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PAPER

Project-Based Learning: Authentic Engineering Assessment Supported by Model Design

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ABSTRACT

In this study, we examined the effects of project-based learning (PBL) on student learning outcomes related to the subject of signals and systems in the field of electronic engineering at the Universidade Estadual de Campinas (UNICAMP) in Brazil and at the Pontificia Universidad Javeriana (PUJ) in Colombia. We used two methods to assess the effect of PBL on student outcomes: (1) we used the Signals and Systems Concept Inventory (SSCI) to measure the increase in conceptual understanding of signals and systems among electronic engineering UNICAMP students as a consequence of implementing PBL; and (2) we compared the results on a comprehensive signals and systems final exam of a group of electronic engineering students at PUJ who received PBL to those who did not. Results indicated that (1) UNICAMP students achieved outcomes comparable to those of Buck and Wage's study: UNICAMP students taught with projects learned more than students in 15 *Signal and Systems* lecture-based courses in the United States; and (2) PUJ students taught with projects received higher final exam grades than students taught via lectures. Students were able to apply their knowledge of signal processing and systems analysis using MATLAB models. These models provide authentic assessments of engineering students' knowledge and skills. The findings of this study indicate that PBL is more effective than lectures in enhancing students' understanding and application of signals and systems concepts.

KEYWORDS

project-based learning, authentic assessment, mathematical modeling, learning outcomes, signals and systems engineering

1 INTRODUCTION

Courses in engineering education are usually theoretical and offer limited possibilities for applying disciplinary concepts. This is frequently the case with *Signals and Systems*, a subject taught as part of the electronic engineering program in the third year at UNICAMP and PUJ. Content is taught in lectures in which the instructor

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explains a topic and students take notes in class. Students frequently present difficulties in understanding some concepts and how to apply them.

Signals and systems is a field of study that involves examining the representation of signals and the changes that occur to them as they pass through systems. Signals and systems have many applications in engineering, including electrical and electronic circuit design, photonics, electromagnetics, telecommunication systems, control systems, and electrical power systems. Thus, it is studied in electronic engineering and other fields such as mechatronics, bioengineering, networks, and telecommunications.

The study of signals and systems is highly mathematical because the focus is on predicting the behavior of a system when it is subjected to different input signals. Students often struggle to appropriately apply the mathematical content required to understand the operation of signals and systems. In surveys carried out with students, one of the recommendations they made to help them understand the content of the course was that students should be required to carry out exercises and applications to be able to "see a signal in the real world" and not just solve mathematical problems. To do this, we set up a series of projects to encourage students to use the ideas they learned in class. Students can also work together to solve problems and learn about them through the projects.

MATLAB, a program for designing, developing, and evaluating solutions, was used to create the projects. MATLAB is a numerical calculation and programming platform used for data analysis, algorithm development, and model creation. Students can use MATLAB to apply mathematical concepts and models to the operation of signals and systems. The program is used in various industries, including the automotive, medical devices, biotech, pharmaceutical, and communications industries [1].

1.1 Project-based learning

Project-based learning (PBL) is used in engineering education to help students achieve learning outcomes [2–5]. PBL is a teaching method in which students improve their understanding of a subject through the completion of meaningful projects and product development [6]. Díaz-Barriga [7] proposed five characteristics of the PBL: (1) it involves focusing on a learning outcome of the curriculum; (2) it is a strategy facilitated by the teacher, and the student actively and purposefully participates; (3) it promotes the learning of knowledge and procedures of project management and collaboration between students; (4) it provides a set of tasks in which all students can participate; and (5) it is oriented toward a specific product. The creation of a concrete product is what differentiates this strategy from problem-based learning [8].

Prince and Felder [9] investigated the distinctions between various teaching methods such as inquiry-based learning, problem-based learning, PBL, and case-based learning. These authors emphasized that all these teaching methods share certain characteristics, such as being student-centered, in the sense that they involve seeking to encourage students to actively participate in their learning. They are all constructivist approaches; that is, they involve assuming that students construct their own understandings of a subject rather than absorbing information presented by their instructors. Similarly, all these methods involve students discussing answers to questions, solving problems, and working collaboratively.

However, Prince and Felder argued that, although the methods are very similar, differences can be found in that the product of inquiry-based learning can simply be the answer to an interesting question: case-based learning involves the analysis of real or hypothetical cases, PBL involves developing a product (which can be a design, a model, an apparatus, a physical product, or a computer simulation), and problem-based learning is characterized by presenting students with ill-defined problems that do not have clear goals, solution paths, or expected solutions. Thus, students participate in the definition of the problem. These authors mentioned that PBL requires the application of previously-acquired knowledge while problem-based learning requires the acquisition of new knowledge, and that the solution may be less important than the knowledge gained in finding the solution.

1.2 Authentic assessment

Authentic assessment enables students to apply theoretical and procedural content to real contexts, like those of their professional practice or daily life, creating a link between what is learned and the contexts where learning occurs. Authentic assessment involves assigning complex or challenging tasks to students that enable instructors to provide frequent feedback on their learning process. In addition, real-life situations usually involve interaction with others, which is why authentic evaluation includes situations of social interaction and positive interdependence [10].

Authentic assessment is inherent to the learning process. Therefore, it cannot be disjointed from teaching methods. For example, transmissive lectures are evaluated through multiple-choice questions that are used to assess how well students memorized the concepts presented in class [11]. Thus, PBL is assessed through the creation of products, designs, models, or simulations, which enables students to demonstrate that they can apply theoretical and procedural knowledge to signal processing and systems analysis, which are authentic performance contexts for engineers.

MATLAB supports the creation of student designs, models, and simulations and enables users to perceive the effects of model variations on signal processing. Students are free to experiment, explore, and discover the implications of the variations of their models in MATLAB. The program has many applications in image processing, computer vision, wireless communications, data science, control systems, robotics, and many others [12].

1.3 Previous investigations

Few articles have been published on the use of PBL in higher education. Researchers who conducted a literature review of PBL in higher education found that only 76 of the 450 studies published before September 2019 met criteria such as: (1) the studies had to be empirical and should provide original data; (2) the studies had to focus on student learning; (3) the implementation of PBL had to be conducted in higher education; (d) the impact of PBL on student learning outcomes had to be measured; (e) the studies had to meet the key characteristic of PBL, namely the development of a product. Furthermore, only 17 of these 76 articles contained evaluations of disciplinary knowledge acquisition, and only 9 evaluated disciplinary skill acquisition [13]. Also, other researchers performed a meta-analysis to compare the effects of PBL with traditional methods of instruction. Only 29 articles published between 1998 and 2017 reported medium to large positive effects on students' academic achievement compared with traditional instruction [14]. Only 6 of those 29 articles contained investigations of the effects of PBL on learning outcomes in higher education.

Between 2000 and 2019, the effects of PBL on engineering education were studied in 73 published articles, 32 documents presented at conferences, and three book chapters [15]. Among these investigations, only 45 involved the use of a quantitative methodology, and only 16 specifically covered PBL in electronic engineering. Likewise, most articles involved studying the implementation of PBL in a course (N = 73), and only a few involved doing so at the curricular level (N = 23).

Several scholars reported that PBL increased students' content knowledge, use of cognitive learning strategies, motivation, self-efficacy, engagement, and skills, including critical thinking, collaboration, lifelong learning, and artifact performance [13]. The authors of another review focused on examining different forms of implementation and the challenges involved in PBL. These authors identified common patterns in the implementation of PBL, such as students working in small groups to solve unstructured, authentic problems. Additionally, these authors found that PBL implementation can be hindered by heavy workloads, limited time and resources, and a lack of pedagogical training for both students and teachers. In contrast, having institutional support for resources, promotion standards, infrastructure, and learning equipment were factors that facilitated the method's implementation [15]. Lastly, the authors of a meta-analysis showed that PBL is more effective than lecture-based instruction and investigated the factors that can moderate the effect of PBL on student outcomes, such as group size, hours of instruction, and information technology support [14].

According to this literature review, this study particularly contributes to the knowledge of the use of PBL in engineering. As mentioned above, few researchers have analyzed the impact of this teaching method on student learning outcomes (i.e., knowledge and skills) in engineering education [13–15].

1.4 Research question

The primary research question in this study is whether PBL improves students' understandings of signal and system concepts. Therefore, we developed specific project assignments that can be used to improve students' understandings of signals and systems concepts. The research objectives were to (1) evaluate how well students learned signals and systems concepts using specific projects designed for the *Signals and Systems* course, and (2) compare the learning outcomes of students using PBL versus traditional instruction.

2 DESCRIPTION OF THE COURSE AND PROJECTS

In the *Signals and Systems* course at UNICAMP and PUJ, signals are studied, and a signal is understood as anything that contains information about the nature or behavior of some physical phenomenon (e.g., an electromagnetic, acoustic, mechanical, and biological phenomenon) [16]. Systems use signals as inputs to generate specific outputs. For example, electronic systems can capture acoustic information, encode it as a signal, process it, and produce an output as an acoustic signal again (like when we communicate on a telephone).

A signal can be mathematically represented by means of a function that depends on one or more independent variables. In *Signals and Systems*, two types of signals are studied (i.e., continuous and discrete signals), each with its own characteristics and classifications. The mathematical functions for calculating continuous and discrete signals are the following:

$$x(t) = 0.5\cos(2\pi 100\, t) - 0.3\sin(2\pi 150\, t) + 0.1\cos(2\pi 250\, t) \tag{1}$$

$$x[n] = 0.5\cos(2\pi 100\, n) - 0.3\sin(2\pi 150\, n) + 0.1\cos(2\pi 250\, n) \tag{2}$$

Figure 1 depicts the signal's continuous-time x(t) graphic representation and a discrete-time signal x[n] graphic representation of a segment of a human voice.

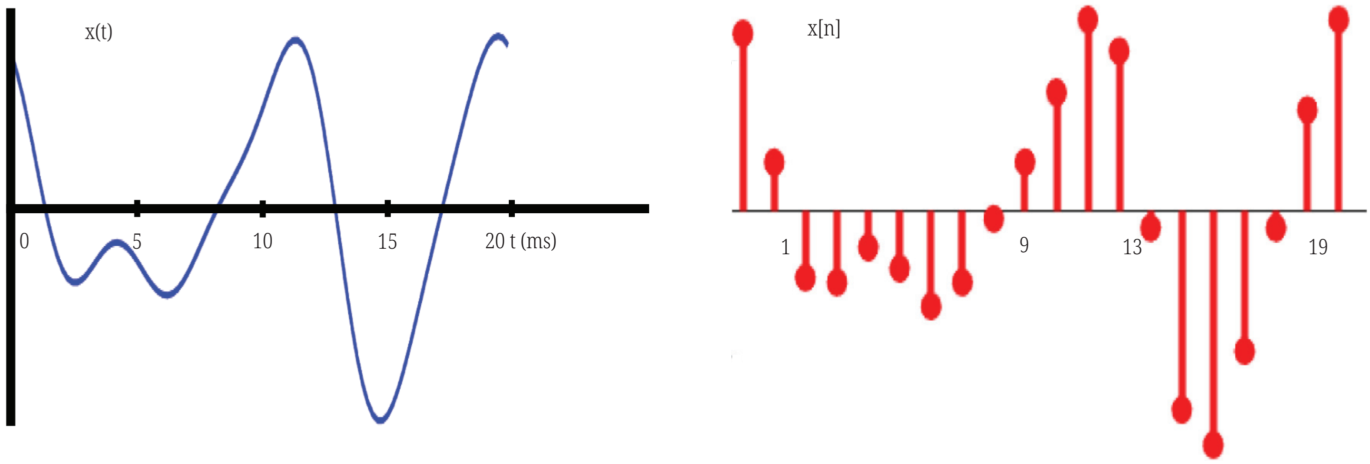

Fig. 1. Graphical representation of a signal's continuous-time x(t) and a discrete-time x[n] segment of a human voice

In addition, students study linear time-invariant (LTI) systems in the *Signals and Systems* course. These systems are those that comply with the properties of linearity and invariance in time [17]. LTI systems are important because they facilitate the analysis of complex systems that can be represented by mathematical models that meet these two conditions. Their practical utility lies in the fact that when the impulse response of a system is known, the output from any input can be known. For example, in the analysis of the acoustics of a theater, or by means of filters, the amplitude of unwanted signals can be reduced until they are almost imperceptible. Finally, in the course, students study the sampling process of a continuous signal and the conditions under which it is possible to recover this sampled signal.

Systems analysis, combined with system interactions, enable students to describe and analyze the behavior of LTI systems that are used in a variety of contexts, including control systems (e.g., the control system of a robot), communication systems (e.g., communication via telephones), digital systems (e.g., computers), medicine (e.g., signals from the brain), and bioengineering (e.g., reading and monitoring the insulin level of a diabetes patient).

Sound processing is one of the most common applications of signal analysis. In Project 1, students can perform different types of time transformations (e.g., inversion, scaling, and delay sequence) on an audio signal to understand their effects. For example, students can use inversion to play an audio clip of a human voice saying the palindrome, "A man, a plan, a canal: Panama" in reverse at different speeds (i.e., perform scaling) until it sounds correct. Delay is commonly used to produce an echo effect on voices. It has been used by artists such as Elvis Presley and U2.

Sound processing can also involve the use of LTI systems. For example, this can be done to combine a singer's voice with an instrument, as Cher does in her song "Believe." Another useful application of LTI systems is in the analysis of the effect of performing in an auditorium. LTI systems also have applications in image processing, such as image sharpening (i.e., reconstructing signals). In Project 2, the impulse response of the LTI systems is used so that the output can be determined from any input using convolution or by combining two signals to generate a third signal.

The Fast Fourier Transform (FFT) algorithm must be used in Project 3 to identify the frequencies generated by pressing a digit on a telephone keypad. When we use a landline phone and dial different numbers, DTMF value identification can be used to recognize the numbers on the target device or the information we want to convey through the phone keypad (e.g., the input of menu options or a credit card number). In this project, students must identify a series of 15 tones generated by pressing the number pad on a telephone in an audio recording. Specifically, they must identify the numbers that were pressed and the order in which they were dialed.

In Project 4, students design an LTI filter to recover the original message from a noisy voice message. In this project, students are given an audio file of a song that has noise added to it. Students must determine the bandwidth of the noise and design a filter that makes the noise imperceptible to the listener while maintaining the song's sound.

The effects of sampling and subsampling on signal visualization are investigated in Project 5. We hope that by completing this project, students can visualize the effects of sampling and subsampling and, thus, comprehend the Nyquist theorem, which describes how to sample a signal so as not to lose information. Any signal containing frequencies higher than those established by Nyquist cannot be reconstructed to its original state. If the signal contains lower frequencies than those established by Nyquist, then the original signal can be reconstructed.

In this project, the students must change the drip rate of a small hose. Students start with a fixed drip frequency and then increase the frequency or speed to see what happens when a signal is under-sampled without meeting the Nyquist conditions. The water may appear to go upward when observed on the screen of a mobile phone, but in real life, the water will always be seen falling. The first four projects are done using MATLAB. The fifth project does not necessitate the use of MATLAB, but a cellphone is needed.

The characteristics of the five projects mentioned above are described in Table 1.

Table 1. Expected learning outcomes, activities, and evaluations of the projects

Expected Learning Outcome	Learning Activities	Evaluation
Project 1: **Apply transformations of the independent variable to audio signals.**	Create the variables corresponding to the audio files in MATLAB. Specify the time variable for each audio file. Perform the transformations of displacement, inversion, and scaling on the audio files.	The student will produce different audio files with different sound effects (i.e., shift, reverse, and scale) from the input audio signal.
Project 2: **Find the impulse response of an LTI system in a physical system.** **Use the convolution of this system's impulse response with an input to an LTI system to identify the produced signal.**	Calculate the impulse response of a real system. Use MATLAB to calculate the convolution between the system's input signal and its impulse response.	The student will simulate the output signals of different LTI systems based on their impulse responses and input signals, identifying the perceptual differences between the input and output signals.
Project 3: **Use the FFT to identify the frequencies that make up a signal.**	Segment the input signal from the identified sounds. Apply the FFT to each of the audio segments. Identify the two main frequency components of each audio segment. Do the mapping between the two main frequencies of each segment and the numbers on the telephone keypad.	The student will design a model to analyze the input signal from the frequencies that compose it. The model indicates the input order of each of the 15 digits in the audio file.
Project 4: **Identify the parameters that a filter must meet to obtain the desired audio when applied to the input signal.** **Design a couple of digital filters (i.e., finite impulse response and infinite impulse response) that reduce the noise added to a song.**	Identify the frequency interval in which the frequency sweep to be eliminated is located. Use the Filter Designer Tool in MATLAB to create the corresponding filter. Apply the designed filter to the signal to be filtered.	Students will create a pair of digital filters that will allow them to listen to a song with low noise levels.
Project 5: **Compare the result of a sampled signal when the Nyquist sampling rate is met and when it is not met.**	The student should run a rubber hose down past a speaker so that the hose touches the speaker. When the speaker produces sound (i.e., vibrates), it will vibrate the hose. Students let the water run and record the flow rate. While the student is recording, they should change the frequency of the speaker's vibrations and watch what happens to the water flow on camera.	The student will make a video to record the water flow and explain the activity. The student will present a model that explains the frequency interval when the water flow is observed moving upward on a mobile phone screen.

The students received continuous feedback throughout the duration of their projects based on the requirements of each assignment. Students can determine which criteria they met and did not meet through formative assessments. The formative assessments also assisted instructors in identifying student areas of difficulty and immediately addressing them. At the conclusion of the project, each group was informed of their most significant achievements. Exemplary outcomes were demonstrated in class. This is done to not only highlight results that exceeded expectations but also inspire other students to make future achievements.

3 MATERIALS AND METHODS

3.1 Research design

We used two methods to test the effectiveness of the implementation of PBL in *Signals and Systems*: normalized gain scores [18] and a quasi-experimental design using a nonequivalent control group post-test only [19]. Students in a signals and systems course at UNICAMP that involved the use of the PBL method were tested before and after the course to assess their gains in conceptual understanding as a result of instruction. In addition, the students in the same course at PUJ were tested the semester before the implementation of PBL techniques and the semester after the implementation of those techniques.

3.2 Subjects

A total of 19 electronic engineering students from UNICAMP participated in this study. The students were juniors, between 20 and 33 years old (on average, 22 years old), and the group was made up of 14 men and 5 women.

In addition, 26 students from PUJ's electronic engineering program who took a *Signals and Systems* course in which PBL was used participated in this study. The students were juniors, aged 19 to 21 (20 years on average), and there were 22 men and 4 women in the group. These students' final exam results were compared to those of the 19 students who took the same course with the same teacher and took the same final exam in the previous year.

3.3 Research instrument

The SSCI is a 25-question, multiple-choice exam designed to assess students' understandings of the fundamental concepts taught in the *Signals and Systems* undergraduate course that is part of the electronic engineering curriculum [20]. When administered before and after the completion of the course, the SSCI measures the gain in a student's conceptual understanding as a result of instruction. Information about the validation of the instrument can be found in the article by Buck et al. [20].

In addition to supporting research on the impact of course-specific instruction on students' understandings of fundamental signals and systems concepts, the SSCI facilitates comparisons between universities and different populations.

3.4 Data analysis

The SSCI makes it possible to obtain a quantitative assessment of student performance. When administered as a pre-test and post-test, it can be used to quantify how much students have learned in a course. For this purpose, the normalized gain is obtained as follows:

$$\langle g \rangle = \frac{post - pre}{100 - pre} \tag{3}$$

The pre-test and post-test values are calculated using only the grades of students who took both exams. The normalized gain represents a fraction of the progress achieved in the course. Another interpretation is that students learn 100$\langle g \rangle$% of the concepts that they did not know before taking the course.

In addition, PUJ students' final exam scores were analyzed using a Shapiro–Wilks test to determine whether the data were normally distributed. The Shapiro–Wilks test is best suited for use in studies with small sample sizes (i.e., less than 50 participants). The Shapiro–Wilks test results indicated that the samples were normally distributed (for the control classroom, W (19) = 0.94, p = 0.23, and for the PBL classroom, W (26) = 0.96, p = 0.43). The Levene's test results, on the contrary, revealed unequal variances (F (1,43) = 8.38, p = 0.01). Thus, a Welch test was used to test the differences between group means.

4 RESULTS

4.1 SSCI results for UNICAMP students

Table 2 shows the normalized SSCI gain obtained by UNICAMP students due to the implementation of PBL.

Table 2. SSCI results

Student	First Week (PRE)	Last Week (POST)	Gross Gain	Normalized Gain
1	80	92	12	60
2	64	68	4	11
3	36	56	20	31
4	40	48	8	13
5	52	80	28	58
6	32	68	36	53
7	52	64	12	25
8	40	72	32	53
9	52	68	16	33
10	80	92	12	60
11	32	76	44	65
12	40	60	20	33
13	52	56	4	8
14	52	80	28	58
15	48	72	24	46
16	56	76	20	45
17	32	52	20	29
18	48	64	16	31
19	40	44	4	7
Mean	49	68	19	38

Additionally, a Welch test was performed to evaluate the effect of instruction on the SSCI score. The analysis revealed a significant difference between pre-test and post-test results ($t(35.88) = 4.24$, $p = 1.47$). On average, students scored higher after PBL instruction than before. These results support the conclusion that students gained knowledge in signals and systems through instruction.

Table 3 shows the mean results of the pre-test and post-test and the normalized SSCI score gain for the UNICAMP students.

Table 3. Comparison of pre and post means and medians, and normalized gain SSCI scores for UNICAMP students

	N	Mean	Median	Standard Deviation	Minimum	Maximum
Pre-test	19	48.84	48	14.15	32	80
Post-test	19	67.79	68	13.36	44	92
Gain		0.38	0.33	0.19	0.07	0.65

Buck and Wage [21] calculated the normalized gain for 20 signals and systems courses. Lecture courses had an average normalized gain of $<g> = 0.20 \pm 0.07$ while the five courses that involved the use of an active and cooperative teaching strategy achieved an average normalized gain of $<g> = 0.37 \pm 0.06$. The results of this study align with those in Buck and Wage's study because we obtained an average normalized gain of $<g> = 0.38 \pm 0.19$ when comparing the pre- and post-test results of the students at UNICAMP (see the results in Table 3).

4.2 Final exam results for the PUJ Students

In the PUJ course, the students from the semesters before and after the implementation of the PBL took the same final exam. The final grades can vary from 0 to 5. Table 4 shows that the mean final exam grade was higher for the students who carried out the projects: 2.30 for the course without projects and 3.06 for the course with projects. The standard deviation was reduced from 1.27 to 0.65. The minimum final exam grade also increased from 0.50 to 1.55.

Table 4. Comparison of final exam means and medians before and after PBL implementation

	N	Mean	Median	Standard Deviation	Minimum	Maximum
Course without projects	19	2.30	2.50	1.27	0.50	4.95
Course with projects	26	3.06	3.18	0.65	1.55	4.25
Difference	7	0.76	0.68	0.62	1.05	0.70

According to the Welch test, the difference in final exam averages between students who took the course without projects and those who took the course with projects is significant ($t(24.86) = 5.69$, $p = 0.025$). On average, students who took the course with projects scored higher than students who took the course before the projects had been included in it. The 95% confidence interval for the average final exam grade in the course with projects is between 2.80 and 3.32. These results support the conclusion that project-based teaching is more effective than lecture-based teaching for signals and systems content.

5 DISCUSSION

PBL is an effective teaching method for promoting student learning in electronic engineering signals and systems courses. The SSCI results for UNICAMP students indicate that those who developed signals and systems projects had a higher average normalized gain than those who were taught through lectures. In addition, according to the final exam results of PUJ students, the course in which the instructor implemented signals and system projects had, on average, higher grades. Therefore, PBL is more effective than lectures for teaching signal and systems related concepts and skills. Moreover, these outcomes are comparable to those of other universities in the world.

In an anonymous course evaluation, most of the students supported the PBL methodology, arguing that it was a more effective way of learning than lectures. Some of them also argued that they felt more motivated to study the signals and systems content in a course taught in this way. Some students suggested that this strategy should be incorporated into other courses. A negative aspect listed by some students was that this methodology is time-consuming.

Moreover, all students achieved the expected learning outcomes in each project. One reason students achieve the expected learning results is that in the application of theoretical concepts to the projects, they realized the conceptual deficiencies that they can solve with feedback from their peers or the instructor. In addition, as they use signals and systems concepts, they begin to widen their grasp of the procedures required to process a signal, consolidating their learning.

MATLAB also enables the integration of conceptual and procedural knowledge of signals and systems into sound or voice processing, which is an authentic performance context for an electronic engineer. "MATLAB projects allow me to deepen concepts and understand the use of signals and system concepts in real life," a student explained. The simulation carried out in MATLAB enables students to change the input and output variables and obtain different results. This means that students can try different strategies and approaches. The program also enables students to engage in simulating processes that, if carried out with the devices intended for them, would cause students to incur costs that must be considered because not all students have the means to do so beyond class. However, it is important to have resources and support students who have not used the program before or do not understand how to use it well.

Another issue to consider is that initially, students were fearful of developing the projects because they did not easily connect the theory seen in class with its application in the specific projects. However, throughout the project's development, students applied theoretical concepts and gained confidence that they could learn the course concepts. Furthermore, some groups proposed additional project parameters (such as user interface and real-time recording) in addition to those asked by the instructors because they believed they could improve the project.

Other researchers at a university in Taiwan found that PBL improved the self-efficacy of 45 engineering students [22] in a manner similar to that of our students, who acquired confidence in their ability to learn course concepts and proposed alternative project parameters. In addition, the students elaborated on their projects beyond what was initially required by their instructors by adding details, creating new meanings or interpretations, and refining their ideas through application. PBL has a positive effect on students' confidence in their ability to learn in a particular course, while also increasing their career aspirations [23]. It is particularly important to have at least one course in which PBL is implemented during the first four semesters of the degree because it positively affects the perception of students that they can obtain and hone career skills, increases their career aspirations, and helps students realize the importance of basic sciences and engineering courses for their careers.

In addition, the projects improved the motivation of the students and their involvement in the course. At the end of the course, we informally asked the students what they remembered the most from the course, and most mentioned the projects because they felt that they "were being engineers" when solving the problems. One reason PBL increases student motivation is that it puts them to work on real-life problems and enables them to observe the impacts of their actions on sound processing [24]. Similarly, other authors found that PBL promotes learning motivation among engineering students [22, 25, 26].

However, we first observed resistance to the teaching method among students who were accustomed to lectures. In addition, some students had conflicts working in groups and difficulties communicating with team members and managing "hijackers" of group work. This was also mentioned by other authors who have used this strategy [27–29].

The following strategy was implemented to reduce the likelihood of students dividing up projects throughout the semester. Groups were freely formed for the first project, but for the second and third projects, students were not permitted to work with students from their previous groups, and for the fourth project, students could freely choose their groupmates. One of the outcomes of implementing this strategy was that, in most cases, the group compositions from the first project did not coincide with those for the fourth project, despite the fact that students freely chose their groupmates in both cases. This is primarily due to the students' ability to meet people with whom they could work and find effective matches for them. They were also more likely to form fellowship relationships with members of the fourth group than members of other groups.

Teachers may be required to form groups that include both academically strong students and students who require additional support. This enables students to understand each other and, thus, creates positive interdependence between them [30]. The dissolution of the groups helped students get to know each other and served as an implicit admonition for those who did not work because they were not chosen for the new teams. The professor monitors the performance of the teams on a regular basis to answer academic questions and help team members get to know each other and evaluate each member's individual performance. Researchers have proposed various strategies for monitoring the individual performance of students on a team [30, 31].

From the instructor's point of view, the implementation of the methodology improves students' understandings of course concepts and procedures and their ability to utilize and apply their knowledge and encourages them to participate in class and ask complex questions. This is achieved because the following steps were followed in each project: (1) Each student must review the theoretical contents before class and, if necessary, review the MATLAB manual, (2) the objective of the project and its relationship with theoretical concepts are presented, (3) doubts about the program and tools that can be used are resolved (a student monitor supports students with the language and syntax used in MATLAB), and (4) the instructor answers students' questions.

Each project must be carefully planned. Therefore, the instructor must have time to define the project, create materials, and review and evaluate completed projects. It would be preferable to have a bank of projects that change from time to time so that students do not rely on the solutions from their senior classmates in the program. Similar considerations in the implementation of the PBL have been raised by other researchers [32].

6 CONCLUSIONS

The results of this study support the conclusion that project-based teaching is more effective than lectures in teaching signals and systems concepts. On the one hand, the normalized gain in knowledge and skills obtained by UNICAMP students (as measured on the SSCI) was greater than that obtained by the students in lecture-based courses at other universities. On the other hand, comparing the final exam grades for the PUJ *Signals and Systems* course taught by the same professor before and after the implementation of PBL techniques shows that, on average, the students who took the course with PBL obtained higher grades than students who took the course when the PBL techniques had not yet been implemented. These results are consistent for the two universities that participated in this study and with the results of the study by Buck and Wage [21] involving 20 courses at universities in the United States.

However, this study has some limitations. The first is the small number of participants at both universities: 19 at UNICAMP and 19 and 26 at PUJ. This limitation could lead to difficulties in generalizing the results. The second limitation is that we did not apply the same measurement instrument at UNICAMP and PUJ, which makes the results of the two universities not comparable. However, the final exam taken by PUJ students was designed by a professor with knowledge of the SSCI and the subject so that he could comprehensively measure students understanding of the fundamental concepts and skills pertaining to the subject of signals and systems. The third limitation is that a student's performance on a test can be explained by the student's prior knowledge, the student's motivation for the larger discipline, the student's learning habits, and the intervention itself. Given that this intervention cannot be randomized, the results of this study might be affected by the factors mentioned before.

Other practical implications of this study include the importance of institutional support for the implementation of PBL, such as giving faculty time to design, implement, and assess PBL with the assistance of instructional designers so that factors such as group size, group dynamics, student needs, and information technology support can be considered. In addition, the implementation of PBL in a course may be supported by curricular considerations regarding the implementation of the teaching method at different levels and the collaboration of faculty members from different courses within the program.

Finally, future research on the impact of the implementation of active teaching methods could benefit from the adoption of measures such as normalized gain to assess the impact of instruction to support decision-making about teaching methods. Hake [18] advocated using normalized gains because the measure differentiated between teaching methods and allowed for a consistent analysis over diverse student populations. International comparisons can lead to disciplinary consensus and reflection on the most effective teaching methods.

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