International Journal on Interactive Design and Manufacturing (IJIDeM) (2019) 13:1103–1113
https://doi.org/10.1007/s12008-019-00569-4

ORIGINAL PAPER

Challenge based learning: the importance of world-leading companies as training partners

Jorge Membrillo-Hernández[1,2] · **Miguel J. Ramírez-Cadena**[1] · **Mariajulia Martínez-Acosta**[1] · **Enrique Cruz-Gómez**[1] · **Enrique Muñoz-Díaz**[1] · **Hugo Elizalde**[1]

Received: 16 January 2019 / Accepted: 2 May 2019 / Published online: 15 May 2019

Abstract

Since 2013, the Tecnologico de Monterrey has been implementing the *Tec21* Educational Model, which promotes student participation under the challenge-based learning framework. This places students in challenging, and interactive learning experiences. One of the central proposals of the *Tec21* model is the posing of challenges to the student so that he/she develops disciplinary and cross-disciplinary skills. In this paper, we report the results of four learning experiences based on challenges where students from Mechanical, Mechatronics and Sustainable Development Engineering undergraduate programs were immersed into real-life challenges of three different world-leading companies (namely Boehringer Ingelheim, Covestro and Becton–Dickinson). These challenges were designed by personnel from the companies and professors from Tecnologico de Monterrey. Skills required in these work places, such as work collaboration, critical thinking, ethics and resilience, were compared with those developed under a school-controlled environment. Our results demonstrated that a CBL experience with an industrial partner increases complexity and uncertainty levels. Consequently, the development of skills is consistently higher compared to learning delivered via traditional methods. In our experimental set up, the learning modules were designed to achieve the goals of both the company and the school. The challenges brought forth issues such as ethical dilemmas, valorization, design planning, scientific methodology and recycling options of solid waste products. We analyzed the resilience of the students to failure, their solutions to the challenges and the knowledge acquisition from the contents of every single learning module. The main difference between having a school-controlled challenge and a highly undefined challenge developed at an industrial plant is the level of uncertainty about solving the problem(s). A lot of factors were evident in our study; for example, cross-disciplinary skills, such as teamwork (collaboration), critical thinking, ethics, problem-solving, planning ahead and resilience were observed. Our results demonstrated that having an industrial partner in the Challenge-Based-Learning experience is essential to increase the complexity of the challenge and the uncertainty level, and it helps dramatically in exposing students to real-life professional problems that need to be solved.

Keywords Challenge Based Learning · Educational Innovation · Engineering education · Tec21 model

1 Introduction

Higher education institutions endeavor to innovate their teaching and learning processes by encouraging their teachers to use new methodologies and technologies as tools in the didactic planning of their subjects. However, the technological evolution exposes the student to an infinity of information, applications and didactic objects, bringing a new challenge to teaching; namely, how to enjoy resources available on the internet to transform the student into the protagonist of his/her learning? In this context, the teacher ceases to be the holder of the knowledge and becomes the facilitator of student learning. More channels for access to content, greater connectivity and sharing of experiences and the possibility of using technologies for learning mean that the student can have more autonomy in the process of learning and building knowledge. Active-teaching methodologies have emerged as an educational tool to deal with this new reality, transforming

---

✉ Jorge Membrillo-Hernández
jmembrillo@tec.mx

[1] Escuela de Ingeniería y Ciencias, Tecnologico de Monterrey, Campus Ciudad de México, Monterrey, Mexico

[2] Writing Lab, TecLabs, Vicerrectoría de Investigación y Transferencia de Tecnología, Tecnologico de Monterrey, Ave. Eugenio Garza Sada 2501, 64849 Monterrey, NL, Mexico

students into the main agents of their learning. In it, the stimuli to criticism and reflection are encouraged by the teacher conducting the class, but the center of this process is, in fact, the students themselves. It is a strategy that stimulates criticism and reflection in the process of teaching and learning. An active methodology is characterized by activities that lead the students to do something and at the same time to reflect on the activity that they are doing. In practice, the students identify a problem and seek to resolve it by means of research, reflection and interpretation of results. The teacher assumes the role of mentor, supervisor and facilitator of learning, letting go of being the only source of information for the students [1, 2]. Challenge-Based-Learning (CBL) [3, 4] is an active-learning methodology which inspires and equips students to face local and global challenges by acquiring knowledge in mathematics, science, social studies, medicine, technology, engineering, arts and many other areas.

CBL was inspired by the 21st century work environments. Students come together to work collaboratively, and, through the use of innovative technologies, solve problems that directly affect them in their society or their school [3]. The teacher needs to adapt and to encourage creativity in this new reality and to instruct students with knowledge of varying levels and in multiple different areas. Several authors studied the benefits of a CBL environment as an educational technique in several areas of engineering [5]; as an interdisciplinary and creative approach to solving public health problems [6]; for English language learning [7]; for the training of students in mobile applications development [8]; for development of an effective, controlled teaching environment in an Intelligent Mechatronics course [9]; in contexts of interaction between people and information [10],for employment of gamification and CBL in the process of engineering [11], among many others.

The Tecnologico de Monterrey has launched the *Tec21* Educational Model that bases its success on improving competitiveness by boosting abilities and developing the skills of its students, so they can meet the requirements of their professional fields. The *Tec21* educational model is based on 4 components that allow the formation of leaders capable of successfully facing the challenges of the 21st century. They are: (1) *Challenge-based learning*: It exposes the student to real problems, which allow them to develop transformational leadership skills, so they can be more competitive in today's world [12]. (2) *Inspiring teachers*: Every teacher is interested in the student and challenges, guides and empowers his/her development, (3) *Memorable experience*: Enforcing the students' involvement in a global, diverse and multicultural learning community leads to enriching experiences. (4) *Flexibility*: Offer students options on the what, how, when and where of their professional training process [13].

One of the central components of this model is addressing challenges to the student so that they develop disciplinary and cross-disciplinary skills. challenge-based- learning (CBL) promotes the development of skills in students [14–16]. This model exposes students to situations of uncertainty and, in some cases, to tolerance of failure in order to develop their resilience [14]. This is a concern for students in the colleges of engineering, as they are required to have the ability to think critically and to solve problems, as outlined by the Accreditation Board for Engineering and Technology Inc. (ABET) criteria. Besides the development of disciplinary skills, with this pedagogical approach, students are motivated to learn transversal skills and to feel their connection to the environment and, in the process of solving challenges, they learn to do collaborative, multidisciplinary work.

It is particularly important to be able to differentiate Challenge-Based-Learning (CBL), Problem-Based-Learning (PrBL) and Project-Based-Learning (PBL). Although the three didactic techniques are based on active learning, they are not similar (See Table 1).

In the case of PBL, students build knowledge through a specific task, while, in PrBL, students acquire new information through self-directed learning based on previously designed problems. In these two methodologies, there is already a path to continue, and the uncertainty is low. On the other hand, the focus of PBL is based on predefined, controlled situations; while PrBL confronts students with problem situations that are sometimes fictitious, not real, and in many cases already solved in advance. Regarding the expected product, the students developing PBL generate a presentation or execution of the solution that is compared with previously developed results. Meanwhile, the students who carry out PrBL obtain as their product the solution development per se, i.e. the process itself. What matters in that case is the procedure. The process of problem resolution in PBL consists of following a series of rules based on the previously established project. On the other hand, in PrBL, students are incited to reason the process to be able to solve the problem and, depending on the level of learning, they may have responsibility for the *quality* of the resolution procedure.

In CBL, students are exposed to relevant situations, real and open, that demand a solution for which there is not a pre-made response. The expected product is a solution that results in a concrete action. In CBL, action is required not only from the students but also from the professors and the experts in the field, so that, together, they can propose and generate a tangible solution to the posed challenge.

This defines the great differences of roles that teachers play in each didactic technique: While in PBL, the teacher is a facilitator and project manager, in PrBL, he/she is a guide, tutor or consultant who helps in the development of the solution process. However, the expected role of a teacher immersed in CBL is to be the coach, to be a co-researcher and to design the solution to the challenge in conjunction with internal and external experts.

Table 1 Differences between CBL, PrBL and PBL

Technique/characteristic	Project based learning	Problem based learning	Challenge based learning
Learning	Students build their knowledge through a specific task [17]. The knowledge acquired is applied to carry out the assigned project	Students acquire new information through self-directed learning, using designed problems [18]. The knowledge acquired is applied to solve the problem at hand	Students work with teachers and experts in their communities on real-world problems in order to develop a deeper knowledge of the subjects they are studying. It is the challenge itself that triggers the generation of new knowledge and the necessary tools or resources
Focus	Confronts the students with a relevant situation and redefined problematic for which a solution is required [12]	Confronts students with a relevant problematic situation, often fictional, for which a real solution is not needed [19]	Confronts students with an open, relevant, problematic situation, which requires a real solution
Product	Requires the students to generate a product, a presentation or an implementation of the solution [19]	Focuses more on the learning processes than the resulting products of the solutions [12]	Focuses more on the learning processes than the products of the solutions [21]
Process	Students work on the assigned project so that their engagement generates products, and they learn as a result [20]	Students work with the problem in a way that tests their ability to reason and apply their knowledge to be evaluated according to their learning level [21]. Students analyze, design, develop and execute	Students analyze, design, develop and execute the best solution in order to tackle the challenge in a way they and other people see and measure
Teacher's role	Facilitator and project Manager [22]	Facilitator, guide, tutor or professional adviser [23]	Coach, co-researcher and designer [24]

Here we report on four important Tecnologico de Monterrey efforts to develop interdisciplinary skills in students through experiential learning with world leading companies as training partners. In all cases, CBL was used as a didactic technique. The challenges and their probable solutions were established by the experts of the companies. The evaluations of competency development and knowledge gains were carried out in a collegiate manner.

2 Materials and methods

2.1 Experimental design

The general purpose of this research was to investigate the use of CBL in the following format: Four groups of undergraduate students of several programs in the School of Engineering and Sciences (EIC) of the Tecnologico de Monterrey (Mexico City Campus) were enrolled in a 14–16 week/4 month challenge-based-education period, or *innovation experience* (*i-exp*). The four *i-exp*s were as follows:

(A) Thirteen Sustainable Development Engineering (IDS) students were enrolled in a program with a training partner, the world-leading pharmaceutical company, Boehringer Ingelheim (BI).

(B) Seven Mechanical Engineering (IME) and five Mechatronics (IMT) students were enrolled in a second program with the pharmaceutical company, Boehringer Ingelheim (Identified as BI2).

(C) Twelve IDS students were enrolled in a program with the world-leading chemical company, Covestro (CO).

(D) Sixteen students of IMT were enrolled with the molecular-diagnostics-leader company, Becton–Dickinson (BD).

The **Boehringer Ingelheim** group is among the 20 most important pharmaceutical companies in the world. Based in Ingelheim, Germany, Boehringer Ingelheim operates worldwide with 145 subsidiaries and a total of approximately 47,500 employees. The focus of the company, owned by a family and founded in 1885, is the research, development, manufacture and marketing of new drugs of high-therapeutic value for human and veterinary medicine. In 2015, Boehringer Ingelheim achieved net sales of approximately 14,800 million euros [25]. The investment in research and development corresponds to 20.3% of its net sales. In Mexico, two Boehringer plants are present, one in Xochimilco, Mexico City (four miles from the Tecnologico de Monterrey, Mexico City Campus) and the other in Guadalajara.

Becton–Dickinson and Company (**BD**) is a USA medical technology company that manufactures and sells medical devices, instrument systems and reagents. Founded in 1897 and headquartered in Franklin Lakes, New Jersey, BD employs nearly 50,000 people in more than 50 countries throughout the world. The company's customers include health care institutions, science researchers, clinical laboratories, the pharmaceutical industry and the general public. BD was one of the first companies to sell U.S.-made glass syringes [26]. In Mexico, its headquarters are located in the State of Mexico, 40 miles away from the Mexico City Campus. The chemical company, **Covestro,** is a spin-off of Bayer formed in the fall of 2015; formerly, Bayer Material Science, its materials science division of $ 12.3 billion. The main industries served by Covestro are the manufacture and supply of automobiles, electrical engineering and electronics, construction and household products, and sports and leisure goods. Its products include coatings and adhesives, polyurethanes used in thermal insulation, adhesives, electrical housings, footwear, mattress components and polycarbonates, which are highly impact-resistant plastics. Today, Covestro belongs to the ten biggest chemical companies in the world [27]. In Mexico, Covestro has its headquarters in the State of Mexico, 50 miles away from the Mexico City Campus of Tecnologico de Monterrey. Interestingly, Covestro explicitly advocates the comprehensive and global approach of the Sustainable Development Goals (SDG-UN) of the United Nations.

As is evident, the three companies are of extremely high international profiles, and their products are among the best positioned in the markets of their specialties. It is important to note that for companies of this caliber to agree to have collaboration agreements with an academic institution that allows students, not being experts, to take on challenges without affecting plant production requires extended sessions of descriptions, discussions, approaches and, above all, common objectives, both professional and academic. In some cases, the logistics involved investments by the company including the setting up of places for student sessions or simply increasing the amount of health insurance. Finally, all students, before accessing the facilities of any of the three plants, had a course in civil protection, occupational safety, hygiene and health. It should be mentioned that the teacher who was responsible for the coordination of each of the cooperative programs had to be at the weekly departmental meetings that the companies programmed to evaluate the progress of the resolutions of the challenges and, if required, to make decisions for the improvement of the groups' academic performances. This teacher was the main mentor of the group and, also, the only link between academia (Tecnologico de Monterrey) and the company.

Every week, the students were immersed in the correspondent companies' plants at least 6 h, and the learning modules consisted of two sessions of 90 min each. Very dynamic learning modules (classroom sessions) were designed to meet the objectives of both the company and the school in each location. These covered the study and resolution of ethical dilemmas, valorization, design thinking, scientific methodology and recycling options for solid-waste products. In many of the cases, experts in the aforementioned subjects were invited to develop presentations that would serve as the bases for the students to generate discussions that would give them not only the required concepts but also the focus on the probable solutions of the assigned challenges. Given the complexities of the challenges, on several occasions, the proposed solutions were not feasible. That allowed us to analyze the resilience of the students to errors and failures and the alternative solutions to the challenges subsequently proposed. Correspondingly, the high level of uncertainty provided the students more opportunity to acquire knowledge of the contents in each learning module. Interestingly, students visited the library almost twice a week on average to get information about sustainability. In all cases, at least three teachers of the Tecnologico de Monterrey served as mentors, and three tutors from the training-partner-companies were present at all times in each of the *i-exp*s.

It is important to note that the experimental design included a strong and strict training period for the Tecnologico de Monterrey-participant teachers. This is noteworthy, because changing the way of teaching after 10 to 30 years is quite difficult and requires time and preparation. Only those expert *Tec21* teachers were involved in these *i-exp*s.

2.2 Indicators

Specific skills assessments were conducted, each based on a rubric (three in each *i*-experience), and challenge-based-learning assessments were evaluated by both written progress reports and oral presentations. These assessments covered the development of the challenge solutions and the development of competency skills, such as oral and written expression, teamwork (collaboration), ethics, critical thinking, abstract thinking and problem-solving abilities. Additionally, student satisfaction surveys and anonymous opinion surveys (ECOA) were conducted to evaluate the *i-exp*. The ECOA are applied twice; namely, after the fourth week of instruction and at the end of the course (week 15). Furthermore, an additional survey was conducted to inquire what pleased the students most and what they least liked.

2.3 Learning-gain scores

Learning-gain scores in the Ethics class were calculated as described previously by Hake [28] for each student. Briefly, each individual student had a pre and post–test on ethical concepts that had to be covered as part of the contents of the Ethics program. Students from all the Challenge-Based Learning *i-exp*s were tested, and their results were compared

Table 2 Description of the scholar settings of this research

Training partner	Dates of the challenge-based-learning *i-exp*	Number of students:	Level of students	Involved programs	Challenges to be solved, number of teams
BOEHRINGER INGELHEIM (BI)	Fall 2016	Female = 7 Male = 6	Freshman: 1 Sophomore: 6 Pre-junior: 3 Senior: 2	Sustainable Development Engineering	3
BOEHRINGER INGELHEIM 2(BI2)	Spring 2017	Female = 1 Male = 11	Freshman: 0 Sophomore: 0 Pre-junior: 8 Senior: 4	Mechanical Engineering Mechatronics Engineering	2
BECKTON DICKINSON (BD)	Fall 2017	Female = 2 Male = 14	Freshman: 0 Sophomore: 4 Pre-junior: 8 Senior: 4	Mechatronics Engineering	1
COVESTRO (CO)	Spring 2018	Female = 9 Male = 4	Freshman: 0 Sophomore: 0 Pre-junior: 8 Senior: 5	Sustainable Development Engineering	2

with those students who had the same class taught in traditional ways in a classroom by the very same teacher who taught also the CBL course.

The following formula was used:

$$\textbf{Learning gain score} = \frac{(\text{Post-assessment} - \text{Pre-assessment})}{100\% - \text{Pre-assessment}}$$

where Pre-assessment is the percent correct on the pre-unit assessment.Post-assessment is the percent correct on the post unit assessment.

3 Results

3.1 Engineering school settings and students

A research study on teaching strategies and their impact on learning experiences was carried out. Four different *i-exp*s were designed. As shown in Table 2, all studies started in the fall of 2016 and were extended until the spring of 2018. Three different academic undergraduate programs were involved; namely, Sustainable Development, Mechatronics and Mechanical Engineering. Three different partnerships were made with world-leading companies. It is important to note that students from all the stages of the careers were selected at the beginning (first *i-exp*), but for the last *i-exp*s, students in the final third of the career were preferred (Table 2). This point is essential, because having students from various stages implies that they have developed competencies in a variable, non-uniform manner, which makes it difficult to resolve the challenges and, in the best scenario, only delays the establishment of an optimal strategy.

Each *i-exp* consisted of two significant moments: (A) a period in which the students developed the on-site challenge solution inside the production plant, basically under the instructions of the staff of the associated training company, and (B) different periods of instruction in the classroom within the Tecnologico de Monterrey, where the expert teachers in the fields of study not only gave advice but also developed the contents of the courses for which they were responsible, always focusing on solving the assigned challenges.

One of the subjects in the classroom invariably corresponded to the topic of Ethics, an interdisciplinary skill that is very important in our institution. Every single challenge had a specific ethical dilemma that had to be discussed and its solution proposed. It is important to bear in mind that the entire syllabus of the course was reviewed during the development of each experience. As a comparative model, a group of students not involved in the *i-exp* took the same courses in the classroom (in a traditional way) with the same teacher and in parallel with the fulfillment of the *i-exp*.

In order to analyze the acquisition of knowledge by the different *i-exp* students, learning-gain scores (see Materials and methods) were calculated by performing pre- and post-exams. As shown in Fig. 1, in all cases, the students of the *i-exp*s had higher scores than the students taking the traditionally taught courses [29].

On the other hand, each company (partner-trainer) participated with at least three experts within the production plant. Immersing themselves in the development of the solution to the challenge, they provided technical and methodological advice. It is important to note that the challenge was always designed based on the structure of the *Tec21* teaching

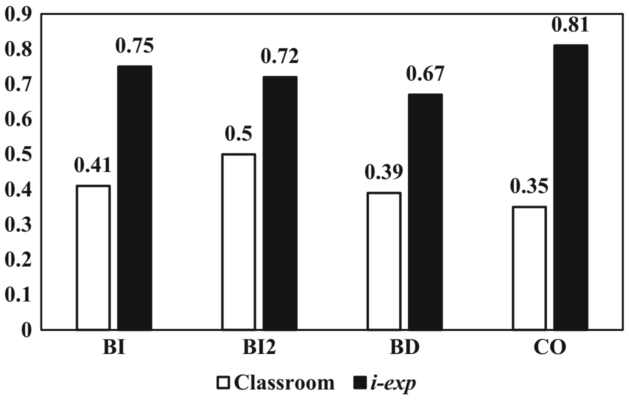

Fig. 1 Average learning gain scores in ethics in the different classroom (empty bars) or *i-exp* (solid bars) groups. Scores were measured as described in Materials and methods. The number of students were as follows: Boehringer Ingelheim 1 (BI) n = 14 and n = 13. Boehringer Ingelheim 2 (BI2) n = 16 and n = 12. Becton–Dickinson (BD) n = 19 and n = 13 and Covestro (CO) n = 13 and n = 16

methodology, that is, a challenge whose solution would help the company to access its areas of opportunity but also provide Tecnologico de Monterrey with the correct strategy for the development of required student competencies. In short, it was more important to develop the skills of the students than to solve the challenge itself.

3.2 Instructional design

Participating teachers were trained during the 2015, 2016, and 2017 summer breaks in a 20 h course, where they discussed suitable strategies to implement CBL teaching techniques to switch to become mentors or coaches rather than teachers in a traditional class. We discovered that the main difficulty was to achieve the objective of covering all the topics of the courses through the resolution of challenges. The teachers of each period met with the corresponding company staff person to determine the challenges to be solved and to establish a strategy for their probable solutions. It is worth mentioning that, in some cases, external teachers were required to give a specific explanation of a particular topic or to provide expertise that was lacking in the teacher of a group. Obviously, this depends on the challenge to be solved. For example, a professor who was an expert in design-thinking and another in economics and valorization was required for the CO challenge, and a basic chemistry teacher was necessary in the BI2 challenge (Tables 2 and 3).

In addition, as we have pointed out, one of the properties of the challenges is the high level of uncertainty. This characteristic required the students to spend at least one 4 h session per week visiting libraries, meeting other experts or making field trips to acquire more knowledge to resolve the challenges.

Table 3 Challenges to be solved by the students

Training partner	Dates of the challenge based learning *i-exp*	Challenges
BOEHRINGER INGELHEIM (BI)	Fall 2016	1. Integral management of a specific solid waste product (Wrapping Al-paper).
		2. Disabling dangerous-category waste, such as blisters and other packaging of medicines.
		3. Use of residual food oil in the industrial plant to make biofuel.
BOEHRINGER INGELHEIM (BI2)	Spring 2017	1. Modelling of a Line of production
		2. Integral management of non-dangerous solid waste.
BECKTON DICKINSON (BD)	Fall 2017	1. Modelling and analysis of a line of production.
COVESTRO (CO)	Spring 2018	1. Sustainable valorization of a polyurethane-foam waste.
		2. Sustainable program of the management of solid waste in the production plant.

3.3 Data collection procedure

The analyses reported herein focused on the performance of the four experiences as described in Table 3. Every *i-exp* had two partial and one final examination based on competencies. Written examinations and oral presentations on developing the solution to the challenges (examined by both training partners and Tecnologico de Monterrey teachers) and two anonymous student satisfaction surveys given at the midpoint and end of the semester were used as evaluation instruments for the *i-exp*. The courses by which this CBL experience strategy was credited were:

(a) For Sustainable Development Engineering students:

- Sustainable products and services
- Environmental and Sustainable research project
- Environmental management
- Ethics
- Cleaner production and industrial ecology

(b) For Mechanical and Mechatronics Engineering students:

- Engineering Project
- Research methods of Mechatronics
- Ethics

3.4 Example of a case study: *disabling dangerous category waste such as blisters and other packaging of medicines*

Twelve students in the sustainable development engineering program set out to solve the challenge of finding a solution to the blister waste generated in the packaging of medicines in the pharmaceutical industry. The delimitation of the problem indicated that up to 100 kg of blister material are wasted daily just in the calibration processes of the machinery for packaging medicines. It is worth mentioning that the material with which the blisters are made is highly polluting (aluminum board paper and other metals) and that it takes at least 90 years to degrade. The first phase of the challenge consisted of determining the daily amount of waste, its current final destination and doing a life-cycle analysis of the material [30]. The second phase consisted in the study of the properties of the materials. For this we required the help of an expert chemistry teacher who helped us to understand the properties of the constituent materials. The mentor-teachers designed teaching modules to help students to confront the challenge. These modules were based on structuring strategies to solve the problem with the help of experts from different disciplines. It was then not difficult to see that the main component of a challenge is the high level of uncertainty. It should be stressed that the main difference between CBL, PBL (project based learning) and PrBL (problem based learning) is precisely the level of uncertainty and that in a CBL-pedagogical strategy, there is no pre-established plan for the solution (Table 1). The third phase consisted of the elaboration of a proposal to solve the challenge with indicators, costs, time required to recover investment and a SWOT analysis (strengths, opportunities, weaknesses and threats). Internal evaluators from Tecnologico de Monterrey and engineers from the companies served as evaluators. Rubrics for assessing the progress of competencies were made, as shown in Fig. 2.

3.5 Analysis or performance

With only one exception, where a student left the experience for personal reasons, the grades of all students were higher (around 15–20%) on average than the grades obtained by students who took the courses traditionally in the classroom, which indicates that through the resolution of challenges, it is possible not only to cover the contents (syllabus) of a complete course completely but also to extract and develop the competencies of the students at a high level of demand. This was in line with our results where we show the learning-gain scores (Fig. 1).

Developing the challenge in a professional, high-demand, labor environment involves not only developing knowledge competencies but also labor competencies, such as collaborative work, resilience to failure, competitiveness and, above all, confidentiality in results, critical analysis and generation of new ideas in a different, ever-changing-and-challenging-technological environment.

4 Discussion

The Tecnologico de Monterrey is a private, non-profit university founded in 1943. It is an institution that has the purpose of transforming Mexico and the world through education. Its educational offerings cover the levels of high school, undergraduate and graduate programs. In the professional field, Tecnologico de Monterrey offers academic programs in the areas of Engineering, Information Technology, Business, Humanities and Social Sciences, Architecture, Art and Design and Health Sciences. This university is characterized by developing and strengthening entrepreneurship, a sense of humanity and the internationalization of its students. It has nearly 90,000 students and more than 10,000 professors spread over 28 campuses in Mexico and 18 international offices. The necessary transformation of higher education institutions and, especially, their educational models to face the changes and demands of the 21st century led the Tecnologico de Monterrey Board of Directors, beginning in 2012, to start a transformation model that would align the key elements of vision, organization and culture of the organization.

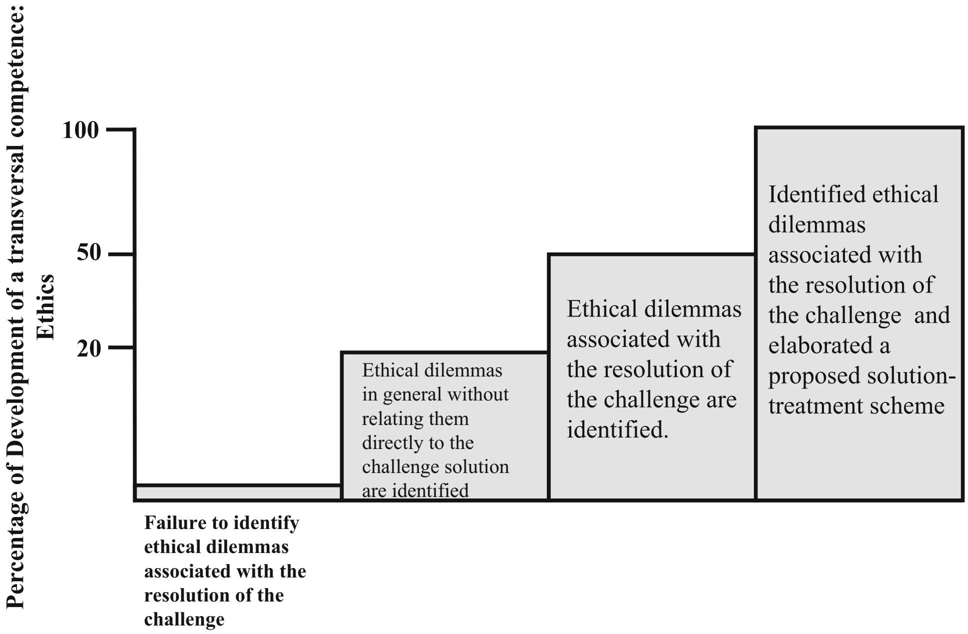

Fig. 2 Example of a rubric to measure the development of a transversal competence. The percentage is described depending on the skills acquired by the student

Subsequently, in 2013, it was proposed to evolve towards the *Tec21* Educational Model to prepare students with an integral formation that equips them to face the challenges posed by a changing and uncertain world and to ensure their international competitiveness by enhancing their skills and competencies to become leaders. The *Tec21* model defines competence as the conscious integration of knowledge, skills, attitudes and values to successfully deal with both structured and uncertain situations. This may involve complex mental processes on the part of professionals training to be involved and committed to society. Two types of competencies are contemplated; namely, disciplinary and transversal. There are ten of the latter, and they range from leadership to collaboration (teamwork); entrepreneurship and innovation; critical thinking; ethics and global citizenship.

Another fundamental pillar of the *Tec21* model is the didactic technique of challenge-based-learning (CBL), an experiential learning whose main principle is that students learn more and better when they participate actively in open learning experiences. A challenge is a real experience with a high level of uncertainty, designed to expose the student to a challenging situation in the real-world environment in order to achieve specific learning objectives. Thus, knowledge is integrated and applied through learning modules (classroom sessions), which contain the set of theoretical and practical contents needed to solve a challenge. In addition, the *Tec21* model establishes the curricular flexibility that is built through trajectories, a system that gives the student the opportunity to explore, decide and specialize throughout his training process by choosing contents from different disciplinary areas. This implies that teachers become advisory, like mentors who will guide students in a personalized manner.

The new teaching–learning process requires an updated teacher profile that must have the following characteristics: inspiring, up-to-date, linked to the professional environment, innovative and an expert user of information technologies. The roles in the new teacher profile that must be fulfilled are professor (design and teach the modules); evaluator (by competencies); designer of challenges; challenge tutor and career mentor.

There is a specific transition system from the current model to the new *Tec21* model. The *Tec21* model has a strategy of progressive implementation that has already begun, and which is expected to be completed in 2020, the year with the first full generation of students trained in accordance with this new model.

Previous work by Freeman et al. [31] examined the use of active methodologies in disciplines of engineering courses. They identified the central elements of each of them and analyzed the student performance in courses of science, technology, engineering and mathematics, comparing indicators of learning in traditional versus active-learning methodologies. Their results revealed that, as in the case reported here, traditional classes build a greater control and monitoring of individual learning (low uncertainty), while active learning as a teaching practice improves student learning outcomes. Interestingly, Desimone et al. [32] examined the professional development of teachers and its effects on the change in teaching practices in mathematics and science from 1996 to 1999. They found that the professional skills of teachers who are focused on diversity of teaching practices (such as CBL) increase the uses of the classroom and improves the amount of acquired knowledge.

Table 4 ECOA surveys applied to students. SD = Standard Deviation

Questions of the ECOA survey	Number of students	Mean (Max 10.0)	SD
Q1. Regarding the methodology and learning activities: (It gave me clear and precise explanations, innovative means and techniques or technological tools that facilitated and supported my learning.)	43	9.12	0.55
Q2. Regarding the understanding of concepts in terms of their application in practice: (I solved cases, projects or real problems; I did internships in laboratories or workshops, made visits to companies or organizations, or interacted with working professionals in applying the topics of the class.)	43	9.52	0.25
Q3. Regarding the interaction with the teacher and the advice received during the learning process: (He supported me to answer questions; the teacher was available in previously agreed sessions and schedules; there was a respectful and open learning environment.)	43	9.54	0.17
Q4. Regarding the evaluation system:(A set of tools was used that gave me feedback on my strengths and weaknesses in the course, based on policies and criteria established in a timely manner.)	43	9.52	0.21
Q5. Regarding the level of intellectual challenge: (It motivated me and demanded that I give my best effort and quality of work to benefit my learning and my personal growth.)	43	9.20	0.47
Q6. Regarding its role as a learning guide: (It inspired me and showed commitment to my learning, development and integral growth.)	43	9.52	0.30
Q7. Would you recommend a friend to take classes with this teacher?	43	9.12	0.41

Many changes in pedagogical practices are largely reported in the literature. At least, the effectiveness of CBL as an employment-oriented-active-learning pedagogy is supported by evidence from several disciplines, which include the learning sciences, cognitive psychology and educational psychology [29, 30]. Seman, Hausmann and Bezerra [34] presented a statistical analysis of students' opinions on Electrical Engineering concerning the process of knowledge formation using a project-based-learning application as a complement to the classic methods of teaching. Finally, in line with our results, Espey [35] and then Freeman [31] examined students' perceptions of the development of academic and thinking skills with a specific focus on learning based on teams (Team-Based-Learning, TBL), which is a strategy of active learning designed to increase interaction and participation of students, producing high numbers in the satisfaction surveys.

Challenge-based-learning promotes the development of skills in students. That is why this educational approach becomes truly relevant in the context of exposing the students to daily-life professional challenges that enable the development of both disciplinary and cross-disciplinary skills. Students experience a thoughtful and inclusive learning, because overcoming the challenge involves conducting research, structuring, implementation and reflection. They acquire the experience and the achievement of a higher-order learning through the use of complex cognitive processes to analyze and solve the challenge that arises. This model exposes students to situations of uncertainty and, in some cases, tolerance of failure, which helps them to develop resilience.

Table 5 Emerging themes for the "best thing" and "worst thing" question on CBL (n = 53)

Rank	Theme (Best)	Theme (Worst)
1	Real-life challenge	Short time
2	Professional contact	No clear order on topics
3	Applied concepts	Too many books to consult
4	Innovation	Self-learning
5	Self-learning	Higher difficulty of exam than traditional

We studied the levels of uncertainty and the experience of developing a challenge inside an industrial environment, where the roles of supervisor-engineers and mentor-professors are essential for the learning process of the students. The main difference between having a local (school controlled) and a highly uncertain challenge being developed at an industrial plant is the level of uncertainty attached to solving the challenge. In our study, cross-disciplinary skills such as collaboration (teamwork), critical thinking, problem-solving, planning ahead and also resilience were observed. Clearly, all the contents of the assigned subjects were covered, however the length of time available to solve the challenge was too short in all cases. It must be noted that the nature of the challenging experience exceeded the standards that a student faces in a traditional academic setting. This was later confirmed by the anonymous survey evaluation (ECOAS, Table 4), where, on average, all the answers were above 9.0 on a scale of 10, a much higher number than the average of the responses from the students taught in traditional classes.

In addition, when the average learning-gain scores were evaluated for the Ethics subject, clearly, the students who were in an *i-exp* course consistently had higher gains of knowledge than students who took the same course in the (traditional) face-to-face modality that was based on contents presented in a systematic and ordered manner typical of a blackboard/chalk course. Our results demonstrated that having an industrial partner in the Challenge-Based-Learning experience is essential to increase the complexity of the challenge and the uncertainty level, and it helps dramatically to expose students to real-life professional problems to be solved.

In a final survey, students were asked two open-ended questions to rate their CBL experience (Table 5). Question 1 asked students to write the best features of the CBL strategy. Five themes arose from the students, as is shown in Table 5. The real-life challenge was the top topic that was mentioned. In addition, having a professional experience was also mentioned. When the students referred to this experience, they described the CBL experience as unique, exceptional and exciting. On the other hand, when the students were asked for the worst features of the CBL strategy, two main issues emerged; namely, the short period of time that was used for the experience and the whole new didactic experience that felt strange to them. Specifically, many students responded that self-learning and high uncertainty were two situations that were new and challenging.

Giving students the opportunity to focus on challenging experiences as a means to acquire knowledge permitted them to be inside a space that allowed them to direct their research and think critically about how to apply all their background of knowledge. Besides the development of disciplinary skills, this pedagogical approach motivates students to learn and encourages their connection to the environment. At the same time, during the innovative process of solving the challenge, collaboration and multidisciplinary work are also encouraged.

5 Conclusions

In this manuscript, we reported the results of applying the Challenge Based Learning (CBL) technique in blocks called innovation-experiences (*i-exp*). The main difference between the challenges designed in the school environment and those described here is the fundamental role of world leading companies acting as training partners in their areas, and, as our results strongly suggest, that role is essential for students to receive a good challenge to be solved. It is still a major test to implement the challenge-based-learning technique in many academic programs, because most of the current teachers have been trained in content-and-teaching systems that do not include a high level of uncertainty.

A fundamental pillar of the new strategy Tec21 is precisely the didactic technique of Challenge Based Learning, which involves that students have an interactive education in challenging environments, close to the future work environment, where they can develop the necessary skills to become professionals competitive and successful. This interactive engineering has been carried out in other areas such as Biotechnology Engineering [36] or in Mechanical or Aeronautical Engineering [37]. These efforts aim to bring collaboration between universities and industry to the next level by allowing the latter to lead the design and delivery of the curriculum through partnership models that include internships, practical training, real life simulations and programs specialized on training of entrepreneurs. In our experience, most academics and industry leaders are on the same page when it comes to collaboration. The benefits are numerous through the improvement of research and innovation through joint research projects/challenges, delivery of innovative commercial products, improvements in teaching, learning and the enrichment of students' knowledge and employability. For students, the mismatch of skills required by the industry has always been the root cause of unemployment, hence the importance of links between academia and industry of the highest level for academic commitment through the curriculum, conferences, internships and now through Challenge Based Learning experiences.

Acknowledgements We thank all the members of the Mechatronics and Bioengineering Departments at Tecnologico de Monterrey, Mexico City Campus for helpful discussions; and Dr. José Carlos Miranda and Dr. Alicia Ramírez for their support throughout this experience. The authors would like to acknowledge the financial support of Writing Lab, TecLabs and Tecnologico de Monterrey, Mexico in the production of this work.

References

1. Meyers, C., Jones, T.B.: Promoting Active Learning: Strategies for the College Classroom. Jossey-Bass Inc., San Francisco (1993)
2. Silberman, M.: Active Learning: 101 Strategies To Teach Any Subject. Prentice-Hall, Des Moines (1996)
3. Nichols, M., Cator, K.: Challenge Based Learning. White Paper. Apple Inc, Cupertino (2008)
4. Nichols, M., Cator, K., Torres, M.: Challenge Based Learners User Guide. Digital Promise, Redwood City (2016)
5. Giorgio, T.D., Brophy, S.P.: Challenge based learning in biomedical engineering: a legacy cycle for biotechnology. In: Proceedings of the ASEE, pp. 2701 a 2711. (2001)
6. Olivares, S.L.O., Cabrera, M.V.L., Valdez-García, J.E.: Aprendizaje basado en retos: una experiencia de innovación para enfrentar problemas de salud pública. Educ. Méd. **19**, 230–237 (2018). https://doi.org/10.1016/j.edumed.2017. **(In Spanish)**
7. Marin, C., Hargis, J., Cavanaugh, C.: IPad learning ecosystem: developing challenge base learning using design thinking. Turkish online J. Dist. Educ. ITiCSE. 184–194 (2015)
8. Santos, A.R., Sales, A., Fernandes, P., Nichols, M.: Combining challenge-based learning and scrum framework for mobile application development. In: Proceedings of the 2015 ACM conference on innovation and technology in computer science education (pp. 189–194). New York, USA (2015). https://doi.org/10.1145/2729094.2742602

9. Kuswadi, S., Nuh, M.: Effective intelligent control teaching environment using challenge based learning. In: 2016 International Symposium on Electronics and Smart Devices, ISESD 2016, pp. 35–40 (2017)
10. Conde, M.Á., García-Peñalvo, F.J., Fidalgo-Blanco, Á., SeinEchaluce, M.L.: Can We Apply Learning Analytics Tools in Challenge Based Learning Contexts? Lecture Notes in Computer Science, 10296 LNCS, pp. 242–256, (2017)
11. Flores, E.G.R., Montoya, M.S.R., Mena, J.: Challenge-based gamification and its impact in teaching mathematical modeling. In: ACM International Conference Proceeding Series, pp. 771–776, (2016)
12. Free document available at: https://observatory.itesm.mx/tec21/ Accessed 13 Aug 2018
13. Gaskins, W.B., Johnson, J., Maltbie, C., Kukreti, A.R.: Changing the learning environment in the college of engineering and applied science using challenge based learning. Int. J. Eng. Ped. **1**, 33–41 (2015). https://doi.org/10.3991/ijep.v5i1.4138
14. Johnson, L.F., Smith, R.S., Smythe, J.T., Varon, R.K.: Challenge Based Learning: An Approach for Our Time. The new Media consortium, Austin (2009)
15. Membrillo-Hernández J., Ramírez-Cadena, M.J., Caballero-Valdés, C., Ganem-Corvera, R., Bustamante-Bello, R., Benjamín-Ordoñez, J.A., Elizalde-Siller, H.: Challenge based learning: the case of sustainable development engineering at the Tecnologico de Monterrey, Mexico City Campus. In: Auer M., Guralnick D., Simonics I. (eds) Teaching and Learning in a Digital World. ICL 2017. Advances in Intelligent Systems and Computing, 715. Springer, https://doi.org/10.1007/978-3-319-73210-7_103 (2018)
16. Membrillo-Hernández, J., Ramírez-Cadena, M.J., Caballero-Valdés, C., Ganem-Corvera, R., Bustamante-Bello, R., Benjamín-Ordoñez, J.A., Elizalde-Siller, H.: Challenge based learning: the case of sustainable Development Engineering at the Tecnologico de Monterrey. Int. J. Eng. Ped. **1**, 137–144 (2018). https://doi.org/10.3991/ijep.v8i3.8007
17. Swinden, C.L. Effects of challenge based learning on student motivation and achievement. Msc. Thesis University of Montana (2013). https://scholarworks.montana.edu/xmlui/handle/1/2817. Accessed 8 May 2019
18. Savin-Baden, M., Howell-Major, C.: Foundations of Problem Based Learning. McGraw-Hill. London, England (2004)
19. Project-Based Learning vs. Problem-Based Learning vs. X-BL (2015). https://www.edutopia.org/blog/pbl-vs-pbl-vs-xbl-john-larmer. Accessed 8 May 2019
20. Moursund, D.: Project-Based Learning Using Information Technology. International Society for Technology in Education, Eugene (1999)
21. Barrows, H., Tamblyn, R.: Problem-Based Learning. Springer, An Approach to Medical Education. EUA (1980)
22. Juliani, A.J.: What should be the teacher's role during project-based learning? (2019). http://ajjuliani.com/teacher-pbl/. Accessed 8 May 2019
23. Ribeiro, L.R.C., Mizukami, M.D.G.N. Problem-based learning: a student evaluation of an implementation in postgraduate engineering education. Eur. J. Eng. Educ. **30**, 137–149 (2007). Recovered from: http://www.tandfonline.com/doi/pdf/10.1080/03043790512331313796. Accessed 8 May 2019
24. Baloian, N., Hoeksema, K., Hoppe, U., Milrad, M.: Technologies and educational activities for supporting and implementing challenge-based learning. In: Kumar, D., Turner, J. (eds.) Education for the 21st Century—Impact of ICT and Digital Resources, pp. 7–16. EUA: Springer, Berlin (2004)
25. Free document available at https://www.boehringer-ingelheim.com/. Accessed 8 May 2019
26. Free document available at https://www.bd.com/. Accessed 8 May 2019
27. Free document available at https://www.covestro.com/. Accessed 8 May 2019
28. Hake, R.R.: Interactive-engagement versus traditional methods: a six-thousand-student survey of mechanics test data for introductory physics courses. Am. J. Phys. **66**, 64–74 (1998)
29. Pollock, S.: No single cause: learning gains, student attitudes and the impacts of multiple effective reforms. AIP Conf. Proc. (2005). https://doi.org/10.1063/1.2084720
30. Muralikrishna, I.V., Manickam, V.: Life cycle assessment. Environ. Manag. **1**, 57–75 (2017). https://doi.org/10.1016/B978-0-12-811989-1.00005-1
31. Freeman, S., Eddy, S.L., McDonough, M., Smith, M.K., Okoroafor, N., Jordt, T.B., Wenderoth, M.P.: Active learning increases student performance in science, engineering, and mathematics. Proc. Natl. Acad. Sci. U.S.A. **111**, 8410–8415 (2014)
32. Desimone, L.M., Porter, A.C., Garet, M.S., Yoon, K.S., Birman, B.F.: Effects of professional development on teachers' instruction: results from a three-year longitudinal study. Educational Evaluation and Policy Analysis **24**, 81–112 (2002)
33. Michael, J.: Where's the evidence that active learning works? Am. J. Phys. Adv. Phys. Educ. **30**, 159–167 (2006)
34. Seman, L.O., Hausmann, R., Bezerra, E.A.: On the students' perceptions of the knowledge formation when submitted to a project based learning environment using web applications. Comput. Educ. **117**, 16–30 (2018)
35. Espey, M.: Enhancing critical thinking using team-based learning. Higher Educ. Res. Dev. **37**, 15–29 (2018)
36. Membrillo-Hernández, J., Muñoz-Soto, R.B., Rodríguez-Sánchez, A.C., Castillo-Reyna, J., Vázquez-Villegas, P., Díaz-Quiñonez, J.A., Ramírez-Medrano, A.: Student engagement outside the classroom: analysis of a challenge-based learning strategy in biotechnology engineering. In: Proceedings of the EDUCON 2019. In press. (2019)
37. O'Mahony, T.K., Vye, N.J., Bransford, J.D., Sanders, E.A., Stevens, R., Stephens, R.D., Richey, M.C., Lin, K.Y., Soleiman, M.K.: A Comparison of Lecture-Based and Challenge-Based Learning in a Workplace Setting: course Designs, Patterns of Interactivity, and Learning Outcomes. J. Learn. Sci. **21**, 182–206 (2012). https://doi.org/10.1080/10508406.2011.611775