ISBN: 978-628-95207-8-1. ISSN: 2414-6390. Digital Object Identifier: 10.18687/LACCEI2024.1.1.743

Enhancing Engineering Competencies through Sustainable Design: A Project- and Problem-Based Learning Approach for Industrial Engineering Students

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Abstract*– In contemporary engineering education, the conventional subject-focused structure often falls short in fostering the necessary problem- and project-based approaches to build necessary competencies. This paper proposes a five-subject modular concept integrating different departments to develop transdisciplinary skills without compromising on content. It links different modern teaching methods to test their eight students' interaction potential and productivity. This proposed concept encourages collaborative supervision by professors from diverse higher education centers, challenging students to participate in a semester-long simulation where two groups emulate start-up companies. Tasked with competing in planning, designing and developing a sustainable solution from plastic waste (HDPE), students delve into hands-on experiences, learning how to integrate the requirements and approaches of sustainable production. During the module, knowledge and fundamental skills in the field of engineering were qualitatively measured before and after to compare with the skills learned through the module.

***Keywords*-- higher education, project-based learning, problem-based learning, sustainability, transversal competencies in education.**

I. Introduction

It is well-known and scientifically proven that universities still fall short in teaching soft skills compared to other providers of higher education that are more application-oriented [1]. While this deficit affects most programs, it is particularly a hindrance for the future careers of graduates in technical studies. In Panama, where a majority of mechanical and industrial engineers are expected to find employment in the tertiary sector (maintenance, service, repair) or in executive roles within the secondary sector (e.g., assembly and manufacturing rather than R&D departments), soft skills associated with a project-based working approach are often more critical for professional advancement than specific technical qualifications. The traditional model, often referred to as a teacher-centered model, emphasizes the role of the teacher in information transmission through an expository style and has been dominant for many decades. In contrast, the increased focus on student-centered learning, also known as the constructivist model, student-centered learning, or learning facilitation paradigm, represents a shift towards actively involving students in their own learning process [2]. In higher education, calls have been made for active learning experiences that place the student at the center of the learning process, moving away from passive listeners [3]. Active student engagement requires the implementation of active methodologies with implications for both the educational process and the mechanisms used to assess the degree and quality of acquired learning. Thus, a shift has been observed in university pedagogy, where lectures are evolving from being the sole or primary instructional method to a combination with active learning methodologies. These include seminars, learning projects, supervised projects, self-directed readings, reviews, document analysis, case studies, literature searches, problem-based learning, and the use of virtual platforms – all more geared towards student autonomy and active learning. Active learning does not negate the need for lectures but provides opportunities for students to reflect, evaluate, analyze, synthesize, and communicate about the presented information [4].

The main objective of this research is to link various modern teaching methods for engineers in an extracurricular project and investigate their interaction, as well as simulate the decision-making processes in agile and innovative companies to improve national higher education. Instead of conducting separate classes, professors from different higher education institutions will collectively supervise the project. Throughout the semester, two groups of students will act as simulated startup companies, competing in their individual planning and design using plastic waste (HDPE). Students will learn from their own experience how to integrate customer requirements and approaches to sustainable production throughout the product life cycle. The involved professors will analyze and

Digital Object Identifier: (only for full papers, inserted by LACCEI).
ISSN, ISBN: (to be inserted by LACCEI).
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evaluate the results, providing recommendations on how to implement the insights into regular curricula.

II. Teaching Methods

Teaching and learning practices in higher education are undergoing a series of changes that have significant implications for the nature of students' learning experiences [5]. The teacher-centered model places special importance on the role of the instructor, considered the fundamental source of information and knowledge. In this model, the teacher is the one who knows, and it is their responsibility to effectively convey knowledge, leaving students with the sole task of reproducing that knowledge [6].

One way to classify student-directed teaching methods: (1) lectures, (2) case commentary, (3) case study, (4) project design, and (5) problem-based teaching method. Both case commentary and case study focus on real-life experience. Case commentary and case study concentrate on case experience for student learning; however, case commentary works with fixed-text cases, while the student must search for cases to be discussed in class as a case study and find solutions. Fig. 1 illustrates the correlation between the teaching method and the type and depth of knowledge developed [7].

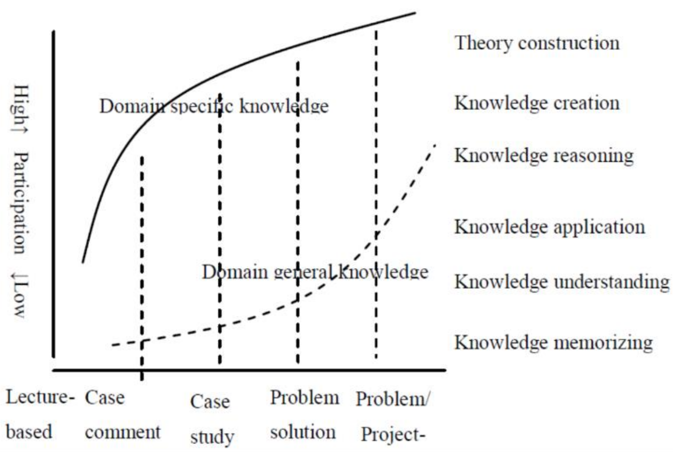

Fig. 1:The influence of teaching method and participation to knowledge development [7]

Project-Based Learning (PjBL) refers to an inquiry-based instructional method that engages students in knowledge construction by having them undertake meaningful projects and develop real-world products [8]. PjBL's characteristics include a focus on learning goals, engagement in educational activities, collaboration among students, and the creation of tangible artifacts. Among all these features, the creation of artifacts that solve authentic problems is crucial, distinguishing PjBL from other student-centered pedagogies, such as Problem-Based Learning (PmBL) [9].

A crucial task of higher education is to provide innovative education for students entering the job market in the future, as it enhances their competitiveness and promotes long-term societal development [10]. Research has suggested fostering innovation by supporting autonomy during learning tasks [11]. PjBL can meet such needs. Although several studies, for example, Helle et al. [12], have indicated differences between PjBL and PmBL, such as different task types, the role of the instructor, and the way knowledge is processed being key. The focus of PmBL lies in applying knowledge, while PjBL, based on the science of active construction learning [9], emphasizes knowledge construction. This process of creating new knowledge allows students to test and achieve their ideas in the way they want, promoting their innovation competence [13].

Both PmBL and PjBL share the quality of high student participation; therefore, they generate greater knowledge value through learning [7]. Moreover, both PjBL and PmBL consist of lectures, case commentary, and case study. Both emphasize student-centered learning [14]. The combined occurrence of both methods in a didactic module is termed "Problem- and Project-Based Learning" (PPBL).

When a particular teaching method determines the level of success in learning specific content, it becomes necessary to conclude that a shift in expectations for individual training also changes the requirements for classroom methods (see Fig. 1). Internationally, this has long meant moving away from a sole focus on knowledge and hard skills reproduction (logic, perseverance, tenacity, etc.) toward the integration of social skills (team spirit, presentation, leadership style, etc.) and skills oriented towards problem-solving and projects (learning strategies, division of labor, knowledge management, etc.). While the content of engineering courses has been following this path for decades, both globally and in Panama, the methodological portfolio has unfortunately lagged behind. An international comparative study has demonstrated the significant qualitative aptitude of PPBL for sustainability aspects in the STEM environment [8], which have been the focus of some studies. Whether the specific combination of selected didactic means and project planning produces the desired result in a specific environment can only be experimentally demonstrated.

III. Competencies

Internationally, there is a growing acknowledgment of the importance of fostering the development of transversal competencies (TVC) in education [15]. These competencies encompass a holistic set of knowledge, skills, values, and attitudes essential for navigating the complexities of contemporary life [15] also referred to as key competencies [16]. In an era of globalization and modernization, individuals navigating an interconnected world must master changing technologies, process vast amounts of information, and address complex collective challenges, necessitating competencies beyond the mastery of narrowly defined skills [15],[16]. It is vital to develop key competencies for sustainability to attain the 17 Sustainable Development Goals (SDGs) [17]. These competencies represent what individuals engaged in sustainability should possess to address contemporary complex challenges [17]. According to [18], a total of eight distinct key competencies for sustainability were identified, which are:

systemic thinking, integrated problem-solving, interdisciplinary collaboration, normative expertise, self-awareness, strategic thinking, impact assessment/ forecasting, and critical thinking (TABLE I).

TABLE I
KEY COMPETENCIES AND THEIR DEFINITIONS ADAPTED FROM [18]

Key Competence	Definition *Ability to…*
Systemic Thinking	Identify and understand interactions between systems and people in diverse contexts. Anticipate problems in relation to sustainability
Integrated Problem-Solving	Address complex sustainability issues and develop viable and equitable solutions that promote sustainable development, considering various dimensions and needs.
Interdisciplinary Collaboration	Effectively collaborate in interdisciplinary teams, respecting the opinions and needs of other members, managing conflicts, and promoting participation in problem-solving.
Normative Expertise	Understand and reflect on the norms and values that guide actions, as well as negotiate sustainability values and principles in situations of conflicting interests.
Self-Awareness	Reflect on one's own role in the community and society, evaluating actions and personal emotions related to sustainability.
Strategic Thinking	Develop and implement innovative actions to promote sustainability in response to environmental and social challenges.
Impact Assessment/ Forecasting	Understand various possible futures, apply the precautionary principle, and assess consequences and risks
Critical Thinking	Question norms, practices, and opinions in the context of sustainability, reflect on personal values, and take an informed stance in sustainability discourse.

IV. METHODOLOGY

A. *Module Conceptualization*

The module was organized in three chains, two of which (practical session / creative session) took place in parallel to the class period and one (workshop) in block during the period between semesters.

To minimize the reliance on traditional frontal teaching and foster participant autonomy in the project, two internationally established yet underutilized methodologies in Panama were employed: the flipped classroom and the mirror classroom. In the flipped classroom, online group work and self-study – are constantly exchanged for the subjects taught, so that, although the weekly proportions of the individual forms always remain the same, the teaching method changes for each subject each week. Thus, four subjects or thematic areas can be placed in just two semester hours without reducing the depth of the content. The idea of the mirror classroom goes beyond just distance learning, as students can experience face-to-face teaching in a group setting without the teacher having to be in the same place. Professors can remain on individual campuses and still be personally available to all students. At the same time, video and audio can be recorded and distributed as a stream through the university's learning platform. This makes it easier to repeat the content and protocol the project progress.

When structuring the content of the subjects for the flipped classroom, attention was, of course, paid to their intercompatibility. Since the project work will only be offered to students in the final year of the bachelor’s degree, therefore, the theoretical foundations of the five subjects (Sustainable design, Quality management for production systems, Project planning, Production sustainability, Production planning) must already be established. There is the freedom to arrange the teaching units according to their suitability to the respective form of teaching to make the course of the flipped classroom as attractive and productive as possible.

The curriculum of the industrial engineering bachelor's degree was reviewed to identify the contents relevant to the five subjects of the module, along with their respective content coverage and the tools used in each course. As a result, Project Management, Work Studies, Production Planning, Quality Management I and II, and Manufacturing Processes were identified as the key courses. Subsequently, a specific questionnaire was developed for each of the aforementioned courses. These questionnaires were applied to final-year students of the bachelor’s degree in industrial engineering and to lecturers who have taught these courses over the past four years at the campuses in Panama City and Chiriqui Province. These questionnaires were sent by email to the students and lecturers, and an advertisement was placed in each of the classrooms. Each questionnaire has three sections, the first one is related to the general description of the respondent. The second section asked about the course topics and tools coverage during the course. The third one is about the reasons why the topic was not discussed during the course. With the results of both questionnaires, the content of the four subjects of the module were elaborated. The content of the sustainable design subject (including creative sessions) was elaborated for the professor at the partner university to the project, the Rochester Institute of Technology.

In the first practical phase, teachers should, as far as possible, strictly adhere to the resulting guideline. In the third semester, after the evaluation of the student learning of the module, the feedback metrics and the experience reports, an adapted study plan must be presented that will be applied in the second practical phase.

B. *Experiment*

The students participating in the project are undergraduate students in the final-year of their bachelor's degree in industrial engineering of the Technological University, at the campus in Panama City and Chiriqui Province. A quantitative representation cannot be implemented here with reasonable group sizes. Since the project examines qualitative sufficiency, this is not even necessary; a sample of 10 participants seems sufficient if no additional selection is performed within the population. The ten participants are selected after an application review and interview. To participate they must meet certain curricula requirements, for example the student must be last year students currently enrolled in their last semester of studies.

The subjects that they must have previously taken, out of our university's curricula are: Project Management, Work Studies, Production Planning, Quality Management I and II, and Manufacturing Processes.

Students attended several online lectures to learn the fundamentals of the module. All the material of the module was stored in the university's learning platform. The theory will be reinforced in face-to-face workshops.

Training in product design was given in creative sessions in a virtual classroom or mirror classroom with a special focus on redesign and sustainable design. The mirror classroom has its advantages for any activity that is best carried out face to face, such as planning or adaptation tasks, brainstorming or developing requirements. Students were divided in two groups to develop the product design independently in each group. They were guided by an expert who paid special attention to feasibility and compliance with all external conditions, but who otherwise mainly advised the students.

After the lectures and workshops, students will be divided in groups of four participants and will embrace the challenge of design and develop a sustainable solution for a specific type of customer. Students then must apply all qualitative and quantitative tools, in a methodological manner, in order to come up with a design that meets the customers' requirements. They will present their progress emulating agile meetings where instructors will give relevant feedback for the next stage. After handing all deliverables, students will take their design to the digital fabrication lab and manufacture their sustainable solution.

In preparation for the production workshop of their prototypes, the two groups were asked to prepare a CAD model of their design. Thus, the students will arrive prepared for the week of the workshop and will be able to focus on getting the production line up and running, which will mainly consist of five stations: sorting and crushing the recyclable materials, washing and drying, filament manufacturing, 3D printing of the final product, and post-processing. Together with the design expert and a project teacher, they created a prototype from waste plastic (HDPE) in a production workshop, so that participants can take a copy as a "test piece."

Part of the challenge as engineers is to set the right configuration on the machines to extrude usable HDPE material and the right filament diameter to feed the 3D printer.

C. *Evaluation of the Competencies*

To select the method to evaluate competencies was used the systematic review of [19] as a guide. Therefore, the questionnaires were applied using time triangulation, pre- and post-questionnaire. This was done before the beginning of the module. Two questionnaires were applied, one to measure the knowledge on the five courses of the module and the other to measure the competencies (self-assessment) before the module. The questionnaire to measure the prior knowledge was structured in three general questions of the student and twenty questions related to fundamental knowledge of the five subject areas of the module. The self-assessment questionnaire consists of three general questions and thirty questions related to the eight competencies for sustainability mentioned previously. A Likert scale of five was utilized.

Moreover, questionnaires were combined with interviews to increment the validity of the study. For this reason, at the end of the module an open feedback round with the student participants was carried out. During the meeting, five questions were asked to the student participants to get their perceptions about the module. In addition, two post-questionnaires were performed after the end of the module.

IV. Results And Discussion

A. *Review of the Curriculum*

A questionnaire was carried out for each course (Project Management, Work Studies, Production Planning, Quality Management I and II, and Manufacturing Processes) where lecturers and students evaluated the level of coverage using a Likert scale. The scale used in both questionnaires was the following: (1): Not given, (2): Assigned as a talk, (3): Assigned for presentation, and the professor expanded the content, (4): The professor explained without solving problems, (5): Fully covered, and both quantitative and qualitative problems were explained.

The main findings by course will be described below:

- Production Planning: According to the lecturers, the level of coverage was high in all the topics surveyed, resulting in an average between 4 and 5. According to the students, only two topics had a lower average score between 3 and 4, these were: Introduction to operations planning and systemic models of holistic operations management.
- Manufacturing Process: Both the lecturer and the students indicated moderate and low coverage in various topics, with average values ranging between 2.5 and 3.5. These topics included Thermodynamics of Processes, Kinetics of Unit Processes, Supply Chain, Traceability, TRIZ, and Material Balances.
- Quality Management I: Students and lecturers assessed the coverage of topics differently. Lecturers indicated that the coverage of the subjects was high. However, students reported moderate coverage in the following topics: Latest Trends, House of Quality/QFD/Quality Function Deployment, Identification of Customer Expectations, Components of a Quality Management Model, Quality Economics
- Quality Management II: The evaluations from both students and lecturers, in general, were good with an average topic coverage ranging between 3.9 and 4.5. However, there were topics where both parties agreed that the content could have been delved into more; these include Lean Manufacturing and Six Sigma
- Project Management: Most of the topics were fully covered except for one, Risk Analysis, where both the lecturers and the student indicated that it was covered

without problem resolution. Only general concepts were discussed.

- Work Study: The topics related to the study of methods and work measurement were covered with high assessment. However, subjects related to the construction of indicators for work measurement received low assessment.

Based on the results obtained, the content of the module's subject was strategically designed. This involved prioritizing topics that had not been thoroughly covered previously and incorporating practical tools not included in the existing curriculum. This approach was adopted to ensure that students could find practical applications for the concepts taught within their study plan. With this in mind, the module was structured as follows in TABLE II.

TABLE II
MODULE SUBJECTS AND CONTENT

Subject	Content
Sustainable design	-Design and creativity. -CAD / CAM
Quality management for production systems	-Technical risk management -Customer requirements' analysis
Project planning	-Agile project management -Operational risk management
Production sustainability	-Sustainable production: assessment and strategies -Bioplastics
Production planning	-Additive manufacturing -Business models

B. Diagnostic Questionnaire

A total of 11 student applications were received to participate in the module from the campus at Panama City and Chiriqui Province. At the end only 8 students finished the module. Subsequently, an assessment was conducted to evaluate the student's knowledge both before beginning the module and after its completion. This approach enabled the instructor to make necessary adjustments to the course content within the module. Additionally, comparing pre- and post-questionnaire results was intended to validate learning effectiveness. The diagnostic test was scored out of a maximum of 25 points; results are shown in TABLE III.

TABLE III
SCORES OBTAINED BEFORE AND AFTER

Student	Before (initial assessment)	After (final assessment)	Difference
S1	21	24	3
S2	8	20	12
S3	23	24	1
S4	20	25	1
S5	19	18	-1
S6	21	21	0
S7	21	22	1
S8	14	21	7

As observed in TABLE III, the difference is obtained from the difference between the final assessment and the initial assessment, and the result of a positive value indicates an enhancement of the knowledge. Six out of the total number of students participants achieved higher scores at the conclusion of the module, indicating that 75% of the participants demonstrated an enhancement in their understanding of the examined topics. One student maintained the same score, while another experienced a slight decrease, with the score difference being just 1 point. In the initial assessment, it is notable that only 25 % of the student participants at the beginning of the experiment did not have the basic knowledge about methods, materials and importance of additive manufacturing. Moreover, it is important to highlight that only 75% of the student participants understand the basic concept for requirement analysis. Another point was only 67% did not know how to identify what is an operational risk and 58% know the concept of agile methodology. However, participants stated that they only know basic theoretical concepts, yet practical applications have not been taught in a traditional classroom. After a semester of our proposed module and on-site workshops, students developed improvements regarding their competences on the previous topics. Now, 88% understand the knowledge about methods, materials and importance of additive manufacturing. Moreover, 100% of the student participants understand basic concepts for requirement analysis. Another point was 63% know how to identify what is an operational risk and 100% know the concept of agile methodology.

C. Self-Assessment

The development of 7 key competencies expected in the participants was evaluated. A self-assessment was conducted at the module's beginning and end. TABLE IV summarizes the differences observed between the self-assessment pre-and post-questionnaire. A positive difference indicates that, in the student's opinion, there was an improvement in the respective competence throughout the module.

TABLE IV
EVALUATED COMPETENCIES

Student	Competencies						
	C1	C2	C3	C4	C5	C6	C7
S1	1	8	1	2	-3	6	8
S2	4	5	-3	3	6	6	4
S3	3	0	4	4	-1	1	2
S4	-4	-2	-4	-6	-2	-2	-2
S5	1	5	0	1	-2	6	0
S6	1	2	1	1	-4	0	2
S7	2	3	0	-3	7	0	6

In the case of the integrated problem-solving competence (C1), 6 students indicated having obtained an improvement. In the interdisciplinary collaboration competence (C2), 5 students indicated having obtained an improvement. In the critical thinking competence (C3), 3 students indicated having obtained an improvement. In the normative expertise competence (C4) 5 students indicated having obtained an improvement. The self-awareness competence (C5) 2 students indicated having obtained an improvement. In the strategic thinking competence (C6) 4 students indicated having obtained an improvement. The impact assessment/ forecasting competence (C7) 5 students indicated having obtained an improvement. As can be seen, more than 50% of the participants stated that they had improved the competencies evaluated by the research group, which implies an impact on the intervention carried out.

D. Open Feedback

During the open feedback session using the five-finger takeaway method, participants of the Module for Sustainable Project Planning (MPPS) provided detailed reflections on their academic experiences, highlighting key aspects of the program that resonated with them, as well as areas for improvement. One of the aspects participants liked the most was the freedom it offered in developing prototypes from the ground up. They found the comprehensive curriculum covering environmental sustainability, operational risks, and innovative design techniques especially enriching. The collaborative environment, underscored by team-building activities and the integration of students from various regional centers, was seen as a unique and valuable aspect of their learning experience. The participants lauded the hands-on approach and expert guidance, which effectively bridged the gap between theoretical concepts and practical application, making the learning process both enlightening and fulfilling.

Participants mentioned the module broadened their understanding, especially in areas like additive manufacturing and sustainable, user-focused product design. The practical exposure to 3D printing was a transformative element, turning abstract concepts into tangible skills and emphasizing the broader impact of their work on sustainable development. This comprehensive educational approach was well-received, as it not only provided technical skills but also fostered a deeper understanding of the environmental implications of product design, making it a balanced blend of theory and practice.

While the MPPS was highly beneficial, students pointed out areas needing enhancement. The limited availability of 3D modeling classes, particularly with Fusion 360, was seen as a gap in fully realizing the potential of these essential tools. The preference for more hands-on, in-person workshops over the predominantly virtual format was evident, suggesting a desire for a more engaging and interactive learning environment. Participants also expressed the need for comprehensive teaching on the operational aspects of 3D printing and a more robust support system for the self-learning components, including interactive forums for inquiries and discussions. Moreover, participants expressed a strong desire for more time to be allocated to critical aspects of the course, such as G-code generation and CAD (Autodesk Fusion 360), highlighting the importance of an in-depth engagement with these technical tools. The need for an extended timeframe to navigate through the design and development stages of their projects was clear, suggesting a preference for a detailed and unrushed creative process. The wish for more team-building activities, in-person workshops, and opportunities for peer collaboration, especially in the final product development stages, highlighted the participants' enthusiasm for a more hands-on and collaborative learning experience.

Finally, the participants of the MPPS carried with them rich and multifaceted memories that highlighted the profound impact of the program on their personal and professional growth. They cherished the value of teamwork, where the fusion of diverse ideas and perspectives culminated in the creation of functional prototypes. The new knowledge and skills acquired during the course were seen as pivotal for their future careers. The sense of belonging, ownership towards the MPPS, and the desire to continue their engagement with the projects were profound. The final three days of the workshop, marked by intensive, hands-on learning and personal interactions, stood out as particularly memorable. The encouraging and nurturing atmosphere fostered by the advisors, instilling confidence in the potential of even nascent ideas, left a lasting positive impression, making the MPPS a truly transformative educational journey.

V. Conclusion

Higher education is undergoing a transformative shift from a teacher-centered to a student-centered model, emphasizing PjBL and PmBL, with a crucial integration known as PPBL essential for equipping students with social, problem-solving, and project-oriented skills for the future job market. Therefore, an extracurricular project, simulating decision-making in innovative companies was created to connect modern teaching methods for industrial engineer bachelor students.

This paper reflects the significant progress made in enhancing engineering competencies through the MPPS, a project- and problem-based learning approach tailored for Industrial Engineering students. The results of the module have been encouraging, demonstrating its effectiveness in fostering a deeper understanding of sustainable engineering practices and soft skills crucial in the modern engineering landscape.

The curriculum review and subsequent module design prioritized areas that had not been thoroughly covered previously in our institution, focusing on integrating practical tools and methodologies. This strategic approach ensured that students could find practical applications for the concepts taught within their study plan, as evidenced by the positive shifts in the diagnostic questionnaire results. Notably, most of the students showed an improvement in their understanding of the examined topics, with significant advancements in their knowledge about methods, materials, and the importance of additive manufacturing. The self-assessment results further underscored this development, with more than half of the participants indicating improvements across key competencies such as problem-solving, interdisciplinary collaboration, and critical thinking.

The open feedback collected through the five-finger takeaway method illuminated the participants' academic journey, highlighting the enriching curriculum, hands-on approach, and the fostering of a collaborative environment as key strengths of the MPPS. Participants also provided constructive feedback, pointing out areas for enhancement such as the need for more in-depth 3D modeling classes and comprehensive teaching on operational aspects of 3D printing. These insights are invaluable for refining the module's structure and content to better meet the needs of future students.

In summary, the MPPS has proven to be a transformative educational endeavor, significantly enhancing the competencies of Industrial Engineering students. The module's focus on sustainable design, collaborative learning, and practical application has not only equipped students with the necessary technical skills but also fostered a deeper understanding of the broader impact of their work. The success of the MPPS in achieving its objectives demonstrates its potential as a model for future sustainable engineering education initiatives, paving the way for further advancements in the field.

ACKNOWLEDGMENT

The authors express their sincere appreciation to the Industrial Engineering Research Group at the Faculty of Industrial Engineering, Energy and Comfort in Bioclimatic Buildings Research Group and Design, Manufacturing and Materials Research Group at the Faculty of Mechanical Engineering, Technological University of Panama and the College of Art and Design at the Rochester Institute of Technology, for their crucial cooperation. This publication has been partially supported by funding from the Panamanian Secretaría Nacional de Ciencia, Tecnología e Innovación (SENACYT), under the project code PFIA-IACP-A-25-2023.

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