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PAPER

Project-Based Learning with Embedded Systems to Strengthen the Teaching of Digital Electronics in Higher Education

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ABSTRACT

This study looks at how project-based learning (PBL) affects the effectiveness of teaching through the use of embedded systems (Arduino and ESP32) in a digital electronics course at the university level. A non-equivalent quasi-experimental design was employed with 40 participants from a Computer Engineering program at a university located in Lima, Perú. The control and experimental groups received different levels of instruction on Digital Electronics using Project Based Methods. The three dimensions considered when evaluating student learning were: (1) analog components; (2) active components; and (3) power supply systems using programming through the use of Arduino. A 20-item, true-false (dichotomous) instrument was developed, piloted, and validated by "expert opinion" as well as calculated using KMO (0.680) and internal consistency (KR-20 = 0.814). Pre-test results did not produce statistically significance between the two groups ($p > 0.05$), indicating the groups were statistical equivalent at the start of the research project. Posttest results indicated the experimental group experienced significant improvements compared to the control group in each of the three dimensions ($p < 0.05$). This study provides evidence that the utilization of low-cost embedded systems in combination with PBL methodology can promote improved understanding of conceptual material as well as greater development of practical skills. The findings from this study provide empirical support for the use of structured active learning methodologies in higher education environments that may have limited resources.

KEYWORDS

project-based learning (PBL), embedded systems, engineering education, digital electronics, learning outcomes

1 INTRODUCTION

Many engineering students enroll in and successfully complete courses in Digital Electronics every semester. They memorize formulas, read circuit diagrams, and

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pass tests on theory; however, many of those students encounter much difficulty applying this knowledge to actual practice (building basic circuits; reading data sheets; troubleshooting basic electronic systems) because there has historically been a direct correlation between theoretical training and practical ability, and with the increase in complexity of electronic systems and industries requiring more workers with only practical skills, this difference has become increasingly evident [1], [2].

This issue has initiated a shift towards more active teaching methods in engineering schools in Latin America (and most notably in Brazil, Mexico, and Colombia). There is an increasing number of schools that are beginning to use active teaching-learning methods that include the participation of students to develop solutions to problems they face in the real world, whereas traditional pedagogical models are primarily focused on the transmission of content. Project-based learning (PBL) has become an increasingly popular methodology within engineering to support student engagement and to reduce the disparity that exists between theory and practical application of what is learned within technical disciplines, such as electronics and computer science, etc., where there tends to be a large disconnect between the two [3], [4]. In Peru, the evolution towards using active teaching methods is not as rapid as in those countries mentioned previously because of barriers such as lack of infrastructure, inability to implement new approaches due to institutional issues, and the continuation of the traditional pedagogical approaches to teaching. In any case, it is increasingly required that there be some type of educational innovation in this area.

Low-cost hardware platforms have become a solution to enhance hands-on learning in electronics classes with the adoption of Arduino and ESP32. These platforms give students the opportunity to create functional prototypes through a well-defined process involving conception, prototyping, evaluation, and implementation within controlled environments. Students can directly interact with electronic and computational concepts as a result of these experiences. In contrast to purely theoretical learning approaches, this type of experience is more hands-on and situated because students are exposed to the complexities of real-world systems [5]. The educational value of these platforms is well-established throughout all types of educational systems. However, the studies are showing consistent limitations in that generally Arduino and ESP32 are included as a component of practical learning exercises in an isolated manner; meaning that they are included as supplemental activities disconnected from the learning objectives for the course or the learning strategy of the teacher [6], [7]. As a result, students are experiencing a fragmented learning experience that is leading to the inability for them to fully consolidate their conceptual understanding or develop their practical skills.

The aim of this study is to explore how the use of the PBL methodology based on embedded systems (Arduino and ESP32) positively impacts the academic performance of engineering students in the Digital Electronics course. Accordingly, the study addresses the following research question: the extent to which the implementation of a PBL methodology mediated by embedded systems (Arduino and ESP32) improves undergraduate students' learning outcomes in a Digital Electronics course, compared with a traditional, lecture-based instructional approach. Quasi-experimental methodology, through non-equivalent groups, has been applied to the sample population. This study, as opposed to individual uses of technology, looks at the continuous use of PBL paired with embedded systems as the primary basis for teaching and learning (the integration of PBL and embedded systems) and aligns practical activities with the curricular content. As a result, this study provides empirical evidence for the effectiveness of this method of teaching in an undergraduate context as well as for teaching and learning in lower-resourced environments.

The current document is structured as follows: The theoretical framework of this study is presented in the second section of this document. The methodology will be presented in the third section of this report, and in the fourth section, you will find the results that were obtained. The discussion of the results of the analysis and conclusions drawn from this study can be found in the fifth and sixth sections, respectively.

2 LITERATURE REVIEW

The traditional approach to teaching digital electronics has focused heavily on the development of abstract skills forming the theoretical basis for the field. This emphasis typically includes teaching concepts like Boolean algebra, truth tables, Karnaugh maps, and timing diagrams, which form the framework for university instruction in digital electronics.

Recently, however, there has been an increasing recognition of the need to augment this approach through practical experience and an opportunity for students to apply their theoretical learning in relevant real-world situations.

Many educational programs have included the use of microcontroller platforms, such as Arduino and PIC boards, in their curricula in order to support an applied learning environment. However, evidence suggests that these efforts frequently do not produce the anticipated results; in many cases, hands-on activities are not sufficiently integrated into the overall curriculum and do not align nicely with learning objectives or with appropriate theoretical content [8], [9]. This results in students experiencing disparate learning experiences when they learn theory and practical application in parallel rather than together, and this will restrict the development of consolidated skills that are required for the effective practice of professional engineering.

2.1 PBL in engineering education

Learning is thought to hold greater value when students are involved in solving real-world/matter problems than when students are being shown or exposed only to the subject-matter being transmitted to them by the teacher using a traditional method of delivery; this entire educational/learning process with the aid of PBL will allow the student to learn by doing, as well as provide them with an opportunity to develop both transversal (21st Century) skills and a greater application of theory in practical application through the integration of their skill/level of learning into a project-based activity within a collaborative group of other students in that class or learning environment. There has been much recent research that supports the effectiveness of implementing/using PBL in higher education. Recent research conducted by Rehman et al. [10] revealed that PBL not only improves the learning of specific subject-matter but also encourages additional skills to be developed, such as critical thinking, teamwork/collaborative work, and independence in learning. Additionally, research conducted by Quinapallo-Quintana and Baldeón-Zambrano [11] demonstrates that PBL leads to deeper and more permanent knowledge construction than traditional/narrative lecture-based methodologies.

From a qualitative viewpoint, Mutanga [12] emphasizes that learners value the autonomy and collaboration involved in PBL. These attributes promote learners' motivation to learn and retain what they have learned. Likewise, Yu [13] shows the correlation between sustained involvement in projects and developing creative thinking, a frequently overlooked aspect of engineering education. Furthermore, Lavado-Anguera et al. [14] refer to a global review indicating that PBL has emerged as

one of the leading educational methods in engineering education, having positive and consistent results throughout various academic and disciplinary areas. Pantzos et al. [15] similarly found that challenge- and PBL raise student motivation when projects are well structured. Strode and Mežinska [16] add that institutional collaboration and adequate infrastructure are key to successful project-based, design-oriented learning.

Some disadvantages exist in using PBL that prevent it from being successful. The effectiveness of PBL highly relies on well-organized instructional design that teachers create to meet the learning goals, purpose, and how they will evaluate students' work. If not aligned, projects run the risk of becoming separate projects (or units) disconnected from generating significant impacts of learning.

2.2 Embedded systems as educational tools

In response to the ongoing transformation of technology and industry, increased adoption of open-source platforms such as Arduino and ESP32 by engineering educators are being used as a means to teach students how to create and implement IoT solutions. As the Internet of Things (IoT), automation, and intelligent systems grow, so does the requirement for employees that can develop solutions on and with embedded systems in today's real-world environments. In this situation, low-cost platforms provide an approachable and practical method for teaching students about integrated circuit (IC) technology.

Participatory, hands-on learning for students is made easier through the use of open-source platforms that provide students with the ability to design, build, and test a complete, functional system with limited equipment and/or materials. While creating and implementing solutions using simulation techniques would provide similar errors and difficulties, the combination of using both actual hardware and operating in the real world has given students the opportunity to learn the concepts of what they were studying by participating directly with both.

There exists empirical evidence to support these findings. For example, Vidal-Silva et al. [17] found students in introductory courses using Arduino had positive learning experiences, even though they had no prior programming background. Hercog et al. [18] similarly describe ESP32-based IoT devices as a low-cost, classroom-ready tool. Additionally, Pereira et al. [19] demonstrated that the use of an ESP32-based platform for instructional delivery in a distance learning environment still facilitated student understanding of electronics and IoT concepts. Additionally, in the CDIO framework, Yong [20] illustrated the simultaneous improvement of theory and hands-on skill development as a result of using projects with microcontroller devices. Dolinay et al. [21] built a similar simulator for teaching embedded programming, and Awwad [22] found that active learning in electronics courses improved performance and engagement over traditional lecturing.

In the Latin American context, studies such as those by Ronceros [23] and Tupac-Yupanqui et al. [24] report significant improvements in both academic performance and student engagement when these technologies are systematically integrated into the curriculum.

Nonetheless, despite these positive outcomes, there is still one important limitation: the overwhelming majority of documented experiences indicate that many of the platforms in question were only used for enhancing an existing curriculum or as separate, standalone events; very few examples include much curricular integration at all [25], [26]. Additionally, numerous investigations report a lack of an effective instructional sequence that allows students to develop the required skills over time [27].

Under this scenario, a significant gap is identified between the pedagogical potential of embedded systems and their effective implementation in the classroom. This gap manifests itself in the lack of instructional models that coherently integrate the use of these technologies with active methodologies such as PBL. This problem is precisely the starting point of the present study.

3 METHODOLOGY

3.1 Research design

For the present study, a quantitative approach was used, employing a pretest-posttest quasi-experimental design consisting of two non-equivalent groups. This type of design is highly relevant in educational settings, in this case at the university level, where random assignment of participants is not possible, which makes it possible to compare the effects of pedagogical participation on classroom development. Such designs present known limitations in terms of sampling and randomization [28].

In this case, the impact of a PBL methodology, mediated by the use of embedded systems (Arduino and ESP32), was evaluated in comparison with a traditional teaching approach centered on theoretical exposition. Both groups of student sections were taught by the same instructor (the lead author), which controlled for variability between instructors but introduces a possible observation/expectancy bias, recognized as a threat to internal validity (Section 5.3).

3.2 Participants

The sample consisted of 40 students enrolled in the Digital Electronics courses of the Computer Engineering program at a national university in Lima, Perú, during the 2025 academic year. The participants were organized into two groups, distributed across two sections of the fourth semester, as shown in Table 1. The non-random assignment of the sections to the experimental and control conditions is consistent with quasi-experimental research designs in educational settings, where intact groups are used instead of randomly assigned samples.

Table 1. Distribution of the study population by section

No.	Section	Group	Total
1	Fourth Cycle, Section A	Experimental Group, which received the PBL-based intervention	20
2	Fourth Cycle, Section B	Control Group, which followed a traditional approach	20
		Total	**40**

Both groups followed the same 16-week calendar and syllabus content [29]; the control group received the same content through traditional lecture-based exposition, without embedded systems or projects, for an equivalent period.

The inclusion criteria were students enrolled in the Digital Electronics course with a minimum attendance of 80% and participation in the pre-test and post-test assessments. The exclusion criteria included students who withdrew from the course

during the semester, those who were absent from any of the assessments, and those with incomplete participation in academic activities.

Although the sample size is relatively small, it is consistent with quasi-experimental studies in educational settings where intact groups are used. Similarly, the use of non-parametric statistical tests contributes to the robustness of the analysis under these conditions.

3.3 Study variables

1. **Independent Variable: Project-Based Teaching Methodology with Embedded Systems:** This variable is defined as a pedagogical strategy that connects theory with practice through PBL, promoting active student participation in solving real-world problems through a structured sequence of stages [30]. Embedded systems are incorporated as core technological tools that enable the materialization of electronic and computational concepts. These systems are processing units integrated into larger products or devices [31], [32], with applications ranging from wearable devices and consumer electronics to aerospace and biomedical systems [33], [34].
2. **Dependent Variable: Level of achievement of learning outcomes in Digital Electronics:** It is defined as the level of improvement that students achieve in attaining the knowledge and skills established in the course's official program [29], particularly in relation to the conceptual understanding and practical application of the fundamental principles of digital electronics, in accordance with the current demands of engineering education and approaches centered on active learning. The Digital Electronics course aims to strengthen students' ability to understand and apply fundamental electronics concepts, including analog components, active components, and power supply systems, while developing technical skills in programming and hardware-software integration through the Arduino platform, which are distributed across the sessions established in the Digital Electronics course syllabus.

3.4 Definition operational variables

The independent variable was implemented through a structured sequence of hands-on activities using Arduino and ESP32. Based on the framework proposed by [35], nine teaching session guides were organized around three content units: Passive Elements, Active Elements, and Power Supplies and Arduino. These sessions were structured according to the four phases of PBL: (1) defining the key question, (2) chronological planning, (3) follow-up and monitoring, and (4) evaluation. (See Table 2, which presents the complete organizational matrix of the independent variable).

From an operational point of view, the dependent variable was measured using an assessment instrument composed of 20 dichotomous items (correct/incorrect), classified into low, medium, and high achievement levels, designed to assess student performance in three specific dimensions: understanding the operation of analog components (1), learning the concepts of active components (2), and learning the concepts of power supply and Arduino (3). Table 3 presents the complete organizational matrix of the dependent variable.

Table 2. Organizational matrix of the independent variable: Project-based teaching methodology with embedded systems

Unit	Strategic Activities	PBL Phases	PBL Indicators
Passive Elements	Session 1: Electronics. Conductors, insulators, and semiconductors. Session 2: What is a resistor? Types of resistors. Session 3: Magnetism. Electromagnetism. Effects of the core in a coil. Session 5: What is a diode? Diode polarization. Session 6: Concept. Classes and types. Physical forms of the transistor. Session 7: ICs. Introduction to Arduino. Session 9: Operation of the linear power supply. Session 10: Arduino Fundamentals. Programming in Arduino: Digital Data OUTPUT. Session 11: Programming in Arduino: Analog Data INPUT.	1. Definition key question	Spontaneous motivation. Community proposals. Educational potential. Project Name
Active Elements		2. Chronological planning	Collective thinking Lines of research Different strategies Schedule
Power Supplies. Introduction to Arduino		3. Monitoring and tracking	Active Learning Cognitive diversity Collaborative work Strategic SWOT Analysis Innovation resources
		4. Assessment	What I learned What is it for? What do I do with it?

The experimental group's calendar spanned 11 of the 16 semester weeks, covering the nine sessions in Table 2. Weeks four and eight were university-wide midterm and progress evaluation periods common to all sections, with no session-specific PBL content, which is why they are not listed as separate rows.

Table 3. Operationalization matrix of the dependent variable: Teaching of Digital Electronics

Dimensions	Indicators	Item	Scale of Values	Dimension Ranges	Levels or Ranges
Understand the operation of analog components	Recognize digital electronics characteristics; resistance identification/operation; coil identification/operation	01–07	Dichotomous	Bad [00–03] Regular [04–06] Good [07–08]	Bad: [00–10]
Learn the concepts of active components	Diode identification/ operation; transistor identification/operation; IC identification/operation	08–13	0: Incorrect	Bad [00–02] Regular [03–04] Good [05–06]	Regular: [11–15]
Learn the concepts of power supply and Arduino	Power supply identification/ operation; digital Arduino; analog Arduino	14–20	1: Correct	Bad [00–01] Regular [02–04] Good [05–06]	Well: [16–20]

3.5 Data collection instruments

To measure the level of achievement of learning outcomes in Digital Electronics, a subject knowledge assessment instrument consisting of 20 dichotomous items (correct/incorrect), specifically designed for the study, was used; as complementary instruments, project assessment rubrics and dichotomous student perception surveys were used. These complementary instruments support qualitative understanding of

the process but are not analyzed quantitatively here; only the 20-item achievement test results appear in Section 4.

Assessments were administered at the beginning and end of the academic semester to both groups, measuring theoretical understanding of digital electronics concepts [36], [37]. Assessment rubrics evaluated project performance, considering theoretical application, originality, problem-solving, and teamwork [38], [39]. Dichotomous surveys, administered before and after the semester, captured students' perceptions of motivation, learning, and the development of practical skills [40]. Additionally, a 20-item achievement test developed by the authors (2025) was used to measure learning outcomes in Digital Electronics. This test was structured around the three dimensions of the study and administered individually in 60-minute sessions.

1. **Validity of the instrument:** Content validity was considered and was assessed by a panel of three expert judges, who reviewed the consistency and precision of the items with respect to the study's objectives. The instrument's internal structure was also assessed through Exploratory Factor Analysis, obtaining a Kaiser-Meyer-Olkin (KMO) adequacy index of 0.680. Bartlett's test produced a statistically significant result ($\chi^2 = 54.399$, df = 15, $p < 0.001$), which means that the values obtained are adequate and allow for the factorial validation of the instrument, as well as its suitability for the proposed application context [41]–[44]. This is shown in Table 4, which summarizes these results.

Table 4. Instrument validity statistics (KMO and Bartlett's test)

Statistical	Value
KMO	0.680
Bartlett test, Chi-square	54.399
Df	15
Significance	<0.001

2. **Instrument reliability:** Instrument reliability was assessed using the Kuder-Richardson 20 (KR-20) coefficient, since the items had to add up to a maximum score of 0 to 20, with a valid answer worth 1 point and an invalid answer worth 0 points, making it appropriate for instruments of this kind with dichotomous-response items. Likewise, an assessment instrument is considered reliable when it produces consistent and stable results in repeated applications, which is in line with [45], [46]. A pilot test was conducted with 30 students, after which items with low discriminative power were removed to improve measurement accuracy. The adjusted instrument was then administered to the population of students selected for the study, obtaining a KR-20 coefficient of 0.814, which indicates a high level of reliability.

3.6 Procedure

There were six main research phases. First we created the sequence of practical projects by choosing the two best embedded systems (Arduino and ESP32) to provide instruction on key Digital Electronics concepts. Second, we used the PBL methodology with the experimental group so students could develop practical projects with the help of their instructor. Thirdly, we collected data using multiple methods such as pre/post-test knowledge checks, project evaluation rubrics, dichotomous surveys, and direct observation. Fourthly, we analyzed this data using SPSS and compared

test results between both groups across three different components. Fifthly, we determined how the intervention affected students' learning outcomes and skill growth and ultimately whether integrating embedded systems into PBL would positively impact academic achievement compared with control subjects. Finally, we put everything together into one complete research paper, including results, analysis, and recommendations for using this method within other engineering courses in the future.

3.7 Experimental design scheme

Figure 1 illustrates the quasi-experimental design used in this study. Two non-equivalent groups of student sections took part: the experimental group of students, which received a PBL intervention using Arduino and ESP32 as the main tools, and the control group of students, which continued with traditional instruction based on lectures without technological mediation. Both groups underwent pre-test and post-test evaluations, which made it possible to carry out a systematic comparison of learning outcomes, partially controlling for external variables.

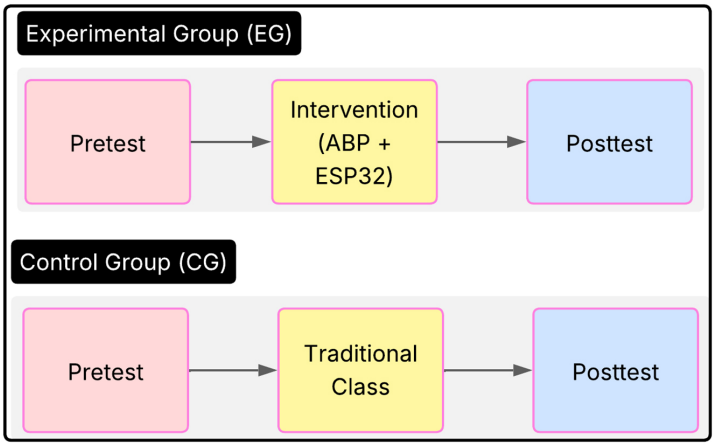


Fig. 1. Educational intervention based on a quasi-experimental design with pre- and post-evaluation of non-equivalent cohorts

3.8 Data analysis

A descriptive analysis using frequencies and percentages was carried out to characterize the data obtained. The Shapiro-Wilk normality test was then applied, taking into account the sample size ($n < 50$). Since the data obtained did not follow a normal distribution ($p < 0.05$), it was necessary to use non-parametric tests.

The Mann-Whitney U test was then used to test all the hypotheses, considering a significance level of $\alpha = 0.05$, in order to identify differences between both groups of students studied: the control group and the experimental group.

3.9 Ethical considerations

Before carrying out the study, consideration was given to applying the ethical principles concerning human participation; accordingly, student participation was voluntary, with all students informed in the classroom, before the research activities took place, about the objectives set out for the study and the use of the data for

purely academic purposes. Likewise, the confidentiality of the information and the anonymity of the participants were guaranteed throughout the research process.

4 RESULTS

At this stage, the results obtained from the quantitative analysis of the data are presented; these are organized and presented at three levels: descriptive results, normality analysis, and hypothesis testing.

4.1 Descriptive results

Table 5 presents the overall student performance according to achievement levels. For the dependent variable, learning outcomes in Digital Electronics, the pretest data show a similar distribution between the control and experimental groups. In the control group, 90% of the students were at the low level, while in the experimental group this proportion was 85%, suggesting comparable initial conditions.

Table 5. Comparison of achievement levels of learning outcomes in Digital Electronics: pre- and post-test analysis

Group	Moment	Low	Medium	High	Total
Control	Pretest	18.0 (90.0%)	2.0 (10.0%)	0.0 (0.0%)	20
	Posttest	15.0 (75.0%)	5.0 (25.0%)	0.0 (0.0%)	20
Experimental	Pretest	17.0 (85.0%)	3.0 (15.0%)	0.0 (0.0%)	20
	Posttest	4.0 (20.0%)	5.0 (25.0%)	11.0 (55.0%)	20

In the post-test, changes were observed in the distribution of achievement levels. In the control group, 75% of students remained at the low level and 25% reached the medium level, with no students at the high level. In contrast, the experimental group showed a more balanced distribution, with 20% at the low level, 25% at the medium level, and 55% at the high level.

4.2 Descriptive results by dimensions

1. **Dimension 1: Understanding the operation of analog components:** As shown in Table 6, in the pretest, 70% of the experimental group had students at the low level, while the control group had 60% at this level. In the posttest, the experimental group showed a reduction in the low level to 0% and an increase in the high level to 85%. Meanwhile, the control group showed a moderate increase in the high level, rising from 5% to 20%.

Table 6. Achievement levels for dimension 1 (analog components): pre- and post-test comparison

Group	Moment	Low	Medium	High	Total
Control	Pretest	12.0 (60.0%)	7.0 (35.0%)	1.0 (5.0%)	20
	Posttest	7.0 (35.0%)	9.0 (45.0%)	4.0 (20.0%)	20
Experimental	Pretest	14.0 (70.0%)	4.0 (20.0%)	2.0 (10.0%)	20
	Posttest	0.0 (0.0%)	3.0 (15.0%)	17.0 (85.0%)	20

2. **Dimension 2: Understanding the concepts of active components:** In the initial measurement, both groups showed a similar distribution, with a predominance of the low level. In the post-test, the experimental group increased the percentage of students at the high level from 10% to 60%, while the control group concentrated 80% of the students at the low level (Table 7).

Table 7. Achievement levels for dimension 2 (active components): pre- and post-test comparison

Group	Moment	Low	Medium	High	Total
Control	Pretest	13.0 (65.0%)	3.0 (15.0%)	4.0 (20.0%)	20
	Posttest	16.0 (80.0%)	4.0 (20.0%)	0.0 (0.0%)	20
Experimental	Pretest	12.0 (60.0%)	6.0 (30.0%)	2.0 (10.0%)	20
	Posttest	3.0 (15.0%)	5.0 (25.0%)	12.0 (60.0%)	20

3. **Dimension 3: Learning the concepts of power supply and Arduino:** In the initial test, 70% of the students in the experimental group were at a low level, while 45% of the students in the control group registered a low level. In the final test, 50% of the students who received the PBL methodology in the experimental group reached a high level, while the control group, who received traditional teaching, only achieved a small increase in the high level, reaching 10% (see Table 8).

Table 8. Achievement levels for dimension 3 (power supply and Arduino): pre- and post-test comparison

Group	Moment	Low	Medium	High	Total
Control	Pretest	9.0 (45.0%)	10.0 (50.0%)	1.0 (5.0%)	20
	Posttest	9.0 (45.0%)	9.0 (45.0%)	2.0 (10.0%)	20
Experimental	Pretest	14.0 (70.0%)	5.0 (25.0%)	1.0 (5.0%)	20
	Posttest	4.0 (20.0%)	6.0 (30.0%)	10.0 (50.0%)	20

4.3 Normality test

The Shapiro-Wilk normality test was applied, considering the sample size ($n < 50$). The results indicated that the data do not follow a normal distribution in the analyzed variables ($p < 0.05$), both in the pretest and in the posttest (refer to Table 9).

Table 9. Results of the Shapiro-Wilk normality test for both groups in all dimensions

Variable	Moment	W	df	Next
Digital Electronics (general)	Pre-test	0.850	20	0.005
	Post-test	0.838	20	0.004
Dimension 1: Analog Components	Pre-test	0.805	20	0.001
	Post-test	0.882	20	0.023
Dimension 2: Active Components	Pre-test	0.903	20	0.046
	Post-test	0.838	20	0.004
Dimension 3: Power supply and Arduino	Pre-test	0.899	20	0.039
	Post-test	0.869	20	0.014

4.4 Hypothesis testing

Since the normality assumptions were not met, the non-parametric Mann-Whitney U test was used to compare the results between the students in the control group and those in the experimental group.

Students who take part in an intervention based on PBL, mediated by embedded systems, are expected to reach significantly higher performance levels compared with those who follow a traditional approach.

1. **General Hypothesis: Teaching Digital Electronics:** In the dependent variable, no statistically significant differences were identified in the pretest ($U = 192.000$; $p = 0.826$), supporting the initial equivalence between the groups. However, in the posttest, statistically significant differences were observed in favor of the experimental group ($U = 44.500$; $p < 0.001$). Table 10 presents the detailed results.
   - Pretest: $U = 192.000$, $Z = -0.220$, $p = 0.826$ (no significant difference).
   - Posttest : $U = 44.500$, $Z = -4.234$, $p < 0.001$ (significant difference).

Table 10. Mann-Whitney U test results for the general hypothesis on the teaching of digital electronics

Statistical Analysis	Group (n = 20)	Control	Experimental
Pretest, average range	Test applied	20.90	20.10
Pretest, sum of ranks	$U = 192.000$	418.00	402.00
Posttest, average range	$Z = -0.220$, $p = 0.826$	12.73	28.28
Posttest, sum of ranks	$U = 44.500$	254.50	565.50
	$Z = -4.234$, $p < 0.001$		

2. **Dimension 1: Understanding the operation of analog components:** In the analog components dimension, no significant differences were found in the pretest ($p = 0.330$), while significant differences were observed in the posttest ($U = 50.500$; $p < 0.001$). Table 11 presents the detailed results.
   - Pretest: $U = 165.000$, $Z = -0.973$, $p = 0.330$ (no significant difference).
   - Posttest: $U = 50.500$, $Z = -4.125$, $p < 0.001$ (significant difference).

Table 11. Mann-Whitney U test results for dimension 1 (analog components)

Statistical Analysis	Applied Test	Control	Experimental
Pretest, mean rank	$U = 165.000$	18.75	22.25
Pretest, sum of ranks	$Z = -0.973$, $p = 0.330$	375.00	445.00
Posttest, mean rank	$U = 50.500$	13.03	27.98
Posttest, sum of ranks	$Z = -4.125$, $p < 0.001$	260.50	559.50

3. **Dimension 2: Understanding the concepts of active components:** In the active components dimension, the pre-test results showed no significant differences ($p = 0.387$); however, the post-test identified significant differences between the groups ($U = 51.000$; $p < 0.001$). Table 12 presents the detailed results.
   - Pre-test: $U = 169.000$, $Z = -0.865$, $p = 0.387$ (no significant difference).
   - Post-test: $U = 51.000$, $Z = -4.126$, $p < 0.001$ (significant difference).

Table 12. Mann-Whitney U test results for dimension 2 (active components)

Statistical Analysis	Applied Test	Control	Experimental
Pretest, mean rank	U = 169.000	18.95	22.05
Pretest, sum of ranks	Z = –0.865, p = 0.387	379.00	441.00
Posttest, mean rank	U = 51.000	13.05	27.95
Posttest, sum of ranks	Z = –4.126, p < 0.001	261.00	559.00

4. **Dimension 3: Learning the concepts of power supply and Arduino:** In the dimension corresponding to power supplies and Arduino, no significant differences were observed in the pre-test (p = 0.105). In contrast, the post-test showed statistically significant differences (U = 110.000; p = 0.013). Table 13 presents the detailed results.
   - Pre-test: U = 141.500, Z = –1.621, p = 0.105 (no significant difference).
   - Post-test: U = 110.000, Z = –2.476, p < 0.013 (significant difference).

Table 13. Mann-Whitney U test results for dimension 3 (power supply and Arduino)

Statistical Analysis	Applied Test	Control	Experimental
Pre-test, mean rank	U = 141.500	23.43	17.58
Pre-test, sum of ranks	Z = –1.621, p = 0.105	468.50	351.50
Post-test, mean rank	U = 110.000	16.00	25.00
Post-test, sum of ranks	Z = –2.476, p = 0.013	320.00	500.00

5 DISCUSSION

The results obtained in this study demonstrate that the implementation of a PBL methodology, mediated by the use of embedded systems, is associated with significant improvements in learning outcomes in Digital Electronics. These improvements were observed in both the dependent variable and each of the dimensions evaluated, suggesting a consistent impact of the proposed pedagogical approach. However, beyond the observed results, it is important to consider that the effectiveness of the approach depends largely on the instructional design and the context in which it is implemented.

5.1 Interpretation of results by dimension

The findings of this study confirm that a teaching methodology based on PBL, mediated by embedded systems (Arduino and ESP32), produces significant improvements in student learning outcomes in the three evaluated dimensions of the Digital Electronics course.

1. **Dimension 1: Understanding the operation of analog components:** According to results, the experimental group experienced a major change, which can be seen through the removal of their original low score and increase to a higher number (high level). This change in score can be attributed to the hands-on nature of the

activity that required students to actively engage with electronic components. This finding relates to the work of Vidal-Silva et al. [17], who have stated that the use of technological devices (such as Arduino) contributes to a better understanding of abstract concepts through their real-world application. It should also be noted that there may be other influencing factors outside of this activity that could have contributed to this improvement, such as motivation levels or type of group interaction.

The decrease in students who were assessed at the "low" level from 70% to 0% and the increase in students who were assessed at the "high" level from 70% to 85% clearly demonstrates a major change in the understanding of resistors and inductors for students. This supports the hypothesis that when students use active learning strategies, including hands-on experimentation with electrical circuits, they are better able to internalize and apply to abstract concepts. The results of this study corroborate the findings in a systematic review by Lavado-Anguera et al., which showed that when students interact with concrete materials and experience solving genuine practical problems, their ability to learn significantly improved. Likewise, it has been shown by Mutanga that students who have had their learning based on PBL will gain more confidence and greater long-term conceptual retention because of the active nature of their roles in problem resolution versus simply passively receiving instruction.

2. **Dimension 2: Understanding the concepts of active components:** The experimental group displayed significantly higher achievement levels than the control group. The results can be understood in light of Yong's work [20], which suggests that students who conduct hands-on projects with microcontrollers develop a deeper and more functional understanding of electronic systems by observing how they work as dynamic systems. Additionally, students at the intermediate level demonstrate that the process of learning is not a homogeneous experience, and the variability in learning can be partially addressed by providing differentiated strategies that accommodate various rates of learning and styles of learning.

   An increase from 10% to 60% of students reaching the "high" achievement level demonstrates that there is significantly higher understanding of diodes, transistors, and ICs. This finding is supported by Yong [20], who states that programming microcontrollers and observing the behavior of active components in controlled settings leads to functional understanding, which is an essential skill for a successful career in electronic engineering. Similar to Yong [20], Tupac-Yupanqui et al. [24] have shown that when Latin American undergraduate college students engaged in hands-on experimentation with microcontrollers, there was significantly greater improvement in their understanding of conceptual materials than through traditional lecture-based instruction; particularly for components that have complex behavior and cannot be easily visualized without performing hands-on experiments.
3. **Dimension 3: Learning the concepts of power supply and Arduino:** While considerable improvements occurred, these were not all as pronounced as the other dimensions (5–50% on the "high" dimension); however, they were still statistically significant ($U = 110.000$; $Z = -2.476$; $p = 0.013$), which could result from the higher levels of complexity involved in programming concepts/content. Since programming is generally a barrier for students initially, these findings may correlate with those found by Pereira et al. [19], who highlight that instructional design and teacher support are two crucial components to the effective use of embedded platforms in learning.

   Perhaps the smaller effect found for this dimension could also be attributed to the higher level of complexity found within the topic of power supply and

the steep learning curve when programming Arduino boards, assuming no prior experience with coding. The findings of this study support those reported by Pereira et al. [19], who note that although device control logic can be easily learned using a variety of accessible platforms, such as XBEE, Bluetooth, or Wi-Fi, the programming of these devices generally requires substantial additional resources for both scaffolding and instruction to fully learn the associated concepts of programming. In addition, it has been found that positive results generated with Arduino are maximized in introductory engineering classes when the lab activities are systematically structured and sequenced progressively; this was achieved in the present study.

5.2 Comparison with studies previous

This study has added to an already-large body of evidence about PBL and Embedded Systems in Engineering Education in two key ways.

First, with regard to the pedagogical structure, this study provides a structured experience with PBL using Embedded Systems. Instead of providing isolated experiences with an Arduino as reported in some studies [17], [24], there is now a structured sequence of nine planned teaching sessions in alignment with the official Digital Electronics Curriculum. The learning outcomes were measured using validated instruments with KMO = 0.680 and KR-20 = 0.814 that provide quantitative data for three measurement dimensions. This represents a level of curricular integration and rigor in measurement that is uncommon in the current Latin American literature on Embedded Systems in Education [7], [23]. This matches Awwad [22], who reported similar gains from embedding active learning directly into an electronics curriculum rather than as isolated activities.

Second, this study provides robust, quantitative statistical evidence of PBL with Embedded Systems using three non-parametric hypothesis tests in the three measurement dimensions (overall: $Z = -4.234$; $p < 0.001$, analog components: $Z = -4.125$; $p < 0.001$, active components: $Z = -4.126$; $p < 0.001$, power supply and Arduino: $Z = -2.476$; $p = 0.013$). The statistical rigor of this study increases the scientific validity of the findings and supports their curricular relevance to Engineering Education at the undergraduate level. These results strengthen the empirical evidence base for PBL in engineering education documented by Lavado-Anguera et al. [14] and Quinapallo-Quintana and Baldeón-Zambrano [11] at the international level, while providing contextualized evidence from a Peruvian public university, an environment that has been underrepresented in the literature on engineering education.

Third, with regard to accessibility and replicability: the use of open-source and low-cost platforms (Arduino and ESP32) makes this methodology especially relevant for Latin American educational contexts characterized by limited material resources, as highlighted by Ronceros [23] and Amaya Huayama and Olazabal Urbina [5].

More broadly, the study's results reinforce the idea that the potential of embedded systems in education lies not only in their use as a technological tool but also in their integration within a coherent pedagogical strategy. Unlike previous studies that report isolated implementations [25], [26], this work proposes a structured articulation between PBL and the use of Arduino and ESP32, which could explain the differences observed in the results. This matches Strode and Mežinska [16], who likewise found that clearly staged, collaborative PBL design improves student outcomes. In response to this situation, the findings contribute to closing the gap identified in the literature regarding the lack of curricular integration of these technologies [27].

5.3 Limitations of the study

Despite the contributions presented in this study, it is necessary to acknowledge certain limitations that arose during the methodological experience and the evaluation carried out in both groups.

As indicated in Section 3.1, the same person acted as both researcher and instructor for both groups, which may have influenced the delivery of classes or the evaluations carried out in ways that cannot be separated from the actual effect of the methodology. For future replications, having independent instructors would help isolate this potential threat to internal validity.

Due to the sample size of 40 (material distributed among 2 classes within one university), it would be hard to generalize findings from this data across diverse educational institutions, types of institutions, or social/economic contexts. Since the participants were assigned to groups in a non-random manner as part of a quasi-experimental study design, any potential pre-existing differences existed between the 2 classes that could not be controlled by using a pre-test. As Ballance [28] notes, this is a recurrent issue in quasi-experimental educational research.

Because the study was conducted over 1 semester only, it cannot be said whether or not long-term retention of learning occurs or whether learning gains from the study are permanent. Future studies should include follow-up measurements no sooner than 1 semester following the learning activity to measure knowledge transfer (applying knowledge in practice) and retention (what students still recall over time).

The dichotomous measure used in the study (while validated statistically) measured only whether answers were correct or incorrect, providing no measure for the depth and quality of conceptual understanding a student demonstrates. Adding a Likert scale measure as a complement to the dichotomous measure would give more complete information about learning processes and the student's perspective on those processes.

This study was only done at 1 college, in the largest city in Peru. Therefore, all institution-related factors, such as infrastructure, faculty culture, and student context, may have influenced the results to limit direct comparisons with any private schools, technical institutes, or educational institutions in a different country and/or region.

While these restrictions do not affect the dependability of the results of this study, they were also identified as specific guidelines for future research. Future research should include investigating different types of samples from a variety of institutions (multiple samples), using a larger variety of research design methods (mixed-methods designs), and determining the long-term effects of implementing PBL and embedded systems on developing professional skills.

The practical implications of this study provide significant solutions to use with caution because of problems with using quasi-experimental designs and having no equivalent groups that would cause selection bias to be affected and impact the internal validity of the results. Although pretest results show comparable conditions at the start of this study, there is no way to control for some additional variables, such as student motivation, prior knowledge, and teacher characteristics, that could influence the results. Additionally, because of the limited size of this sample, it cannot be assumed that the findings from this study are equivalent to the larger population of students; therefore, the duration of the intervention does not show the sustainability of the learning over the long term.

Future research may further explore this approach through additional study methodology, study designs that are more robust, and the use of body-oriented methods. In addition, longitudinal studies could be conducted to evaluate the short-term impact of this approach and the transfer/retention of learned material on transversal skills, such as critical thinking, creativity, and collaborative work, after utilizing PBL as mediated through embedded systems.

6 CONCLUSION

This study assessed the effect of using a PBL approach through embedded systems on improving student academic performance regarding conceptual understanding and practical application within digital electronics.

The results demonstrate that the PBL approach used in conjunction with hardware development tools (such as Arduino and ESP32) is an effective way of bridging the gap between theory and practice in electronics education, thus providing students with enhanced understanding of the technical content and providing for a more active, contextualized, and problem-solving approach to their education, consistent with the needs of today's engineering education.

From a pedagogical perspective, this study supports the need to move away from traditional pedagogical methods of teaching in technical fields and towards more active methodologies, allowing for greater student participation in their own learning process. Within this context, the relevance of creating active learning experiences that will progressively integrate theoretical content with meaningful practical experiences is emphasized in order to eliminate their isolated treatment.

This study is an addition to existing literature by concluding that in a coherent pedagogical framework, an embedded system no longer has a supplementary role and can become a key element of that framework. This has implications for higher education institutions with very limited financial resources, where low-cost technologies would allow for the possibility of educational innovation.

Another consideration is that the findings are limited, and the findings should be interpreted within the limitations of the study; these limitations include the use of non-equivalent groups, a small sample size, and an intervention lasting for a relatively short period of time. These limitations may indicate how generalizable the results are and how durable the effects observed in this study may be over time.

From an educational perspective, future research should be conducted to further analyze this pedagogical perspective with more rigorous experimental designs, larger sample sizes, and longitudinal studies to measure how long learning outcomes will be sustained. Another suggestion for future studies is to investigate how this method impacts the development of transversal skills like critical thinking, creativity, and collaboration through instructional methods.

The findings of this study assess the integration of active learning strategies with the ongoing access to and use of technology, whether hardware or software, in combination with traditional means, as important avenues for improving teaching across the different areas of engineering, especially in situations where a gap between theory and practice persists. In this context, there is clear evidence of the need for greater integration between pedagogical methods that reflect the demands of today's technological environment and engineering teaching methods. Based on what was found in this study, there is also clear evidence of an urgent need to develop various pedagogical models that provide effective integration between the theories taught in the classroom, directing each class session toward field practices

oriented at different levels of engineering programs in order to better respond to the constantly changing challenges currently faced by engineering instructors.

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