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An Integrated Project-Based Learning Approach Across the Engineering Curriculum

Vilma V. Ojeda-Caicedo; Hernando Altamar-Mercado; Jorge L. Muñiz-Olite; Jenifer Vásquez-Aguilar; Sonia H. Contreras-Ortiz

Universidad Tecnológica de Bolívar, Colombia, vojeda@utb.edu.co, haltamar@utb.edu.co, jmuniz@utb.edu.co, jenvasquez@utb.edu.co, scontreras@utb.edu.co

Abstract– ***In engineering education, the development of practical skills is essential to enable students to apply scientific and engineering principles to real-world problem solving. Throughout the curriculum, multiple learning experiences, such as laboratory work, workshops, and projects, aim to foster both technical and interpersonal skills. This article presents a Project-Based Learning (PBL) strategy integrated throughout the engineering curriculum, designed to strengthen students' technical skills (such as engineering design and product development) and their interpersonal skills in effective communication and teamwork. Three key experiences are articulated: the first-semester project at the STEAM challenge, the science projects developed between the second and fourth semesters and presented at the Science Fair, and the final-year engineering project, which is geared toward solving real-world problems in the productive or social sectors. These experiences provide progressive immersion in design, experimentation, validation, and technical communication, aligning with the ABET-established student outcomes. Longitudinal cohort analysis reveals a systematic evolution in design and teamwork skills as students progress through their academic journey. The results suggest that the strategic repetition of the project model throughout the curriculum functions as a spiral curriculum scheme that consolidates technical memory and engineering judgment.***

Keywords—Project-based learning, Engineering Design, Interpersonal skills, Engineering education.

I. Introduction

Project-based learning (PBL) in engineering education is an active learning approach in which students acquire skills and knowledge by working on projects, often in teams, to solve real problems contributed by industry or stakeholders [1]. PBL promotes student ownership of learning objectives through iterative design, prototyping, testing, and structured reflection, thereby fostering deep conceptual understanding and practical competence.

Previous studies have analyzed the benefits of PBL across different engineering courses throughout the curriculum, from freshman to senior years. Hadim and Esche found that PBL improved freshmen's motivation and interest, as projects provided practical demonstrations of real-life applications of their academic programs [2]. Sharma et al. observed that PBL helped students improve technical skills and teamwork by developing a mechanical engineering project in four steps: conceptualization, design, testing, and manufacturing [3]. Furthermore, PBL can also help engineering students develop a clearer understanding of the engineer's professional role and the methodologies used to address industry needs [1].

In this article, we investigate and contrast how several PBL experiences across the engineering curriculum promote the ability to apply engineering design to produce solutions that meet specific needs, the ability to communicate effectively with a variety of audiences, and the ability to function effectively in a team, which are required student outcomes according to the ABET accreditation criteria [4].

All engineering programs at the university have three main PBL experiences:

1) In the first semester, the students develop a bounded project to solve a problem using fundamental knowledge of their disciplines. The project is developed in teams and helps students connect their studies to real-world problem-solving and societal impact. The projects are presented to the academic community at the STEAM Challenge Fair.
2) During the second to fourth semesters, students develop Physics, Biology, or Chemistry projects that are presented at the Basic Science Fair.
3) In their senior year, students develop a major engineering design experience to propose a solution to the problem of the industry, a group, or a community. The projects are presented at the Engineering Projects Fairs to the academic community and stakeholders.

Science and Engineering Fairs are didactic strategies that use PBL as a fundamental learning method. They assume that higher-order psychological processes originated in interpersonal interaction before being internalized into intrapersonal processes. This conception, based on a developmental psychology closely associated with moderate constructivist currents, responds to the need to transform the traditional teaching-learning process into one that fosters significant learning through cognitive processes such as students' understanding and giving meaning to the scientific and technical knowledge they develop.

A limited understanding of the above precepts, together with insufficient solid pedagogical training among teaching staff, often leads science and engineering fairs to focus primarily on the presentation of prototypes, where the emphasis is placed on the final product rather than on the construction of scientific and technical knowledge (i.e. the processes of problem formulation, experimentation, and validation) thus reinforcing traditional educational approaches grounded in associationist and empiricist paradigms.

To address these risks, a process of continuous monitoring and teacher-student feedback is needed so that learners understand the scope and goals of participating in a fair, enabling them to actively engage in their learning.

The participation of students in science fairs allows the development of scientific and critical thinking skills through which learners face new realities that they must assimilate and accommodate in their cognitive structure in order to understand and transform them. By appropriating these competencies, students acquire essential skills to interpret and represent complex data, as well as to formulate and execute systematic procedures that involve the analysis, synthesis, and argumentation of physical and engineering phenomena. This process contributes to the acquisition of ABET student outcome 6 [4], which concerns the development of appropriate experimental methods and the drawing of informed conclusions through engineering judgment. Furthermore, this cognitive evolution is supported by the Model-Based Reasoning (MBR) framework [5], where students transition from purely descriptive observations in basic physics to the construction of predictive models in engineering design. By engaging in these practices, students cultivate what are defined as 'Engineering Habits of Mind', specifically the ability to iterate systems and visualize data patterns, thereby bridging the gap between fundamental scientific principles and the implementation of viable, high-impact technological solutions [6].

II. Methodology

The proposed approach is based on a spiral curriculum scheme [7] and on longitudinal analysis of PBL experiences from the first to the last year of engineering programs. The process begins with the STEAM challenge in the first semester and continues with the Basic Science Fair, which are strategies designed to provide early immersion in the engineering design process and the scientific method. In the last year, students design, implement, and validate an engineering product to solve a real problem, thereby integrating technical standards, economic viability, and engineering judgment. This transition can systematically assess the maturation of design, communication, and teamwork competencies throughout the student's academic life cycle.

A. STEAM Challenge

The first-semester project experience involves well-defined, bounded problems with open-ended solutions. The development of the projects relies on fundamental concepts (elementary mathematics, introductory physics, or basic design principles) and follows a guided design methodology that includes problem definition, idea generation, solution selection, basic prototyping, and simple testing. Prototypes should be low complexity (e.g., mock-ups, scale models, basic simulations, or conceptual tests), with the primary goal of understanding the engineering design process.

B. Science Fair

The Basic Science Fair is an annual event that promotes the dissemination and debate of scientific knowledge. It targets students in the basic cycle of engineering programs who take courses in Biology, Physics, and Chemistry. The purpose of the fair is to foster students' interest in scientific inquiry and practice, strengthen their critical thinking through questioning, analysis, and the explanation of scientific models, and enhance their research, communication, and argumentation skills through the application of the scientific method [8]. This is achieved through the development of course projects that demonstrate significant learning of the topics of the courses participating in the fair. The fair seeks to contribute to the development of social awareness and ethical responsibility, encouraging participants to address problems that benefit society and the environment. In this way, an approach oriented to sustainable development and positive impact on the community is promoted, for which projects must contribute to at least one Sustainable Development Goals [9]. The science fair also seeks to improve participants' attitudes towards science and scientific inquiry and to positively influence their technical, communication, and teamwork skills [10,11].

The projects are presented in the courses in groups, in three moments over the course's academic period (16 weeks). At each moment, the groups present a progress report, in which the development of experiments, prototyping, and models that confirm theories from the formulation of hypotheses is appreciated. In each presentation, the students report their progress using the rubric in Table I to receive feedback and guidance. In the last moment, the two best projects in each course are chosen to present at the Science fair.

In the first report of the project, students present a detailed description of their project, including objectives, theoretical framework, and methodology used. They must also provide a review of the relevant literature that supports their progress to date, including prototypes, preliminary results, and analyses conducted. For the second report, students implement the suggestions and corrections received in the initial evaluation of their project. They present an updated, improved version of the report, showing the adjustments made and further progress. The students finish their project and present the results and conclusions obtained. In addition, they prepare presentation materials, such as posters, demonstrations, or complete prototypes, for the fair. In this presentation, they will be asked to describe how they developed their proposal. The final report should include a description of the model used, an explanation of the prototype or experiment, detailed calculations, and a description of the relationship to the SDGs. An evaluator conducts a final review of the report to ensure that all the above recommendations have been implemented and that the project is ready for presentation at the fair. Students receive final approval to participate in the Science Fair event, where they will share their work with the academic community and the public. The projects presented at the event will be evaluated by a jury made up of at least two professors who will issue a concept for each project. For the evaluation, the jury will have the rubric to assign a score to the project (Table I).

TABLE I
RUBRIC FOR EVALUATING BASIC SCIENCE FAIR PROJECTS

Level of attainment	Expert	Advanced	Apprentice	Beginner	%
Description of the topic and variables	They identified the topic addressed in the project and clearly described how they developed it. They identify the variables involved in the project and define those that notoriously influence the result.	They identified the topic of the project discussed, but they do not clearly describe how they developed it. They identify the variables involved in the project, but do not define those that notoriously influence the result.	They did not identify the topic discussed, but described what was developed in the project. They identify some variables that intervene in the project and do not define those that notoriously influence the result.	They did not identify the topic dealt with or describe what was developed in the project. They do not identify or define the variables that notoriously influence the outcome of the project.	15
Description of the methodology	The methodology was described step by step with excellent explanations	The methodology was described step by step with a good explanation.	The methodology described was somewhat incomplete or in disarray.	The methodology was not described, and its explanations were deficient.	20
Development & results	They showed a lot of evidence of the development of the project. The information was summarized and clearly described what was discovered	They showed several evidence of the development of the project. The information was summarized and described what was discovered.	They showed some evidence of the project's development, but they do not clearly summarize what was discovered.	The data shown were scarce or difficult to summarize what was discovered.	20
Conclusion	The group provided a detailed conclusion, clearly based on the data and related to previous research.	The group provided a somewhat detailed, but clearly data-driven conclusion related to previous reference	The group provided a conclusion with some references to the data and previous references	The conclusion was obvious and important details were overlooked	15
Presentation & questions	In its presentation, the support for citations and bibliographic references is noted. All objects, diagrams, graphs, etc. were carefully labeled and correctly. They answered each question of the evaluator clearly and accurately.	In its presentation, the support for some citations and bibliographic references is noted. Most of the objects, diagrams, graphs, etc. were labeled correctly and carefully. They answered clearly to almost all the questions of the evaluator; few answers were not correct.	In its presentation, the support for very few citations and bibliographic references is noted. Few objects, diagrams, graphs, etc. were correctly labeled. They did not answer several questions from the evaluator, or their answers were not correct.	In its presentation, there is no support in citations and bibliographic references. The exhibition seemed incomplete or tangled and without a clear plan. Many labels were missing or incorrect. They were noted to be deficient in answering the evaluator's questions.	30

C. *Engineering Projects Fair*

Engineering students develop a major engineering design experience (engineering project) in which they integrate and apply the knowledge and skills acquired throughout their programs. The engineering project consists of the design, implementation, and validation of an engineering product: system, device, machine, component, structure, application, software, or process, to provide a solution to a real problem of the productive sector, public, a group, or a community.

The engineering project starts from a need and, with the stakeholders, a set of functional and non-functional requirements is defined that are validated by means of simulation tools, prototyping, and/or different tests such as laboratory, operational, functional, performance, quality, usability, in vitro, or in vivo tests.

This methodology requires students to develop engineering and design proposals that meet specific needs, while considering public health, safety, and well-being, as well as global, cultural, social, environmental, and economic factors. In this context, a series of preliminary activities is conducted at the beginning of each academic semester with local companies, social organizations, and faculty members leading ongoing research projects to support the development of engineering projects. The purpose of these activities is to identify and define real-world problems, as well as to establish the limitations and conditions of the projects to be developed, as shown in Fig. 1.

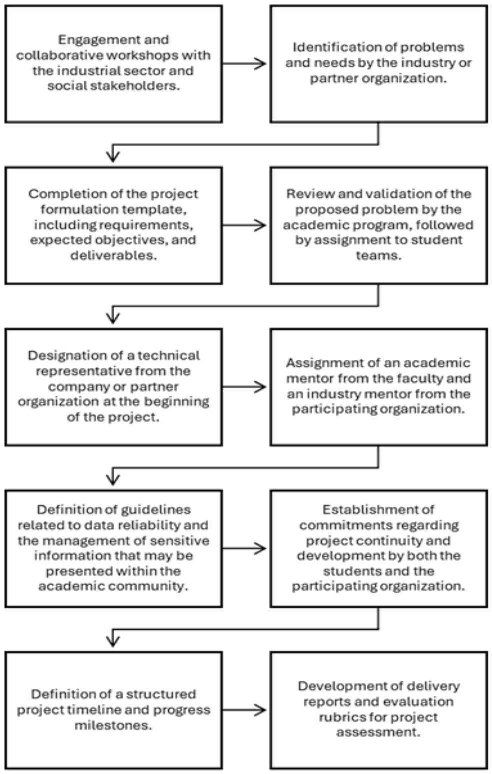

Fig. 1 . Activities to evaluate the relevance of engineering projects

The project is expected to take two semesters in the Engineering Project I and Engineering Project II courses, and it is recommended that it be developed in groups of two to four students, who may belong to different disciplines, depending on the project's requirements. These courses are in the eighth and ninth semesters of all the engineering plans of study.

Through the development of the engineering project, students will be required to demonstrate the achievement of the following student outcomes, aligned with the ABET accreditation model:

1) An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.
2) The ability to communicate effectively with a range of audiences.
3) The ability to function effectively on a team whose members together provide leadership, create a collaborative environment, establish goals, plan tasks, and meet objectives.

The engineering project covers a wide range of applications for each program, as shown next.

Environmental Engineering: The projects focus on sustainable water resource management and the strengthening of experimental capacities. There is a clear orientation toward circular economy principles, industrial effluent treatment, and practical training through pilot-scale systems applied to real industrial problems in Cartagena and Mamonal.

Biomedical Engineering: The projects address challenges related to clinical care, rehabilitation, and social inclusion. Innovative solutions based on artificial intelligence, additive manufacturing, and medical automation stand out, aiming to improve the quality of life of patients.

Electronic Engineering: The projects focus on the design and implementation of electronic systems applied to industrial and experimental environments. There is a strong interest in telecommunications, sensing and instrumentation, control, and laboratory platforms to strengthen practical competencies in applied electronics.

Systems Engineering: The projects demonstrate a strong orientation toward digital transformation and the use of artificial intelligence to solve social, educational, agricultural, and healthcare-related problems. Data analysis tools, process automation, and intelligent systems focused on decision-making support and child well-being stand out.

Civil Engineering: The projects respond to territorial and urban development needs in Cartagena and other regions of the Colombian Caribbean. Issues related to mobility, emergency response, airport infrastructure, and the strengthening of community and recreational spaces are addressed.

Chemical Engineering: The projects reflect a focus on sustainable chemistry and the use of biomass for environmental and industrial applications. Research efforts are directed toward the development of functional materials and contaminant removal technologies using natural resources.

Electrical Engineering: The projects demonstrate a strong commitment to energy transition and the use of clean energy sources. The proposals include rural electrification solutions, energy efficiency systems, and hydrogen generation, aligned with global sustainability trends.

Industrial Engineering: The projects show a strong orientation toward continuous improvement and organizational efficiency. The use of simulation, Lean Manufacturing, artificial intelligence, and predictive analytics is evident in optimizing industrial operations, logistics, maintenance, human resources, and customer service across different business sectors.

Naval Engineering: The projects are aimed at the sustainable development of Cartagena Bay through maritime mobility solutions, ecological tourism, and renewable energy systems. Conceptual designs of solar-powered vessels, floating platforms, and maritime waste management systems stand out.

Mechanical Engineering: The projects address issues related to automation, energy efficiency, and structural design.

There is a clear interest in emerging technologies such as multifunctional drones, wind turbines, and operational improvements in industrial and laboratory equipment.

Mechatronics Engineering: The projects integrate mechanics, electronics, and artificial intelligence to develop robotic solutions and intelligent devices. Applications in physical rehabilitation, residential energy analysis, autonomous robots, and robotic swarm systems for applied research stand out.

Overall, the projects reveal an institutional trend toward applied innovation, sustainability, and the use of emerging technologies to solve industrial and social problems, while also strengthening students' research and professional competencies.

The students defend their projects at the Engineering Fair, where they are evaluated by at least two jury members, considering different criteria for each learning outcome, as shown in Table II. The levels of attainment are: Excellent (5.0), Good (4.0), Fair (3.0), and Inadequate (2.0).

TABLE II
ASSESSMENT CRITERIA FOR ENGINEERING PROJECTS

Engineering design	Communication	Teamwork
• Problem definition • Effective design strategy • Viable and efficient design • Consideration of multiple alternatives • Consideration of multiple evaluation criteria • Consideration of engineering standards	• Technical and discipline-specific writing style appropriate for the target audience • Correct grammar and syntax • Organization of slides • Appropriate use of color, text, and graphics • Body language • Clarity of presentation	• Teamwork strategy • Collaborative and inclusive work environment • Effective task and goal planning • Goal achievement

III. RESULTS AND DISCUSSION

Fig. 2, 3, and 4 show students presenting their projects in the STEAM Challenge, Basic Science Fair, and Engineering Projects Fair. In these examples, an increase in the complexity of the projects and the maturity of the students can be observed.

Tables III and IV present the competency progression matrix and a longitudinal analysis of the attainment levels of three learning outcomes (Design, Teamwork, and Communication). The reported values correspond to the average project evaluation scores obtained during the 2022 Basic Science Fair and the 2025 Engineering Project Fair, which involved the same student cohort. The scientific fair event included mechanical physics (2nd semester), electrical physics (3rd semester), and heat and waves (4th semester).

The data in Table IV were organized by training competencies to identify systemic progression or gaps. It is observed that, in terms of design and teamwork, there is progression, but a gap in communication. This can go hand in hand with the fact that in the first semesters the rigor of professional technical writing is less than that of the end of the academic career.

The results for Projects I and II show that design capacity and teamwork progress from the basic to the professional cycle (due to technical complexity), while communicative competence does not seem to evolve. This is a curricular opportunity, which allows evolving from phenomenological to technical communication from the first to the last semesters of the degree.

Fig. 2 First-semester students presenting their projects in the STEAM Challenge.

Fig. 3 Projects presented in the Basic Science Fair

Fig. 4 Students presenting their Engineering Projects at the Fair.

TABLE III
COMPETENCY PROGRESSION MATRIX: PROGRESS IN DESIGN, COMMUNICATION, AND TEAMWORK THROUGH THE ACADEMIC ROUTE.

Skill	Science Fair (2nd-4th semester)	Engineering project (9th semester)	Diagnosis of the Trajectory (What happened?)
Design	3.75 - 4.50	4.20	Systemic Evolution: The student moves from the modeling of isolated physical phenomena to the integration of solutions under real constraints, achieving technical optimization in the final phase.
Teamwork	4.00 - 4.60	4.45	Operational Professionalization: A transition from collaboration by social affinity to management based on roles, milestones, and group resilience in the face of technical failure is observed.
Communication	4.30 - 3.95	4.27	Professional Maturation in Communication: Students progress from expressive presentations to structured, evidence-based technical discourse. Despite a slight mid-stage decline due to increased complexity, final performance demonstrates consolidation of professional standards in written and oral communication, with clearer argumentation, precise technical language, and audience awareness.

TABLE IV
LONGITUDINAL TRAJECTORY OF COMPETENCIES FROM FIRST TO LAST SEMESTER

Skill	Mechanical Physics	Electrical Physics	Physics Heat and Waves	Eng. Project I	Eng. Project II	Learning gain (Δ)
Design	3.75	4.05	4.50	4.09	4.20	+0.45
Team-work	4.00	4.25	4.60	4.34	4.45	+0.45
Communication	4.30	4.15	3.95	4.38	4.27	-0.03

In addition, when analyzing the results of the students across their academic trajectory, it was observed that students who participate in fairs of more advanced semesters (heat and waves, 4th semester) present a greater robustness in the Engineering project compared to those who only participated in initial fairs (mechanics, 2nd semester). This suggests that iteratively applying the scientific method over semesters builds technical memory that facilitates the acquisition of engineering design skills. Table V shows the main contributions of the strategy in the first and last semesters. The use of PBL, whose approach is characterized by promoting collaborative, constructive, self-directed, and contextual learning, shows great relevance in STEM domains, where the implementation of project-based experiences can strengthen the perception of usefulness, self-efficacy, and interest of students [12].

In STEM education, activities based on solving real problems are an important strategy for the development of professional competencies, as they allow the integration of existing limitations and the promotion of contextualized learning. Unlike traditional controlled projects, where the variables are usually delimited and the expected results can be predictable, the real problems require decision-making, evaluation of alternatives and technical justification considering social, environmental and economic factors [13].

TABLE V
MAIN CONTRIBUTIONS

Intervention	First semesters (STEAM challenge and Science fair) ¿What was gained?	Last semesters (Engineering Project I and II) ¿What Was Transformed?
Design	Technical synthesis capacity.	From academic to industrial.
Teamwork	Resilience and roles.	From social cooperation to milestone management.
Communication	Technical vocabulary	From oral eloquence to the rigor of the discipline.

PBL based on real problems favors the increase of motivation, critical thinking, and transfer of learning, due to the need to integrate constraints of engineering design. In addition, this type of project generates conditions closer to professional scenarios, strengthening transversal competencies such as collaborative work and communication with diverse audiences [14], [15]. In contrast, traditional controlled projects can be useful for reinforcing specific technical foundations, but they tend to limit the comprehensive development of competencies associated with contextualized design and decision-making in real-world actions.

In addition, a valuable outcome of final-year engineering projects is students' opportunity to incorporate these projects into their curriculum vitae, enabling them to perform more confidently in interviews for professional internships and jobs. Defending their final projects helps them develop stronger skills to address questions related to their field of practice as engineers.

The proposed incorporation of PBL at different points in the curriculum, with corresponding assessments of learning outcomes, has helped us identify the progression of essential skills in students during their undergraduate studies. However, our approach has several limitations. It was not possible to perform an individualized evaluation of all students participating in the three learning experiences, as students follow different academic trajectories, and cohorts do not progress at the same pace. In addition, the assessment instruments were not fully aligned to measure equivalent performance indicators across experiences. Future work should focus on reviewing and updating the assessment instruments in a more integrated and coherent manner, incorporating qualitative evidence and student perception data, as well as analyzing long-term outcomes such as knowledge retention and graduate employability.

IV. CONCLUSIONS

The results show that the proposed PBL approach including the projects' fairs, works within a spiral curriculum scheme, promoting the acquisition of technical and interpersonal skills in engineering students. Each intervention reinforces the structure of the scientific method, so that when they reach the professional cycle (Engineering Projects I and II), the students can apply a competence that has been consolidated through the years.

The students' performance in the final engineering cycle is directly influenced by the methodological accumulation effect derived from the previous academic route. Beyond the subject area of physics, the recurrence of project formats in the 1st, 2nd, 3rd, and 4th semesters serves as a reinforcement mechanism that consolidates engineering judgment.

Among the skills assessed in the three PBL experiences, improvements were observed in technical skills (engineering design) and teamwork. Regarding technical communication, although the scores showed a stable trend, communication skills progressed toward a more professional style, characterized by evidence-based argumentation and precise technical language.

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