tests. With peer interaction, students can achieve the synthesis of experimental data, the evaluation of different sample characteristics, and a logical conclusion is drawn from their work in creating their final written report. This learning stage stresses the higher cognitive level of bloom's taxonomy of analyze and evaluation (i.e., C4 & C5) and are indicated in the attainment of PO4(b). The activities focus on active cognitive learning theory of acquisition of knowledge by experience, internalization, and the ability to store memory in a meaningful manner. In another word, the skills acquired from these tasks provide a domain knowledge base that is transferable to dissimilar tasks and or new problem situation.

The project proposal is a holistic evaluation strategy to portray tasks that encourage synthesis of learning through constructivism. The proposal gives each team a chance to construct their understanding and validate experimental set-up through social negotiation with their instructor. For example, inadequacy in measurable parameters, sample size, ideal sequential procedures, time management, cost of materials, experimental set-up insensitive to equipment constraint is discovered, highlight, negotiate, refining and or remove if necessary, during proposal stage. The proposal assessment criteria as follows: (i) Proposed procedures that fulfill the testing condition; (ii) Adequacy of sample preparation; (iii) Selection and integration of tools to run the investigation and analysis; (iii) Design of experimental set-up and cost; (iv) Creativity of experimental set-up. At the initial stage of design, instructor observation found that students are using the guided rubric in a linear manner to generate complex problem solutions. The solving of complex problems itself improves only through the reviewing process of the proposal with their instructor. The proposal feedback provides a chance for quality improvement and performance before execution of the open-ended project. Students are not pressured to get answers in a hurry and are able to redo the experimental design. They work in a team that could divide the workload and make connections with like-minded peers that sparked excitement. The observation throughout the proposal review process indicates students performed self-checking on their confidence level of understanding the concept (metacognitive knowledge), how effective or accurate is their discussion or solving problem (metacognitive regulation & experiences) and remember the effective ways of performing task (metamemory). The key motivation of students in performing metacognition is the recognition of mutual "joy of understanding". In Vygotsky's view [16], the proposal serves as guidance, motivation and activity provided by instructor that led learner through the zone of proximal (ZPD) development. The project proposal submission work is done at least a week before the start date of the open-ended project. The project proposal assessment contributes to the attainment of PO5(b).

The open-ended project activity incorporates Washington Accord of Complex Engineering Activities (EA): (i) Range of resources attributes (EA1) that involve the use of diverse resources (and for this purpose, resources include people, money, equipment, materials, information, and technologies) and (ii) Innovation (EA3) involve creative use of engineering principles and research-based knowledge in novel ways. The open-ended project instructions embedded ABET complex problem definition of having no obvious solutions, and addressing problems not encompassed by current standards and codes. The overview of the open-ended project activity is shown in Fig.2 of a cultural-historical map of a complex solving problem and the representation chain between matters in the material world and model world, adopted from [17, Fig.1 & Fig.2]. As shown in Fig.2, the task is: (i) To design a simple and cost-effective experimental set-up to study the buckling behavior of non-metallic materials, and (ii) To design an experimental set-up to study the hardness and microstructural features of metallic materials. The cultural-historical map of the open-ended project reveals the integration and interaction of diverse resources such as people, equipment and technology, materials, information, regulations, and involves creative use of engineering principles and research-based knowledge. The outcome of the open-ended project shows no obvious solution. Therefore, students can address problems not encompassed by current standards and codes. Students are empowered to find their solutions, feelings of competence as their experiences contribute to knowledge of phenomena.

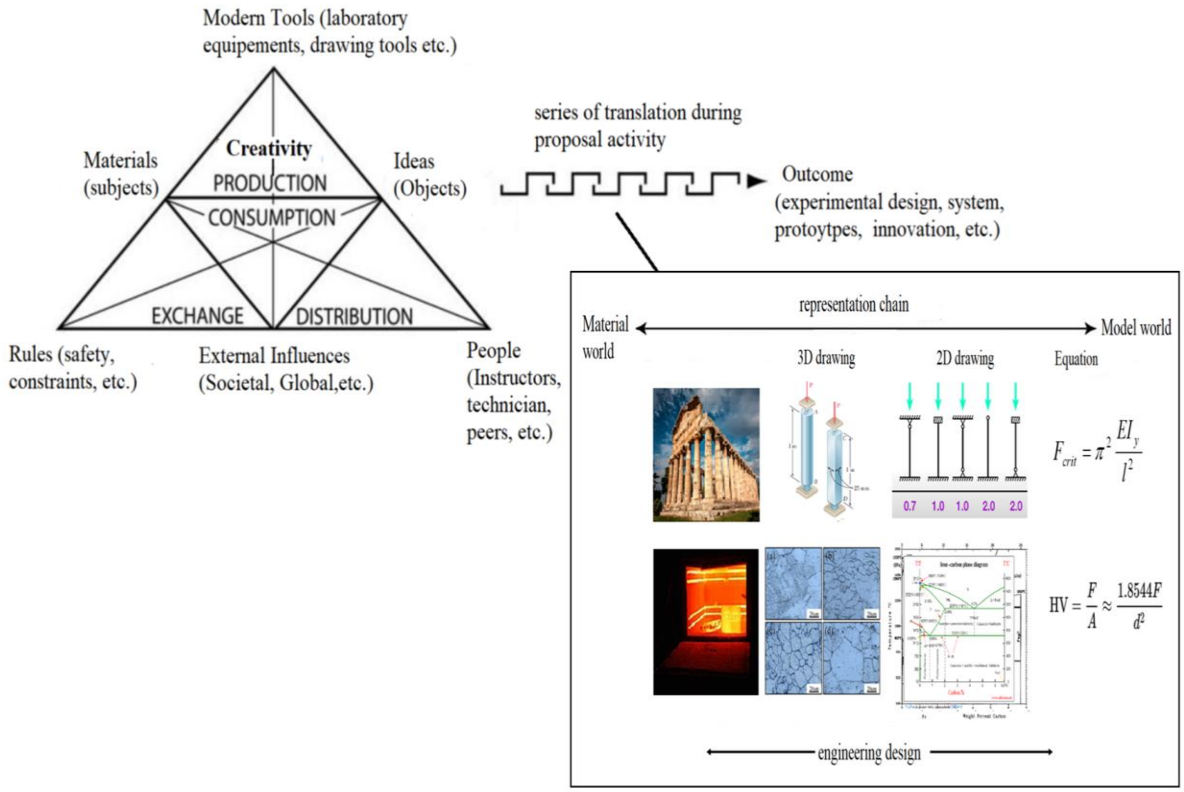

Fig.2. The cultural-historical map of a complex solving problem and the representation chain between matters in the material world and model world for the open-ended project of mechanic and materials laboratory course, adopted from [17, Fig. 1 & Fig. 2].

In ideal situations, the translation movement during engineering design seems to be from right to left as the ideas are formulated, translated into diagrams, and object in materials world. However, in practical situations, students will engage the discovery learning concept [18], in which the design thinking involves a dynamic interaction between representations, and pair-wise reference to each representation are required. Therefore, the proposal activity requires students to perform cognitive movement of back-and-forth between material world and model world. The representation chain shows the open-ended project tasks: (i) A study of column's buckling with key representations such as equation of Euler's critical load for buckling, 2D-, 3D-drawings, and column in real world; (ii) A study of heat treatment process with key representations of hardness measurement, 2D-phase diagram, 3D-microstructure analysis, and a heat treatment process in real world. The mechanical or metallography assumptions are used to map from one representation to another representation i.e., closing the gap. The role of instructor at this stage is crucial as students may have difficulties in closing the gap. These assumptions are important as they relate to forming a series of smooth representations translation, with the goal of achieving a desired and representable outcome. Overall, the proposal is an explicit guidance into process of solving open-ended project that enables each team to frame solutions, make appropriate assumptions, generate many ideas (alternative) of experimental set-up, and participate in selection activity and evaluation work.

Results and discussions

The Assessment-Course Outcomes matrix shown in Table I and Fig.1 is used to identify, enable, and track the contribution of a particular assessment to PO attainment. Fig. 3 shows the program outcome attainment of PO4a, PO4b, PO5b and PO9b that is related to the open-ended project's PO analysis. PO5b shows the attainment of the students' ability to apply proper tools to execute complex engineering problems related to engineering materials and mechanics of materials. PO4a, PO4b and PO9 are related to attainment of students' ability: (i) to conduct experiment, collect required data and related observation; (ii) analyze and interpret data to explain the behavior of materials, and (iii) communicate effectively by means of report writing, respectively. All the relevant PO's, i.e., PO4a, PO4b, PO5 and PO9b show an attainment of at least 70% for five consecutive semesters (S1 2019 - S12021) from the year 2019 to 2021.

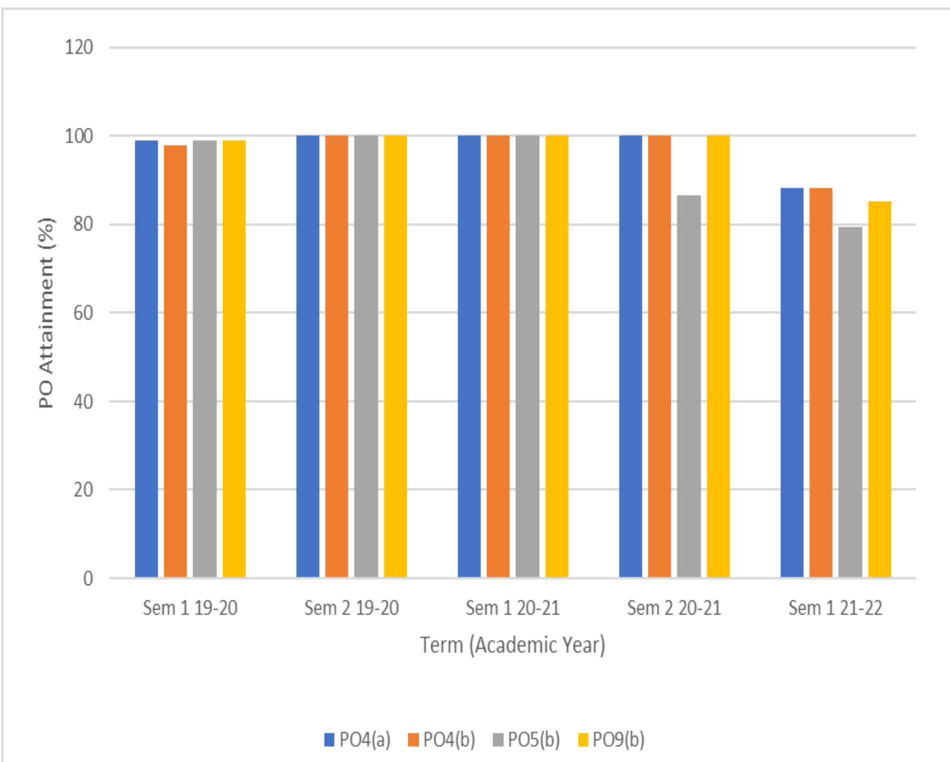

Fig.3.   Program Outcome (PO) Attainments of Five Consecutive Semester from Year 2019-2021 (Sem 1 2019 – Sem 1 2021).

Conclusion

In brief, engineering is a process about problem identification, formulation and provides solutions or services. During the process, engineering students or engineers use existing tools or creatively develop new tools, in an ever-increasing skills demand of the 21st century engineering discipline. More than 70 percent of PO5b attainment results indicated that open-ended project was highly effective in attaining the learning domain on the ability to create appropriate techniques, select resources, and apply or manipulate modern engineering tools to execute complex engineering activities. The open-ended project is addressing the four key features on the basis that learner is exposed to the perspective of others individual during teamwork, and able to construct multiple perspectives issues associated with exposure to it in different contexts. To the instructor, their greatest achievement is observing the student performing metacognition in recognition of “joy of understanding”. The proposal in advance of undertaking an open-ended project provides the chance for faculty to help students coordinate, modify, refine, or adapt alternate ways of thinking during solving complex problems. The laboratory course with an open-ended project is cost effective, encompasses the three pillars of learning theory associated with behaviorist, cognitive, and constructivist learning, and is easily designed according to existing laboratory equipment and, therefore transferable to any institution.

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