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A comparative study of a new challenge-based learning model for engineering majors

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Current society needs professionals able to identify and collaboratively solve the main challenges of the 21st century. Students must be trained to face real challenges in their future workplaces and to acquire the necessary competencies to succeed in the current-day global world. As an answer to such needs, the Tecnologico de Monterrey launched in 2019 its competency-based *Tec21* educational model, emphasizing the development of disciplinary and transversal competencies using a challenge-based learning (CBL) model. The present contribution is aimed at measuring the effectiveness of this model compared to the more traditional previous learning (PL) model. We present a quasi-experimental study comparing the academic performance of 1705 freshman engineering students, 43% enrolled in the PL model and 57% enrolled in the CBL model. Although the CBL model was applied to all the institution's majors, the paper is focused on the freshman physics courses of the engineering majors. The study spans seven semesters, from Spring 2018 to Spring 2021. It was found that the overall student performance, measured by the average final course grades, improved by 9.4% in the CBL model compared to the PL model. On the other hand, the challenge average grades of the CBL model were like the project average grades of the PL model. Additionally, two-year opinion surveys about the CBL model were administered to 570 students. It was found that 71% of the students expressed a favorable perception of the CBL model in terms of their competencies development and their ability to solve problems. It is suggested that the explicit integration of physics, math, and computing concepts through the solution of real-life challenges in the CBL model bears a stronger student engagement and thus yields better general learning outcomes than the PL model.

KEYWORDS

challenge-based learning, competencies development, educational innovation, higher education, professional education, physics education

1 Introduction

The world is changing at such an accelerated rate that it is hard to cope with all the technological advancements and recent improvements in diverse areas as artificial intelligence, transportation, communication, entertainment, commerce, and other human activities that have dramatically shifted in the last decades (Chang et al., 2019; Roser, 2023; Wolff, 2021). However, education schemes in many institutions remain as more traditional teaching, in which students' academic performance is generally based on lectures and on final exams (Charytanowicz, 2023; Constante López, 2023; Galván Cardoso and Siado Ramos, 2021). To maintain its status as a world-class institution in educational innovation, *Tecnologico de Monterrey* launched in 2019 its competency-based *Tec21* educational model, which shifts the focus away from mere content acquisition by the student, aiming for a more comprehensive approach to learning. This change obeys the rapidly changing world in which the marketplace requires people who can work well under pressure to solve complex scenarios with efficient, low-cost and sustainable solutions (Tec 21, 2024). Nowadays, academic content is one click away, not to mention the boost given by artificial intelligence chatbots and other educational cutting-edge technologies. Therefore, the *Tec21* model goal is to cultivate student specific disciplinary and transversal competencies through a challenge-based learning approach, in which the students need to find out solutions to crafted ad-hoc challenges tailored to their semester and major. Some of these disciplinary engineering competencies include analysis and explanation of engineering systems, problem-solving, and critical thinking. On the other hand, some transversal competencies include collaborative work, digital literacy, and communication skills, which are fundamental skills needed in a globalized world (López-Guajardo et al., 2023; Tec 21, 2024).

The introduction of the Challenge-Based Learning (CBL) model at Tecnologico de Monterrey reflects a transformative approach to education, designed to prepare students for the demands of an increasingly complex and interconnected world. In recent years, higher education institutions worldwide have recognized the necessity of moving beyond traditional content-delivery, toward innovative models that emphasize active learning, collaboration, and real-world and practical application of knowledge. This shift aligns with trends such as Education 4.0, which prioritizes interdisciplinary learning and the integration of technology, including artificial intelligence, to enhance student outcomes (Doulougeri et al., 2022; Membrillo-Hernández et al., 2019). By adopting the CBL model, Tecnologico de Monterrey positions itself at the forefront of educational innovation in Latin America, addressing both the demands of the global job market and preparing students to tackle our context's unique challenges.

Although many of the competencies that students are expected to acquire in both PL and CBL are common, such as problem solving, communication and collaborative work, critical thinking and creativity are emphasized in CBL. On the other hand, the opportunity to address challenges that solve real problems of companies or organizations provides the students with an interaction between academic content and its practical application, resulting in a deeper understanding of the acquired knowledge (Gaskins et al., 2015).

Comparing the newly implemented CBL model with the previous learning (PL) model, used at our institution before August 2019, is therefore essential to validate its efficacy, to identify areas for improvement, and to provide evidence-based insights into how pedagogical strategies influence student learning outcomes and competency development. Moreover, as educational methodologies evolve to address the rapid pace of technological advancement and societal needs, understanding the strengths and limitations of each model becomes a critical step in ensuring the relevance and sustainability of new approaches. Evaluating these models not only benefits the institution but also contributes to the broader academic discourse on best practices in engineering education (Alvarez et al., 2024; Johnson et al., 2009). The findings of this study may suggest future enhancements to the CBL model and support its potential adoption in other institutions seeking to innovate their curricula.

Consequently, the objectives of the present research are (a) to describe the main components of the CBL model and its implementation with freshman engineering students of the School of Engineering and Science of the Tecnologico de Monterrey, and (b) to assesses the suitability of the CBL model by comparing the average grades and performance of students enrolled in the CBL and PL models by means of (i) final exam grades, (ii) challenge and project report grades, and (iii) final course grades. The assessment of the level of development of disciplinary and transverse competencies by the students in the CBL model will be addressed as future work.

Therefore, the research questions of this study are:

(a) What are the advantages and disadvantages of the CBL model compared to the PL model?
(b) How does the CBL model compare with the PL model in terms of students' academic outcomes considering (i) final exam grades, (ii) project and challenge report grades, and (iii) final course grades?
(c) What are the students' perceptions about the CBL model regarding their development of competencies and problem-solving skills?

The paper is structured as follows: Section 2 presents the theoretical framework, and Section 3 includes related work. Section 4 presents the implementation of the CBL and PL models as well as the methodology employed. The experimental design is highlighted in Section 5. The main results and analysis are presented in Section 6. Section 7 presents a general discussion of the results, and finally, Section 8 presents the main conclusions and outlines the related future work.

2 Theoretical framework

Developed at Vanderbilt University through a collaboration among bioengineering researchers, pedagogues, and technologists, the CBL methodology was intended to address authentic, real-life situations, shifting away from pure-abstract problem solving (Johnson et al., 2009). Educational modules, focusing on the learner, knowledge, assessment, and community, were envisioned to actively engage students by integrating multidisciplinary learning modules with *real-life* challenges, thus fostering the development of key competencies (Birol et al., 2002).

In the context of Education 4.0, CBL is an active-learning methodology that encourages students to tackle both local and global issues using collaborative and technology-driven approaches. This process promotes the development of various competencies essential for success in the professional arena, including problem-solving, critical thinking, and digital literacy (Alvarez et al., 2024; Membrillo-Hernández et al., 2018; Vázquez-Villegas et al., 2022). Key features of CBL experiences encompass immersion in relevant cultural and societal contexts, flexibility in format and subject matter, and collaboration with training partners who are expected to provide insightful feedback to the students during the process. Professors assume thus a mentorship role, guiding students in integrating academic content into practical solutions for the challenges they encounter (Doulougeri et al., 2022; López et al., 2021; Membrillo-Hernández et al., 2019).

The main differences between CBL and other successful methodologies such as Project-Based Learning and Problem-Based Learning (De Graaff and Kolmos, 2003; Savery, 2015) are (a) even though the students need to research the solution of the problem at hand, in CBL there are not predefined steps that need to be followed to obtain the solution, (b) the CBL scenarios are related as much as possible to real problematic situations of the community or global issues, therefore motivating the student, and (c) in the CBL model, the figure of training partners from external companies involved in the process give formality and rigor to the proposed solutions (Membrillo-Hernández et al., 2019). On the other hand, common aspects among the three techniques are that the students (a) must learn the basic academic contents, (b) engage in the learning process, and (c) learn how to work in a collaborative environment.

In summary, CBL is a student-centered approach to learning that emphasizes real-world challenges, interdisciplinary collaboration, and the development of essential competencies crucial for success in today's complex society (Tec 21, 2024; Vilalta-Perdomo et al., 2022).

3 Related work

Various CBL initiatives worldwide showcase its versatile application across diverse educational settings and subjects. For instance, collaboration between Apple and high school educators replaced simple projects with real-world challenges, leveraging technology to improve water consumption and air quality (Nichols and Cator, 2008). Similarly, in response to the Flint water crisis in Michigan, educators across districts employed CBL to deeply engage students in behavioral, cognitive, and emotional dimensions (Mebert et al., 2020). Moreover, Brock et al. (2008) revamped a water treatment course, integrating an industry partner to ground CBL activities, resulting in students surpassing expectations by acquiring workplace-relevant competencies. However, Leijon et al. (2021) argued that a scientific-grounded approach toward learning must be addressed when implementing CBL in higher education.

Regarding the application of CBL in engineering, Taconis and Bekker (2023) highlight how CBL can create an authentic learning environment, enhancing STEM identity among students, and emphasizing the integration of real-world challenges to foster a deeper connection between academic learning and social impact. An example of CBL applied to agriculture has been given by Poudel et al. (2005) who highlight its interrelation with environmental issues, where the complexity of the problems demands creativity and innovation. CBL has also been incorporated in dental education (Nizami et al., 2023) as well as in forensic medicine and nursing (Eraña-Rojas et al., 2019; Tang and Chow, 2020). Furthermore, collaborations between academic institutions and external organizations, such as the Mexican State Institute of Forensic Sciences, have enabled students to work on multidisciplinary challenges, broadening their perspectives and enhancing their learning experience (Eraña-Rojas et al., 2019).

CBL has also been implemented in cybersecurity (Cheung et al., 2011), where these authors reported that students showed improvement in their computer and security skills, interest in learning about security, and the ability to teach others. In the business contexts in higher education, the implementation of CBL along with a design-thinking methodology has been described by Romero Caballero et al. (2024), who found an improvement of 55% of students' generic competencies compared to previous periods when the strategy was not implemented.

At Tecnologico de Monterrey, examples of CBL initiatives include projects like the *Axolotl* challenge (Vázquez-Villegas et al., 2022), in which students addressed biodiversity conservation issues through engineering solutions. Additionally, the multidisciplinary *Borregos Team* reports the implementation of a challenge about the design of sustainable components for electric vehicles, fostering innovation and entrepreneurship (López et al., 2021).

Preliminary work on the effectiveness of the Tec 21 CBL model vs. the PL model at the Tecnologico de Monterrey for junior engineering students enrolled in electricity and magnetism courses has been presented by Robledo-Rella et al. (2022). These authors report that students in CBL-based courses obtained 3–7% higher final average grades as compared to the PL courses and discuss possible explanations for this result.

4 Methodology

4.1 Previous learning model

The previous learning (PL) model implemented at Tecnologico de Monterrey prior to the Fall 2019 term adhered to a more traditional educational approach, supplemented with some inquiry-based active learning methodologies such as Problem-Based Learning (PBL) (De Graaff and Kolmos, 2003; Savery, 2015). The common-core physics courses for freshman engineering students, delivered across the first three semesters, included: (a) *Physics I*, covering foundational topics in classical mechanics (first semester); (b) *Physics II*, addressing fluids, waves, and thermodynamics (second semester); and (c) *Electricity and Magnetism* (third semester). Each course consisted of 50 h of lecture-based instruction and 15 h of laboratory sessions, distributed over a 16-week period. In addition to lectures, approximately 80% of these courses incorporated two projects, each lasting one to 2 weeks, utilizing the PBL methodology, while the remaining 20% of the courses featured projects focused on research or the investigation of specific course-related topics. Laboratory sessions typically involved standard experiments conducted according to provided guidelines. Course evaluation was based on: (a) two mid-term exams, (b) a final exam, (c) course projects, (d) individual or collaborative homework and class assignments, and (e) laboratory reports. The exams were primarily designed to assess students' mastery of course content and specific problem-solving skills.

However, starting in the Fall 2019, the institution changed its whole educational paradigm adopting a new competency-based approach implemented though a challenge-based learning (CBL) model. With this new methodology, the students develop disciplinary and transverse competences, besides the theoretical concepts while addressing more problematic and realistic scenarios.

4.2 Challenge-based learning model and course description

The *Tec21* educational model for undergraduate engineering students at Tecnologico de Monterrey is characterized by a small number of academic entries and several potential graduation outputs. Incoming engineering students have the option to pursue any of the following four academic avenues: (a) Bioengineering and Chemical

Processes (BIO), (b) Innovation and Transformation (IIT), (c) Computing Sciences and Information technologies (ITC), and (d) Applied Sciences (ICI) (Tec 21, 2024).

One notable characteristic of this model is its *flexibility*. During the initial two semesters of the *Exploration stage*, students can take foundational courses across different avenues. The challenges associated with the courses during this initial stage are more oriented to the development of basic problem-solving strategies, initial research competencies, and to promote proficiency in utilizing computational software to model systems and analyze results. Therefore, the freshman physics courses are meant to give the students the required background of physics, mathematics and computing skills for their forthcoming engineering courses.

Along their major, students are required to develop several specific *competencies* according to each major, at three different increasing complexity levels: *A*, *B*, and *C*. These competencies are distributed across the eight semesters comprising the duration of the programs, and are divided into *disciplinary competencies*, directly associated with the academic content, and *transversal competencies*, applicable to all majors.

During the first year, each semester is divided into three periods, each lasting 5 weeks. In each period, students enroll in three courses each requiring 4 h of study per week, and one course requiring 12 h per week, called "*block*," lectured by two or more professors. In the blocks, physics, mathematics and computing concepts are integrated through the development of the associated challenge or problematic situation (scenario). The fundamental structure of the CBL model involves guiding students through the resolution of an assigned *ad hoc* challenge, which is a complex pedagogical given that its solution requires the application of as many academic concepts as possible, as outlined in the block's institutional analytic program.

The first period of the first semester starts with an introductory block, called *F1001B Modeling in Engineering and Science*, in which students are given a brief introduction to the different avenues (BIO, IIT, ITC, and ICI), and at the same time, they review basic Physics, Mathematics and Computing concepts (vectors, kinematics, statics, dynamics, algebra and initial *Matlab* commands). A preliminary analysis of student performance and competency acquisition for this introductory course was presented by Neri et al. (2020).

In each first-year *block*, the students work 12 h per week during 5 weeks, for a total of 60 h. Each block contains a *Physics* component (70%), a *Math* component (15%), a *Computing* component (15%), and a "*Challenge*" component, covered mostly throughout the physics academic contents. The course is usually taught by two to four professors, specialized in Physics, Math, and/or Computing Science. This multi-professor structure of the CBL model is a key characteristic of the *Tec21* model and requires close collaboration among the professors to define the challenge's solution, its extension, and the deliverables.

The distribution of activities throughout the 12 h per week is as follows:

(a) the physics professor presents the students with the main course physics concepts, using active learning strategies in the classroom and allowing the students to address *ad hoc* examples aimed to understand the main concepts related to the challenge, working both individually and in small groups. The tools used for these weekly assignments include online exercises using our LMS (Canvas) and web platforms (such as WebAssign or Wolfram Alpha), online simulators (e.g., Colorado's *PheT*), online tailored quizzes (e.g., *Quizizz* or *Socrative*) or active videos (e.g., *Edpuzzle*).

(b) The professor in charge of the challenge guides the students through a discipline-based approach to solve the assigned challenge. Usually, there are two deliverables; the first one is due during the third week, in which the student poses the problem, understands the theoretical framework, proposes a solution path, and collect the data. The second deliverable, the challenge Report, is delivered in the fifth week of the course, when the students present their main final findings and challenge conclusions through an oral presentation/interview. The interviews are individual and take about eight to 10 min per student, where the professor poses questions regarding either the course content or the challenge to complement judging the student's performance. On occasions, an auto- and co-evaluation format is also administered to the team members, to differentiate each members' contribution to the solution of the challenge and the elaboration of the final report.

(c) The math-and-computing-science professor gives the students the basic mathematical and computational skills needed to model the challenge's physical situation. The preferred programming software is *Matlab*, although Python or other programming languages are also considered, especially for the ITC or ICI avenues. The incorporation of a computing component in the courses is another important contribution of the CBL educational model since this initiates the students to develop a programmer perspective by applying computing tools and algorithms to model and interpret a physical problematic situation.

4.3 Example of a challenge-based learning scenario

CBL is a powerful tool since it motivates the students through the application of the concepts and physical laws discussed in the course to the formal solution of a "real problematic scenario." In this manner, physics and math formulae are no longer abstract isolated items but they take meaning when they are applied to a first-hand practical solution that the students can understand (Johnson et al., 2009).

An example of a challenge implemented in the second period of the first semester in the *F1004B Computational modeling of motion* block for ICT students is presented next. The block's main academic content includes vectors, kinematics in 1D and 2D, particle dynamics, and frictional forces. Therefore, a useful challenge scenario requires to analyze the risk of an (assumed) population close to an active volcano (as is the case for small towns around the *Popocatépetl* volcano near Mexico City). To solve the challenge, the students must build a computer simulation to model the motion of different projectiles thrown by the volcano, considering air-resistance and different initial conditions such as speed, angle, altitude, projectile size, shape, and drag coefficient. To have a more realistic simulation, the students are asked to model the orographic surface surrounding the volcano to find the landing position, impact velocity and released energy of the ejecta. After analyzing the results, the students have more elements to give sound advice to the local authorities about the minimum-secure distance of the settlements around the volcano.

5 Experimental design

The processes of the experimental design for comparing the PL versus CBL models are described below.

5.1 CBL model during the pandemic

The CBL model was fully deployed by the Tecnologico de Monterrey during the Fall 2019 term, along its 26 campuses all over the country. The Spring 2020 semester began in February 2020, and the pandemic arose in Mexico in March 2020, so having only one semester of experience in face-to-face instruction, all activities had to transition online. Online instruction was not unfamiliar to our faculty and students at our Mexico City Campus, since all teachers were fully trained in online solutions back in 2017, during the aftermath of a major earthquake that strained the facilities of the campus.

Throughout the pandemic, CBL challenges of physics courses relied increasingly on simulations and the creativity of the professors. Subjects like electric or magnetic courses, with abstract content, were especially difficult to grasp during the pandemic, and simulators were therefore used to explain these concepts. Other courses, such as the fluids and the thermodynamic blocks were more easily handled online, where relatively simple homemade simulated challenges were proposed and that, surprisingly, often surpassed expectations. On the downside, human interaction during this period was greatly missed as well as the benefit of enjoying the campus facilities. The impact on the pandemic on CBL-based courses for freshman engineering students has been reported by García-Castelán et al. (2021) and by Robledo-Rella et al. (2022).

5.2 PL and CBL course comparison

The contents of the former physics courses of the PL model were distributed in different *blocks* in the CBL model. The topics covered in the former *Physics I* course were divided into two parts: (a) a *Modeling Motion block* in which vectors, kinematics 1D, 2D, circular motion (for some avenues), and dynamics were studied, and (b) a *Conservation Laws block* comprising work, potential energy, conservation of energy, conservation of linear momentum, and fluids (for some avenues). The thermodynamics and waves contents of the former *Physics II* course were transferred to a *Thermodynamics block*. Finally, the traditional Electricity and Magnetism course of the PL model (*Physics III*) was naturally divided into an *Electricity block* and a *Magnetism block*. Table 1 shows the different courses, disciplines, and course content covered in the PL and CBL courses discussed in this work. In the CBL part of Table 1, the main goal of some examples of the challenges worked by the students for each theme is also indicated. These challenges were carefully selected both to cover the main topics of the course and to exemplify a realistic situation that can be built and analyzed by the students, and in which they see direct application of the course content to a particular problem relevant for STEM areas (e.g., Damped oscillations, RC circuits, or a Magnetic break).

The main difference between the PL and CBL models is that PL courses were mostly based on academic content, even though a project was worked out, while the CBL courses are mainly based on competencies development through the solution of a challenge. The academic content is still at the core of both models, but the competencies are intentionally evaluated in the CBL model. As mentioned above, the assigned projects in about 80% of the PL courses were based on the Problem-Based Learning methodology (PBL), while the remaining 20% of the cases included research essays or short experiments. They were typically performed within one to 2 weeks. On the other hand, the challenges in the CBL model explicitly integrate physics, math, and computing concepts (including numerical methods with *Matlab* or Python) in real-life scenarios and are performed along the 5 weeks that last the block.

As mentioned above, in the CBL model, the final week of each block is used for competency evaluation through an argumentative exam, the challenge solution report, and a team or individual oral presentation. The argumentative exam demands the student to show an overall understanding of the course's main concepts and the challenge solution.

The CBL challenges can be compared with previous PBL projects worked in the PL model because both strategies follow an inquiry-based methodology, in which students work collaboratively in teams to solve the challenge or the project. Nevertheless, there are important differences such as (a) knowledge is intentionally blended in the CBL approach and competencies are also evaluated, while the PL model projects were more limited to traditional physics contents, (b) in the CBL model the challenge is explicitly tailored according to the student *entrance avenue* (BIO, ICT, IIS, and ICI), while projects in the PL model were the same for all careers, and (c) a team of two to four professors enriches the different points of view of the challenge solution in the CBL model, as compared to only one professor in the PL model.

In what follows, the analyses are divided into three main disciplines (a) mechanics (including motion and conservation laws), (b) fluids, waves, and thermodynamics, and (c) electricity and magnetism.

The comparison of the total time dedicated to the different topics in the PL and CBL courses (Table 1) is as follow: (a) The mechanics topics (excluding fluids) have 70 h in the CBL model (50 h for physics and 20 h for the challenge) in the Modeling Motion and Conservations laws blocks, as compared to the 65 h allocated in the Physics I course of the PL model, (b) the fluids, thermodynamics, and waves topics have 50 h in the CBL model (10 h for fluids in the Conservation Law blocks and 40 h in the Thermodynamics blocks) as compared to the 65 h allocated in the Physics II course of the PL model, and (c) the electricity and magnetism topics have 80 h in the CBL model (40 h for the Electricity blocks and 40 h for the Magnetism blocks), as compared to the 65 h allocated in the Electricity & Magnetism course of the PL model.

5.3 Student and course database

This work presents a quasi-experimental study that presents the analysis of the performance of $N = 1705$ freshmen students from the PL and CBL educational models. For the PL sample, three terms were considered: Spring 2018 (18-I), Fall 2018 (18-II), and Spring 2019 (19-I), with $N_{\mathrm{PL}} = 741$ students enrolled in 30 sections. For the CBL sample, four terms were considered: Fall 2019 (19-II), Spring 2020 (20-I), Fall 2020 (20-II), and Spring 2021 (21-I), with $N_{\mathrm{CBL}} = 964$ students in 38 sections.

TABLE 1 Names, topics, and content for PL courses and CBL blocks.

Previous Learning (PL) Model		
Course code and course name *	**Theme and Topic ****	**Course content**
F1002 Physics I	*Mech*	Vectors, kinematics 1D, kinematics 2D, circular kinematics, linear and circular dynamics, conservation of energy, conservation of linear momentum, rotational dynamics
F1003 Physics II	*Flu, Wav, Ther*	Hydrostatics, hydrodynamics, oscillations, waves, sound, temperature, ideal gasses, heat and calorimetry, thermodynamic processes
F1005 Electricity & Magnetism (Physics III)	*Elec, Mag*	Electric forces and fields, Gauss' law, electric potential, capacitors, resistors, circuits, magnetic force, sources of magnetic fields, Biot-Savart's law, Ampere's law, Faraday's law, inductance.

Challenge-Based Learning (CBL) Model		
Block code (Avenue) and Block name *	**Theme and Topic ****	**Block content and challenge examples**
• F1002B (BIO) Motion modeling in Bioengineering and chemical processes • F1004B (ICT) Computational modeling of movement • F1006B (IIT) Modeling of movement in engineering • F1008B (ICI) Modeling of movement in science	*Mech*	Content: Vectors, kinematics 1D, kinematics 2D, circular kinematics, linear and circular dynamics Challenge examples: *Kinematic simulation of projectile motion with drag* *Dynamics analysis of an elevator* *Simple harmonic motion and Damped oscillations*
• F1003B (BIO) Application of conservation laws in process engineering • F1005B (ICT) Computational modeling applying conservation laws • F1007B (IIT) Application of conservation laws in engineering systems	*Mech*	Content: Conservation of energy, conservation of linear momentum, hydrostatics, hydrodynamics Challenge examples: *Analysis of elastic and inelastic collisions in 1D* *Analysis of elastic and inelastic collisions in 2D* *Building, analysis, and simulation of a rocket launch*
• F1015B (IIT) Thermodynamics applications in engineering systems • F1018B (ICI) Application of thermodynamics in science	*Ther*	Content: Temperature, ideal gasses, heat and calorimetry, thermodynamic processes, waves Challenge examples: *Analysis and simulation of passive cooling* *Building and analysis of a Stirling machine*
• F1013B (ICT) Computational modeling of electric systems • F1016B (IIT) Electric system analysis in engineering systems • F1019B (ICI) Electric systems analysis in science	*Elec*	Content: Electric forces and fields, Gauss' law, electric potential, capacitors, resistors, Circuits, RC Circuits, RLC Circuits Challenge examples: *Modeling of an electric dipole using superposition* *Analysis and modeling of a RC circuit*
• F1012B (BIO) Electromagnetic systems analysis in processes engineering • F1014B (ICT) Computational modeling of electromagnetic systems • F1017B (IIT) Electromagnetic systems analysis in engineering systems	*Mag*	Content: Magnetic force, sources of magnetic fields, Biot-Savart's law, Ampere's law, Faraday's law Challenge examples: *Analysis and modeling of a magnetic brake* *Building, analysis and modeling of a linear magnetic motor*

*In the CBL model, there are four different blocks (one per avenue) for each period with the same course content. The difference is that the assigned challenge is tailored to the student major.
** Mech, mechanics; Flu, fluids, Wav, waves, Ther, thermodynamics; Elec, electricity; Mag, magnetism.

5.4 Student performance indicators

The evaluation plans of the PL and CBL models for the selected physics courses are presented in Table 2, including the weights of each activity for each model.

It is worth mentioning that the argumentative final exam in the CBL model comprises four components: (a) the *physics section,* covering general concepts addressed during the course, particularly those related to the challenge solution, (b) the *math section*, focusing on the mathematics taught during the course and applied to the challenge solution, (c) the *computing section*, concerning the algorithms and methods employed to solve and analyze the challenge, and (d) the *avenue section*, pertaining to the applications of the assigned challenge.

The list of themes, topics, and acronyms considered in both PL and CBL models is presented in Table 3. The specific topics covered in the PL and in the CBL models are included in Tables 4–6 below.

To measure student performance for both models, the following indicators were selected: (a) midterm exam grades, (b) final exam

TABLE 2 PL and CBL evaluation activities and weights for freshman physics courses of engineering majors.

PL courses		CBL blocks	
Physics I (mechanics), *Physics II* (fluids, waves, and thermodynamics), *Physics III* (electricity and magnetism)		*Motion modeling; conservation laws,* *Fluids and thermodynamics.* *Electricity; Magnetism*	
First midterm exam Second midterm exam Homework assignments	20% 20% 10%	Physics, math, and computing assignments (software), in-class activities and homework assignments	40%
Final exam	25%	Written argumentative exam (physics, math, and software computing)	30%
Project report (total)	10%	Challenge report	15%
Laboratory	15%	Team oral presentation	15%
Final course grade	100%	Final course grade	100%

TABLE 3 Themes and topics used for the PL and CBL models.

Theme	Acronym	Topic	Theme	Acronym	Topic
Vectors	*Vec*	Vectors	Thermodynamics	*Ther*	Temperature
Kinematics	*Kin*	1D			Calorimetry
		2D projectile motion			Gasses
		2D circular motion			First law of thermodynamics
Dynamics	*Dyn*	Linear dynamics			Thermodynamic processes
		Circular dynamics	Electricity	*Elec*	Charge and electric field
		Rotational dynamics (rigid body; rolling; angular momentum)			Gauss law
		Equilibrium			Electric potential
Energy	*Ene*	Work			Capacitance
		Conservation of energy			Electric circuits (RC, RLC)
Linear momentum	*Lin mom*	Conservation of linear momentum	Magnetism	*Mag*	Magnetic force & torque
Fluids	*Flu*	Hydrostatics			Sources of magnetic field (Biot-Savart and Ampere's laws)
		Hydrodynamics			EM Induction (Faraday's law)
Waves	*Wav*	Waves/Oscillations			Inductance
		Sound			
		Superposition			

grades, (c) final course grades, and (d) challenge (or project) report grades. It is important to mention that this study was performed according to the institutional research ethics guidelines of Tecnologico de Monterrey, that specify that studies based on aggregated student grades that do not include personally identifiable information do not require formal ethical approval or specific consent procedures.

For hypothesis testing, Welch's t-test was used (Welch, 1951), which does not assume equality of variances between populations. The assumption of normality is valid given that the sample sizes are sufficiently large. Sample means for grades obtained in each model and variances were calculated using the usual formulas for pooled data. Welch's t-test was selected as it is particularly robust for comparing means between two independent groups when the assumption of equal variances may not hold. This test is appropriate for our study due to potential differences in variance between the PL and CBL models, which could arise from variations in instructional methods, assessment formats, or sample sizes. By using Welch's t-test, we ensure the validity of our comparisons even in the presence of unequal variances. The test statistics were calculated using:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

and the number of degrees of freedom (d.f.) using:

TABLE 4 PL and CBL average grades comparison for mechanics topics.

PL				CBL			
Activity topics	N_S (*)	N (*)	Average grade	Activity topics	N_S (*)	N (*)	Average grade
Kinematics Midterm exam 1 *Vec; 1D Kin; 2D Kin*	11	306	68.6	Kinematics Argumentative physics exam *2D Kin*	4	88	75.5
				Argumentative total exam 2D Kin	4	88	75.6
Final exam *Vec; 1D and 2D Kin; Dyn; Ene; Lin mom; Rot Dyn; Equi*	11	306	62.8	Argumentative physics exam *1D and 2D Kin; Dyn; Ene; Lin mom; Rot Dyn*	13	351	62.9
				Argumentative total exam *Physics: 1D and 2D Kin; Dyn; Ene; Lin mom; Rot Dyn* *Math:* 1D Calculus *Computing:* Matlab; numerical integration	13	351	78.5
PL Project	11	306	89.6	CBL Challenge	13	351	93.5
Final course grade Physics weekly assignments Midterm and final exams Laboratory PL projects report	11	306	77.0	Final course grade Physics, math, and computing assignments Final argumentative exam Oral presentation Challenge report	13	351	85.7

(*) N_S: number of sections; N: number of students.

TABLE 5 PL and CBL average grades comparison for fluids and thermodynamics topics.

PL				CBL			
Activity topics	N_S (*)	N (*)	Average grade	Activity topics	N_S (*)	N (*)	Average grade
Midterm exam 1 *Flu*	9	230	63.8	Argumentative physics exam *Flu*	4	119	67.5
				Argumentative total exam *Flu, Math, Comp*	4	119	73.7
Final exam *Flu, Wav, Ther*	9	230	64.3	Argumentative physics exam *Ther*	5	126	76.9
				Argumentative total exam *Ther, Math, Comp*	5	126	82.1
PL project 1 *Flu*	6	154	94.1	Challenge *Flu*	4	119	87.1
PL project 2 *Ther*	6	159	95.4	Challenge *Ther*	5	126	92.6
Final course grade *Flu, Wav, Ther*	9	230	78.3	Final course grade *Flu, Ther, Math, Comp*	9	245	87.2

(*) N_S: number of sections; N: number of students.

TABLE 6 PL and CBL average grades comparison for electricity and magnetism topics.

PL				CBL			
Activity topics	N_S (*)	N (*)	Average grade	Activity topics	N_S (*)	N (*)	Average grade
Average midterm exam 1 and midterm exam 2 *Elec*	10	205	79.1	Argumentative physis exam *Elec*	8	192	82.8
				Argumentative total exam *Elec, Math, Computing*	8	192	83.2
Final exam *Elect, Mag*	10	205	61.4	Argumentative phys exam *Mag*	7	180	83.9
				Argumentative total exam *Mag, Math, Computing*	7	180	87.1
PL Project 1 *Elec*	8	161	95.5	Challenge *Elec*	8	192	93.1
PL Project 2 *Mag*	12	249	94.1	Challenge *Mag*	7	180	91.9
Final course grade *Elec, Mag*	10	205	84.9	Final course grade *Elec, Mag, Math, Computing*	15	372	89.9

(*) N_S: number of sections; N: number of students.

$$d.f. = \frac{\left(s_1^2/n_1 + s_2^2/n_2\right)^2}{\left(s_1^2/n_1\right)^2/\left(n_1-1\right)+\left(s_2^2/n_2\right)^2/\left(n_2-1\right)},$$

where n_1 and n_2 are the sample sizes of the two populations, respectively; $\overline{X}_1$ and $\overline{X}_2$ are their means and s_1 and s_2 are their corresponding sample variances.

6 Results and analysis

The comparison among the PL and CBL selected courses is given below.

6.1 Classical mechanics comparison

In this section, a comparison of the PL and CBL grades for different topics of the mechanic courses is presented. The weighted average grades for all mechanic courses in each model are included in Table A1 of the Appendix. The *modality* indicates whether the course was given face-to-face (F2F) or online. For the PL model, both midterm exam 1 and midterm exam 2 grades are given. Likewise, for the PL model, the grades for the two projects (Project 1 and Project 2) are given, along with their corresponding topics (Table 3 above).

For a meaningful comparison between PL and CBL courses, it is necessary to consider similar topics covered in both models, as different courses within the two models may encompass somewhat different topics. Therefore, in what follows we will compare only similar themes and topics covered in each model. Although a comparison for specific physics topics could not be made, the Physics I content of the PL courses is like the classical mechanics contents of the two CBL blocks during the first semester (see Table A1 in the Appendix).

In Table 4, a detailed comparison of the PL and CBL grades for the mechanics topics is presented. It includes (a) the average exam grades for the kinematics topics only, (b) the average final exam grades for all the physics topics covered in the courses, (c) the average PL project grades and average CBL challenge grades, and (d) the final course grades. For the CBL model, it is presented both the argumentative physics-only exam grade and the argumentative total exam grades (which includes the physics, math, and computing parts). This CBL total argumentative exam is more focused on assessing procedures and reasoning, while the PL final *Physics I* exam gave more emphasis to numerical results. Table 4 also presents the number of sections (N_S) and the number of students (N) considered to compute the average grades for both models. Note that the number of students used to calculate the average grades for the PL and CBL models is different since the models consider different students (the PL model ran before Fall 2019 and the CBL ran from Fall 2019 onwards).

Notice also that the PL project average grades and the CBL challenge average grades presented in Table 4 refer to the common topics between *both* models. Finally, the PL and CBL final course grades for equivalent courses are presented, including the main activities considered in each evaluation: midterm and final exams, weekly homework and in-class assignments, labs, oral presentations, and project or challenge solution (see also Table 3).

For mechanics, the PL model kinematics midterm exam average grade (68.6) was lower than the corresponding CBL kinematics argumentative exam (75.5). However, the PL final exam average grade (62.8) was like that of the CBL physics argumentative exam (62.9). Regarding mechanics projects and challenges, the average PL project grade (89.6,) is somewhat smaller than the average CBL challenge grade (93.5). Overall, for classical mechanics contents the Final course grade was better for the CBL model (85.7) than for the PL model (77.0).

6.2 Fluids and thermodynamics comparison

This section presents a similar comparison between the PL and CBL grades for courses and blocks regarding fluids and thermodynamics topics. As before, the comparison is focused on (a) midterm and final exam grades, (b) PL projects or CBL challenge grades, either for fluids or thermodynamics contents, and (c) final course grades. As with the mechanics section, Table A2 in the appendix shows the whole data for the PL and CBL courses, while Table 5 below summarizes them.

For the PL courses, the first midterm exam contained fluid-topics only, while the final exam covered fluids, waves, and thermodynamics, so the final grade for these PL courses covered all these three topics. Regarding the PL projects, some of them covered fluids, waves, or thermodynamics as indicated in Table A2.

As can be seen in Table A2, some of the CBL blocks are focused on fluids topics (e.g., F1007B) while others are focused on thermodynamics topics (e.g., F1015B), so the comparison between PL courses and CBL blocks presented in Table 5 considers only courses and blocks with similar content. That is, the midterm exam grades and the project grades for the PL courses are compared with the physics-only final argumentative exam and the PL projects are compared with the CBL challenges having similar topics.

For fluids and thermodynamics, the PL fluids midterm exam average grade (63.8) was lower than the corresponding CBL fluids argumentative exam (67.5), covering the same topics. Likewise, the PL fluids plus thermodynamics final exam average grade (64.3, which also included waves) was considerably smaller than the CBL thermodynamics exam average grade (76.9). Note that it was not possible to separate the fluids and thermodynamics topics in the PL final exam. On the other hand, the PL Project 1 average grade for Fluids (94.1) and for Thermodynamics (95.4) are both higher than the corresponding CBL challenge average grades (87.1, and 92.6), respectively. Note that in this case, we were able to separate the projects dealing exclusively with Fluids or Thermodynamics. Overall, as with mechanics topics, the CBL average block grade was larger than the PL average course grade for fluids and thermodynamics topics (87.2 vs. 78.3, respectively).

6.3 Electricity and magnetism comparison

As before, Table A3 in the appendix presents the whole data for electricity and magnetism PL vs. CBL activities comparison, while Table 6 below summarizes the main results. The PL midterm exams and projects of electricity topics were compared to the eight CBL electricity blocks. However, the PL magnetism topics were evaluated only until the final exam, along with electricity topics (about 50% of the exam), so a direct comparison of the magnetism topics was not possible with the seven CBL magnetism blocks (see Table 6). In the case of the PL projects and CBL challenges, only projects having similar content (either electricity or magnetism) are compared in Table 6.

Observe that the PL electricity midterm exam average grade (79.1) was smaller than the corresponding CBL electricity argumentative exam average grade (82.8). As mentioned before, it was not possible to separate the magnetism-only part of the PL final exam. In any case, the PL electricity and magnetism final exam average grade (61.4) was much smaller than the CBL argumentative exam average grade considering the electricity and magnetism blocks together (85.0). Regarding the electricity and magnetism projects and challenges, the PL project average grade for electricity topics (95.5) and for magnetism topics (94.1) were a bit larger than their corresponding CBL challenge average grades (93.1 and 91.9), respectively. It was also found that, as with the previous two sections (Tables 4, 5), the CBL average block grade was larger than the PL average course grade for electricity and magnetism courses (89.9 vs. 84.9).

6.4 Summary of results

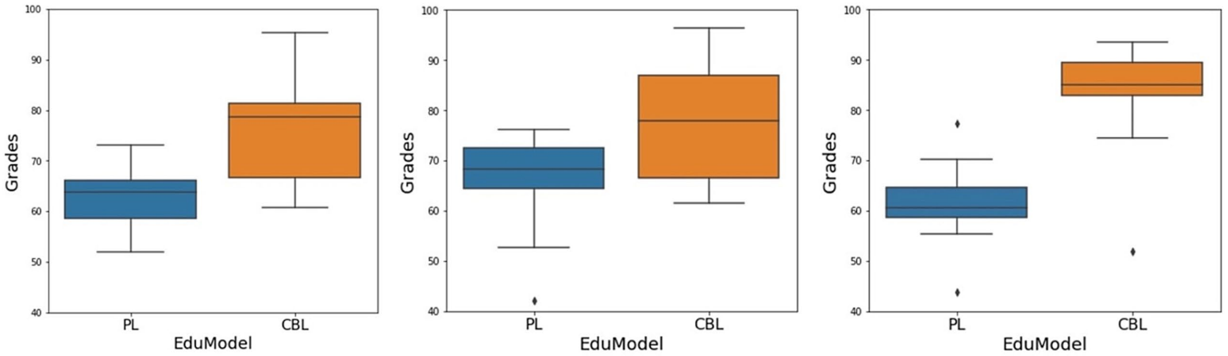
Table 7 summarizes the PL and CBL models' average grades for the three disciplines: mechanics, fluids and thermodynamics, and electricity and magnetism for the three selected instruments: final exam

TABLE 7 Summary of PL and CBL average grades and *p*-value per discipline and measuring instrument.

Discipline	Metric	PL mean	CBL mean
Mechanics ($N_{PL} = 306$; $N_{CBL} = 351$)	Final exam average grade	62.8	78.5
	Project/Challenge average grade	89.6	93.5
	Final course average grade	77	85.7
Fluids and thermodynamics ($N_{PL} = 230$; $N_{CBL} = 245$)	Final exam grade	64.3	82.1
	Project/Challenge average grade	94.7	89.9
	Final course average grade	78.3	87.2
Electricity and magnetism ($N_{PL} = 205$; $N_{CBL} = 372$)	Final exam average grade	61.4	87.1
	Project/Challenge average grade	94.6	92.5
	Final course average grade	84.9	89.9

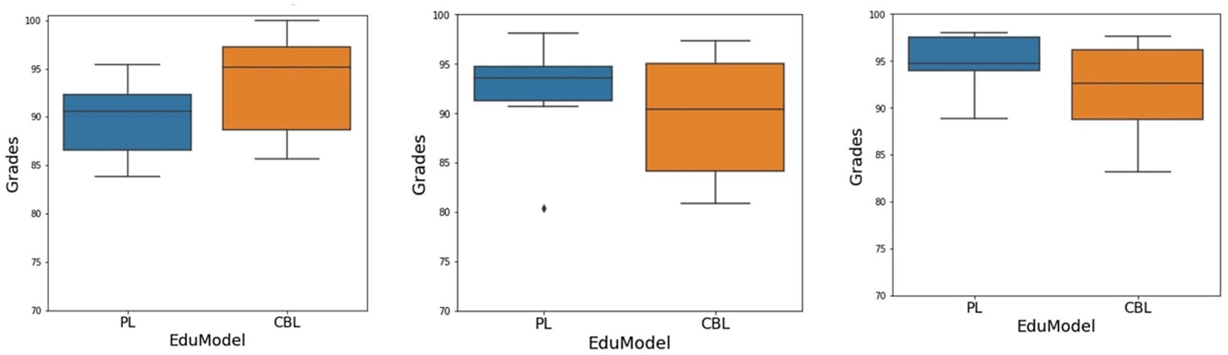
grade, challenge and report grades, and final course grades. Figure 1 presents boxplots for the final exam grades of the different disciplines, Figure 2 displays the corresponding results for the project and challenge grades, and Figure 3 shows the final course and block grades.

A *t*-test study was performed to evaluate the statistical significance of these results, following the equations given in Section 5.4. The statistical hypothesis tests conducted are based on:



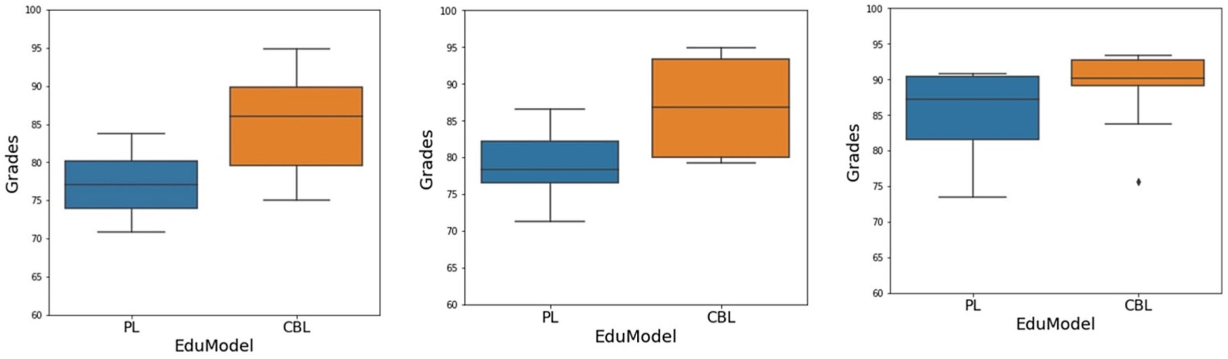
(a) Mechanics (b) Fluids and thermodynamics (c) Electricity and magnetism

FIGURE 1
Final exam grade boxplots for **(a)** Mechanics, **(b)** Fluids and thermodynamics, and **(c)** Electricity and magnetism.



(a) Mechanics (b) Fluids and thermodynamics (c) Electricity and magnetism

FIGURE 2
Project/Challenge grade boxplots for **(a)** Mechanics, **(b)** Fluids and thermodynamics, and **(c)** Electricity and magnetism.



(a) Mechanics (b) Fluids and thermodynamics (c) Electricity and magnetism

FIGURE 3
Final course grade boxplots for **(a)** Mechanics, **(b)** Fluids and thermodynamics, and **(c)** Electricity and magnetism.

Null Hypothesis: There is no difference between the mean grades of the PL and CBL models (H_0: $\mu_{PL} = \mu_{CBL}$).

Alternative Hypothesis: There is a significant difference between the mean grades of the PL and CBL models (H_1: $\mu_{PL} \neq \mu_{CBL}$).

The results indicate that the differences between the average grades for the CBL and the PL model are all statistically significant at the 0.001 level ($p < 0.001$), where the CBL model outperforms the PL model in most metrics and disciplines. However, for the Project/Challenge average grades in fluids and thermodynamics, and electricity and magnetism, the differences are reversed, with the PL model achieving somewhat higher average grades than the CBL model.

6.5 CBL student perception survey

To know the student's perception about the courses and outcomes in the CBL model, an exit survey was administered to $N = 529$ students taking mechanics, fluids, thermodynamics, electricity and magnetism courses during four terms: 20-I, 20-II, 21-I, and 21-II. The survey consisted of ten 5-step Likert questions and eight open questions, as shown in Table 8. The online questionnaire was optional for the students, who were informed that the results derived from the questionnaire may be used in aggregate form for a research study.

6.5.1 Likert questions results

The quantitative results of the survey are presented in Table A4 in the Appendix, where the average answer to each of the 10 Likert questions (*Q1* – *Q10*) is shown for the three periods (P1, P2, and P3) included in each term of the CBL model. The number of students *N* is also included. As an example, Figure 4 shows the student perception for question *Q8* (Comparison of PL and CBL problem-solving skills development) and question *Q10* (Recommend CBL model?) from February 2020 (20-I P1) to December 2021 (21-II P3).

Figure 5 show the distribution of the overall student perception for the whole sample ($N = 529$) for the 10 Likert questions included in the survey (Table 8), where the percentage of students in each bin is presented.

6.5.2 Open questions results

In addition to the 10 questions of the perception survey (Table 8), students were asked to voluntarily answer some open questions to allow them express more freely their general perception of the CBL model in terms of the concepts and skill acquired, as well as the advantages and disadvantages of the CBL model as compared to the PL model.

Some examples of common answers given by the students to these open questions are presented in Table 9 below.

7 Discussion

In this section, we discuss the PL vs. CBL models' results presented in the previous sections as well as the possible causes of these outcomes.

7.1 Comparison between PL midterm and final exams with CBL argumentative exams

From Tables 4–6, the PL midterm and final exam grades are in general smaller than the corresponding CBL *physics* argumentative exams average grades. There are several possible explanations for these results: (a) the PL exam was based more on traditional end-of-chapter

TABLE 8 CBL student perception survey items and average results.

Question item	Answering scale	Average answer
Q1. How do you consider your experience with the CBL model in terms of *knowledge acquired* during the course?	1 = Very Poor; 2 = Poor; 3 = Indifferent; 4 = Good; 5 = Excellent	4.0
Q2. How do you consider your experience with the CBL model in terms of developing *problem-solving skills* during the course?	1 = Very Poor; 2 = Poor; 3 = Indifferent; 4 = Good; 5 = Excellent	4.1
Q3. How do you consider your experience with the CBL model in terms of *competencies developed* during the course?	1 = Very Poor; 2 = Poor; 3 = Indifferent; 4 = Good; 5 = Excellent	4.1
Q4. How do you rate the CBL model in terms of the *multidisciplinary* approach implicit in solving the assigned challenge?	1 = Very Poor; 2 = Poor; 3 = Indifferent; 4 = Good; 5 = Excellent	4.2
Q5. How do you rate the CBL model in terms of the *intellectual dare* implicit in solving the challenge?	1 = Very Poor; 2 = Poor; 3 = Indifferent; 4 = Good; 5 = Excellent	4.3
Q6. How do you compare the CBL model with the PL model in terms of promoting *knowledge acquisition* during the course?	1 = Much worse; 2 = Worse; 3 = Equal; 4 = Better; 5 = Much better	3.6
Q7. How do you compare the CBL with the PL model in terms of *integrating knowledge and skills* to solve a challenge?	1 = Much worse; 2 = Worse; 3 = Equal; 4 = Better; 5 = Much better	4.0
Q8. How do you compare the CBL with the PL model in terms of *developing problem-solving skills*?	1 = Much worse; 2 = Worse; 3 = Equal; 4 = Better; 5 = Much better	4.0
Q9. The course content provided by the teacher was linked to the solution of the challenge.	1 = Disagree; 2 = Partly disagree; 3 = Indifferent; 4 = Partly agree; 5 = Agree	4.6
Q10. Would you *recommend the CBL model*?	1 = No; 2 = Partially no; 3 = Indifferent; 4 = Partially yes; 5 = Yes	3.8

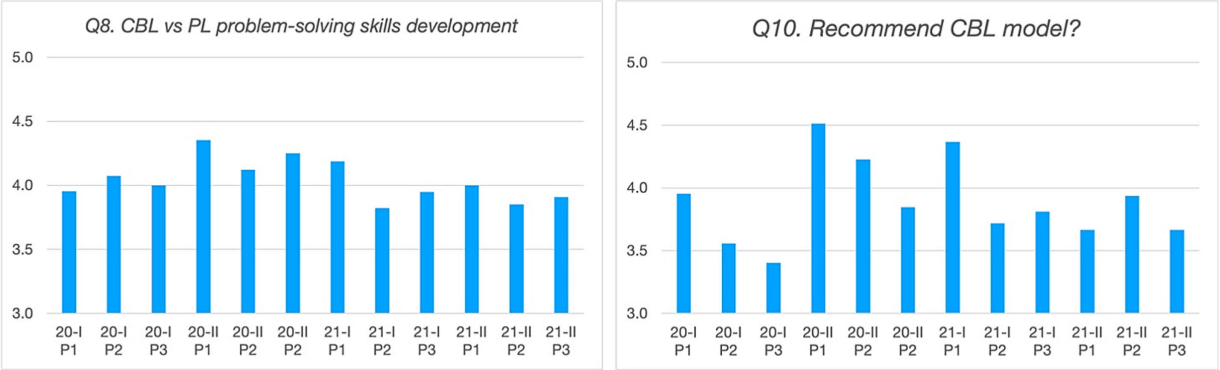


FIGURE 4
Examples of student perception results for Likert questions *Q8* and *Q10* of the administered perception survey as a function of time.

textbook problems, which turned out to be more difficult for the students than the CBL argumentative exam, which were more tailored to the challenge's concepts and solution. For example, for mechanics, the PL midterm exam included 3D Vectors, as well as classical 1D kinematics and projectile motion exercises, which may pose difficulties for some students. (b) The PL course lasted 16 weeks while each CBL block lasted only 5 weeks, so the PL final exam covered a range of physics topics broader than the CBL final exam, representing a higher cognitive load for the students. This behavior was apparent when electricity and magnetism was split in the CBL model into two *blocks*, allowing a more focused approach in each topic.

It was also found that, in all three disciplines (mechanics, fluids and thermodynamics, and electricity and magnetism) the CBL *total* argumentative exam average grade (which incorporates the math and computing components) was *higher* than the corresponding *physics-only* argumentative exam: 78.5 vs. 62.9 for mechanics; 73.7 vs. 67.5 for fluids; 82.1 vs. 76.9 for thermodynamics, 83.2 vs. 82.9 for electricity, and 87.1 vs. 83.9 for magnetism. These results suggest that the integration of physics, math, and computation concepts around a given scenario in the CBL argumentative exam promotes a better understanding of the physical phenomena involved, compared to the PL final exam, which focuses more on rather isolated physics concepts.

7.2 Comparison between PL projects and CBL challenges

As stated previously, timelines for projects in the CBL and PL models were different. Challenges for the CBL model were designed to be developed during the five-week long block and were planned to be close to real-world scenarios, while projects in the PL model were typically short enough to be developed during one or 2 weeks along the 16-week long term and usually comprised more idealized, limited and focused academic problems. Therefore, CBL projects were far more complex, interdisciplinary, and integral than their PL counterparts, and accordingly were given a larger weight in the evaluation plan of the course. On the other hand, as PL projects were usually limited to further investigating typical physics concepts with no explicit inclusion of mathematical and computational techniques, they were assigned a lower weight in the final course grade.

As observed from Table 7 above, there is not a clear trend in the average grades between the PL short projects and the CBL five-weeks long challenges across the three different disciplines, with relatively small differences among them. This is a multi-factor problem, and several contributions may be envisaged. On one hand, the traditional PL project scenarios, lasting only one to 2 weeks, were more focused on physics topics only, with a more limited complexity, requiring a more direct approach and solution from the students. Therefore, these projects often adopted a more theoretical approach to specific physics topics and involved the analysis of experimental design only in some cases. These projects generally followed the classical PBL methodology to guide the students to the scenario's solution such as brainstorming, problem definition, research for resources, etc. (De Graaff and Kolmos, 2003). On the other hand, the CBL challenges, lasting 5 weeks, were structured *ab initio* to integrate physics, math, and computing concepts within a real-life scenario, with the final 2 weeks becoming more immersive. The purpose of these challenges was to develop transverse competencies, such as reasoning for complexity, critical thinking, and learning to learn. As a result, the CBL challenges were designed to be more comprehensive and demanding, encompassing a broader range of concepts and skills, and were aimed at achieving a more challenging outcome. Although in the CBL model the students received closer guidance from the professors during the solution of the challenge, its higher expected outcome could pose a higher task for some students, yielding smaller grades for the CBL challenges than for the PL projects, for fluids, thermodynamics, electricity and magnetism topics (Table 7).

7.3 Comparison of PL and CBL final course grades

According to Tables 4–6 and Figures 1–3, overall, the first-year CBL blocks' final average grades were about 9.4% higher than the corresponding PL average grades for Physics courses, in agreement with results reported by Membrillo-Hernández et al. (2019, 2021, 2022), and by Borgaonkar and Patil (2024). This result can be considered an important success of the new CBL model implementation over the former PL model for common core Physics courses for engineering majors at Tecnologico de Monterrey. Among the possible reasons for this outcome, it can be considered: (a) the content covered in the CBL courses is shorter and more focused on real-life scenarios, making more sense to the students as compared to PL courses. This focused approach may allow for a better understanding of the material and reduce the cognitive workload for students. (b) As commented in Section 7.1, the

FIGURE 5
Distribution of student perception results (as percentages) for the whole sample (*N* = 529) for questions *Q1* to *Q10* of the administered exit questionnaire (Table A4 of the Appendix).

CBL final exam tended to be more focused than the PL final exam leading to an increased average final grade. (c) On top of this, the final evaluation in the CBL model includes evaluations from the math and computing professors, having thus a positive impact on the course final average grade for the CBL courses. In summary, the CBL model provides a more holistic and integral evaluation than the PL model, giving an important weight both to the development of the challenge and to the argumentative exam instead of mainly considering the traditional assessment based on problem-solving of the PL model, where students often obtain lower grades. With the results obtained, evidence was obtained that by solving challenges related to real problems, students had interaction between the academic content and its practical application, achieving a greater understanding and retention of the knowledge acquired (cognitive competences). Therefore, in this study we consider that these factors are mainly responsible for the higher grades obtained by students in the CBL model than in the PL model.

Note however that, within this 9.4% grade increment, about 4–5% may be attributed to the *face-to-face vs. online effect* mentioned before

TABLE 9 CBL student responses to open questions in perception questionnaire.

Question	
(a) Mention two or three physics, math or computing concepts learned during the course.	• Matlab to solve physics problems with numerical methods. • Measurements error propagation and statistical analysis.
(b) Mention two or three disciplinary or transversal competencies or skills developed during the course.	• Teamwork. • Problem-solving skills and self-driven research to find solutions.
(c) Comment on two positive aspects (if any) that you consider should be maintained in the implementation of the CBL model.	• Solution of real-life challenges by applying the concepts discussed in class. • Course schedule flexibility and variety of multidisciplinary knowledge.
(d) Comment on two negative aspects (if any) that you consider should be improved in the implementation of the CBL model.	• The five-week period does not allow me to delve deeper into the topics and complete assignments. • Avoid leaving complex or important subjects solely for self-learning.
(e) Mention two or three advantages of working with CBL model as compared to the PL model.	• Application of knowledge in real-life situations. • Faster learning pace.
(f) Mention two or three disadvantages of working with the CBL model as compared to the PL model.	• Too many topics to be covered in a short time do not allow a thorough understanding. • The lack of continuity between blocks and the need to constantly adapt to different professors and classmates.
(g) Which one, the CBL model or the PL model, do you think is best to develop the knowledge and skills you will need as an engineer? Why?	• The CBL model is focused on practical application of knowledge and prepares you to solve real-life problems and situations after college. This practical approach enhances my understanding and prepares me for future professional challenges. • The CBL model encourages problem-solving, critical thinking, and the application of knowledge to real-world situations.
(h) General comments	• The limited time of five weeks per subject makes it difficult to cover all the material and fully understand the solution to the challenge. • The CBL model has advantages and challenges, but with effort and support from teachers, it is possible to achieve the goals.

(García-Castelán et al., 2021; Robledo-Rella et al., 2022). For the CBL courses, 46% were taught online for mechanics, 33% for fluids and thermodynamics, and 100% for electricity and magnetism (see Tables A1–A3 in the appendix). This increment in online courses grades was noted during the COVID-19 pandemic, when instructors gave relatively higher grades partly to offset students' sense of isolation at home, and lacking face-to-face interaction with peers and teachers.

7.4 Student perception questionnaire results

The student answers given to the perception questionnaire (Tables 8, 9) showed that the students appreciated the fact that the challenges dealt with issues appealing to them, having the opportunity to apply right away concepts learnt in class, and working with their peers, in agreement with similar findings reported by Borgaonkar and Patil (2024) and by Mebert et al. (2020). It is also concluded that a successful scenario offers multifaceted opportunities for all the students to find meaning in the activity.

From the administered questionnaire (Table 9 and Figure 5), it was found that: (a) 70% of the students had an overall good perception of the CBL model, with most Likert questions having opinions above or equal to 4.0 (except questions *Q6* and *Q10*). (b) For question *Q6*, regarding whether the students consider if the CBL model promoted the acquisition of knowledge during the course, only 58% of them considered that it does. Being the CBL model focused on the development of competencies and problem-solving skills, the students felt that some topic contents were partly left aside. (c) Finally, question *Q10* provides the overall student impression of the CBL model. It was found that only 68% of the students would recommend it, but 13% would not. Being such a disruptive model, the freshman students that answered the survey did not perceive its full potential yet.

7.5 Main limitations of the study

The present study has the following limitations:

(a) The PL and CBL models' outcomes were applied to different student generations. The PL model was applied to students enrolled from Spring 2018 to Spring 2019 terms (three semesters), while the CBL model was implemented with students enrolled from Fall 2019 to Spring 2021 terms (four semesters). Since the models were implemented at different timelines and with different student cohorts, a direct comparison of academic outcomes of the two models may introduce uncontrolled biases in the study.

(b) The comparison made among the exams of the PL courses and CBL blocks did not exactly consider the same contents in all cases. For example, we could not separate the electricity-part only of the PL final exam to be compared with the corresponding part of the CBL blocks. However, we could compare the final electricity *and* magnetism final exam of the PL courses with the average of the electricity exam and magnetism final exams of the CBL blocks. A similar limitation occurred with part of the mechanics topics. Additionally, the time assigned for the exams and the type of questions were not exactly similar in both models, making the comparison of grades a difficult task. A similar observation can be made for the comparison of the results of the PL projects and the CBL challenges, which were different in structure and in the time assigned for the students to develop them.

(c) The face-to-face vs. online grades-increment effect was present in part of our analyzed data, introducing an extra component in the observed larger average grades of the CBL model as compared to the PL, which was given entirely face-to-face.

Nevertheless, even considering the above limitations, the main finding of this research is that, overall, the CBL final average grades were higher than the corresponding PL final average grades for common core physics courses for freshmen engineering students, suggesting than the CBL model promotes better student learning outcomes than the previous model. This might be considered as one of the main indicators of the effectiveness of the CBL model.

It is worth commenting that, as students advance through their majors at Tecnologico de Monterrey, the incorporation of a training partner associated with the posed challenge after the 4th semester, introduces another important aspect of the CBL model (Membrillo-Hernández et al., 2019; Membrillo-Hernández and García-García, 2020). This allows students to observe the direct application of their knowledge and skills to practical, real-world situations, thereby reinforcing a stronger commitment to life-long learning.

Regarding the research questions, it can be concluded that: (a) the more comprehensive and holistic evaluation in the CBL model (as compared to that of the PL model), with explicit integration of physics, math, and computing topics through the development and solution of a real-life motivating challenge, promotes a stronger student engagement, in agreement with similar findings reported by Taconis and Bekker (2023) and by Garay-Rondero et al. (2024), yielding thus better general learning outcomes, as measured from project and challenge average grades, final exam average grades, and final course average grades. (b) It was found that most of the students consider that the CBL courses helped them to develop transversal competencies as well as solving-problems skills.

In conclusion, this active and focused learning is certainly one of the main pedagogical characteristics that should be retained in the ongoing redesign of the CBL model at our institution.

8 Conclusions and future work

The main goal of the CBL model based on competencies development is no longer the academic content itself, but the pursuit of specific disciplinary and transversal competencies, such as critical thinking and problem-solving skills developed through the solution of a carefully *ad-hoc* challenge designed for each CBL course, and according to the student major and semester.

The present work made an exhaustive comparison of the average grades obtained by 1705 students enrolled in the previous learning (PL) model, based on concepts acquisition and complemented with short projects, and the new challenge-based learning (CBL) model, based on the development of student competencies through the analysis and solution of a more inspiring and defiant real-life challenge scenario. The study covered a data collection spanning nine terms, and three mayor disciplines were addressed: (a) mechanics (including kinematics), (b) fluids and thermodynamics, and (c) electricity and magnetism. The comparison included (a) midterm and final exam average grades, (b) project/challenge average grades, and (c) final course average grades. Overall, it was found that the inclusion of physics, math and computing components in the analysis and solution of the longer, more guided challenge in the CBL model, produced higher learning outcomes (up to 10% increment) than in the PL model. This explicit integration of physics, math and computing curricula is probably one of the most important strengths of the CBL model for engineering majors started by the Tecnologico de Monterrey in the Fall 2019 term.

In this work, the success of the CBL model was assessed by comparing average grades in the CBL model with those of the PL model. As future work, the authors plan to assess the level of development of disciplinary and transverse competencies by students enrolled in the CBL.

This new CBL model approach goes in hand with the current swift development of generative artificial intelligence, which is demanding, with an ever-increasing rate, the development of critical thinking, design, curatorship, and prompt-development skills, needed by future engineers. As future work, a more ambitious study could include the follow-up of CBL-students along their professional activities regarding behavioral, cognitive, and emotional dimensions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

VR-R: Conceptualization, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing, Data curation, Supervision. LN: Writing – original draft, Conceptualization, Investigation, Methodology, Validation, Writing – review & editing. RG-C: Investigation, Methodology, Writing – review & editing. AG-N: Methodology, Writing – review & editing, Data curation, Software, Validation, Visualization. JV-R: Validation, Supervision, Writing – review & editing. JN: Writing – review & editing, Investigation, Methodology, Project administration, Supervision, Validation.

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Conflict of interest

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1545071/full#supplementary-material

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