Multidisciplinary Integration in Mechatronics Engineering: An Advanced Problem-Based Project Approach

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Abstract:

The education in Control and Automation Engineering within the context of Industry 4.0 and 5.0 requires a paradigmatic shift, moving from fragmented curricula to competency-based integrated models. This paper presents an analysis of the implementation of an integrative project model grounded in Project-Based Learning (PjBL), applied over five years in the Control and Automation Engineering program at Instituto Mauá de Tecnologia. The project evolved along two curricular axes: Axis I (Instrumentation, Control Systems, and Microcontrollers, 2019 - 2024) and Axis II (Industrial Automation, Programmable Logic, and Actuator Systems, 2024 - 2025). A mixed methodology was employed, using unified analytical rubrics to directly assess competencies aligned with ABET Student Outcomes, enabling the measurement of proficiency and pedagogical impact. The results reveal significant improvements in design (SO 2), complex problem-solving (SO 1), and teamwork (SO 5), as well as strengthening transversal skills such as critical thinking and project management. The model demonstrated strong alignment with the CDIO framework, contributing to the education of engineers prepared for Industry 5.0. However, lower performance in User Experience (SO 2) was identified, indicating the need to reinforce human factors in the curriculum.

Introduction

Engineering education in the fields of Control, Automation, and Mechatronics is undergoing a profound transformation driven by the technological, social, and organizational changes associated with Industry 4.0 and the emerging paradigm of Industry 5.0. These transformations demand engineers who are not only technically proficient, but also capable of operating within complex sociotechnical systems that integrate hardware, software, data, and human-centered considerations. As a result, traditional curricula organized around isolated disciplinary courses have increasingly struggled to provide students with the integrative competencies required by contemporary professional practice [1,2].

Within this context, a growing body of literature argues for a paradigmatic shift from content-centered education toward competency-based models that emphasize systems thinking, interdisciplinarity, and experiential learning [3,4]. Project-Based Learning (PjBL) has emerged as one of the most prominent pedagogical approaches to address these challenges, as it situates learning within open-ended, authentic problems that resemble real engineering practice. By engaging students in the conception, design, implementation, and validation of functional systems, PjBL promotes deeper learning, autonomy, and the development of both technical and transversal competencies [5,6].

However, despite its widespread adoption, PjBL is often implemented in a fragmented manner, confined to individual courses or short-term projects. Such implementations may limit its potential impact, as they fail to address one of the central challenges of engineering education: the structural compartmentalization of knowledge across curricular units. In programs related to Control and

Automation Engineering, this fragmentation is particularly problematic, given the inherent interdependence between instrumentation, control theory, embedded systems, industrial automation, and actuation technologies. Without intentional curricular integration, students may struggle to transfer knowledge across domains and to understand engineering systems holistically.

To address this limitation, the CDIO (Conceive–Design–Implement–Operate) framework has been proposed as a complementary model to PjBL, offering a structured approach for integrating disciplinary knowledge with professional engineering practice across the curriculum [3,4]. When aligned with accreditation frameworks such as the ABET Student Outcomes and national curriculum guidelines, CDIO-oriented projects can provide a coherent structure for developing and assessing competencies over time, rather than within isolated educational experiences.

This paper presents a longitudinal analysis of an Integrative Project model implemented over five years in a Control and Automation Engineering program. The model was structured around two curricular axes: Axis I, focusing on Instrumentation, Control Systems, and Microcontrollers (2019–2024), and Axis II, emphasizing Industrial Automation, Programmable Logic Controllers, and Actuator Systems (2024–2025). The central premise of the model is that mandatory, curriculum-wide integration, supported by unified analytical rubrics aligned with ABET Student Outcomes, can mitigate curricular fragmentation and foster the progressive development of technical and transversal competencies.

The objective of this study is to analyze the pedagogical impact of this integrative PjBL model by examining student performance across multiple competency dimensions, including complex problem solving (SO 1), engineering design (SO 2), teamwork (SO 5), and related transversal skills. In addition to identifying areas of improvement, the study also seeks to diagnose persistent gaps, particularly in human-centered aspects such as user experience and interface design, which are increasingly central to the vision of Engineering 5.0. By doing so, this work contributes empirical evidence to ongoing discussions on how multidisciplinary integration and long-term project-based approaches can enhance the formation of engineers prepared for contemporary industrial and societal challenges.

Methodology

This study adopts a longitudinal, descriptive research design to examine the pedagogical impact of a multidisciplinary Integrative Project grounded in Project-Based Learning. The analysis focuses on direct assessment of student competencies over time, complemented by systematic qualitative observations from instructors.

Given the curricular and institutional nature of the intervention, the study aims to identify performance trends and patterns rather than to establish causal relationships.

Educational Context and Participants

The study was conducted within an undergraduate Control and Automation Engineering program at a higher education institution. The Integrative Project was embedded as a mandatory curricular component involving multiple coordinated course units.

The implementation was structured along two curricular axes:

- Axis I (2019–2024): Instrumentation, Control Systems, and Microcontrollers. Projects in this axis emphasized signal acquisition, conditioning of physical variables, implementation of control algorithms, and integration with embedded systems.
- Axis II (2024–2025): Industrial Automation, Programmable Logic Controllers (PLCs), and Actuator Systems. Projects focused on industrial communication networks, sequential logic and pneumatic actuation.

Each academic year involved approximately 30 students in Axis I and 35 students in Axis II, organized into multidisciplinary teams. All enrolled students participated, as the project was a required curricular activity.

Structure of the Integrative Project

The Integrative Project was designed to emulate the engineering product development lifecycle and was aligned with the CDIO framework through four main stages:

1. <u>Conception:</u> Problem definition, requirements analysis, and identification of technical, operational, and human constraints.
2. <u>Design:</u> System modeling, component selection, control strategies, and preliminary interface design.
3. <u>Implementation:</u> Hardware assembly, software development, PLC programming, and system integration.
4. <u>Validation and Operation:</u> Functional testing, performance evaluation, iterative refinement, and final demonstration.

This structure enabled progressive integration of disciplinary content while reinforcing professional engineering practices. Figure 1 presents the overall structure of the Integrative Project and the interaction between the two curricular axes, illustrating how disciplinary contents are intentionally integrated across project stages.

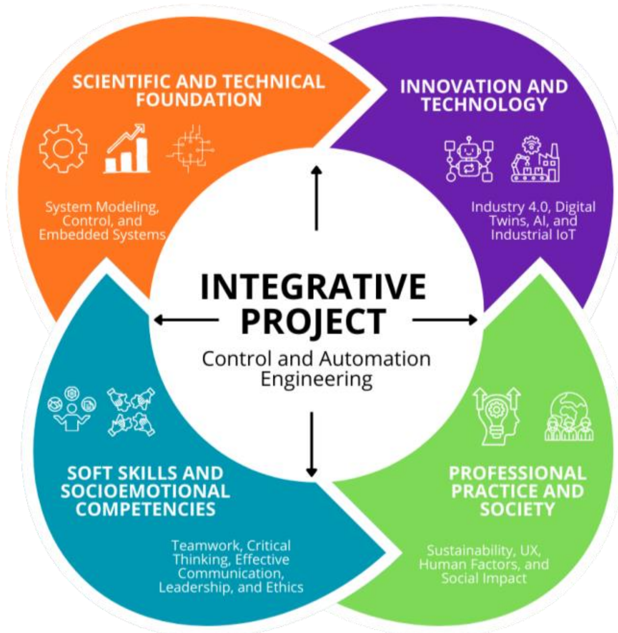

Figure 1. Structure of the Integrative Project

Figure 2 illustrates the operational workflow of the project, highlighting the iterative cycles between simulation, physical prototyping, testing, and validation that characterize the PjBL approach adopted in this study.

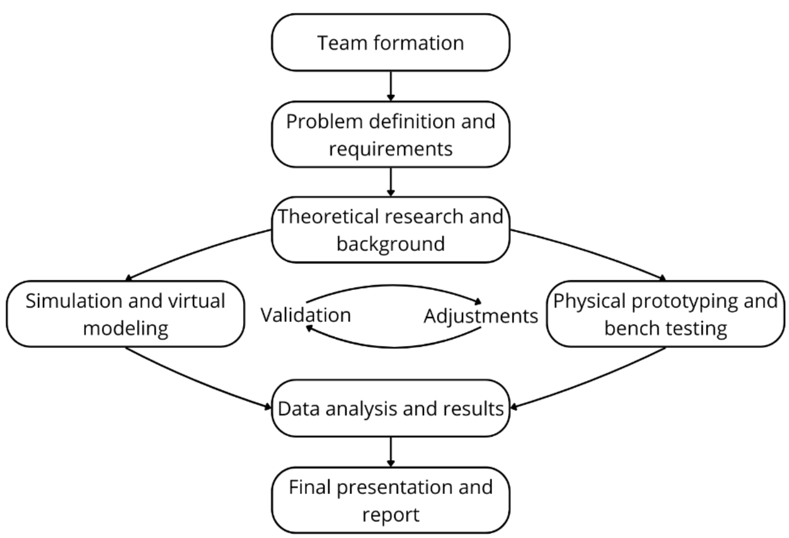

Figure 2. Flowchart of the stages of the integrative project

Assessment Instruments and Rubrics

Student performance was evaluated using unified analytical rubrics aligned with the ABET Student Outcomes (SO) and the Brazilian National Curriculum Guidelines (DCNs). The rubrics were jointly developed and applied by instructors from the participating course units to ensure coherence and comparability across disciplines.

Each criterion was assessed on a numerical scale from 0 to 10, corresponding to four performance levels: Insufficient, Basic, Proficient, and Excellent. The assessed competency dimensions included:

- Complex Problem Solving (SO 1): Identification, modeling, and solution of engineering problems under realistic constraints.
- Engineering Design (SO 2): Development of technically viable solutions that meet defined requirements.
- Teamwork (SO 5): Effective collaboration, leadership, task allocation, and ethical interaction.
- Communication (SO 3): Quality and clarity of technical documentation and oral presentations.
- Project Management: Planning, scheduling, and adherence to project milestones.
- User Experience (UX): Usability, clarity, ergonomic adequacy, and safety of HMIs and control interfaces.

Table 1 presents representative examples of the analytical rubric criteria, illustrating how ABET-aligned competencies were operationalized into observable performance indicators.

Table 1. Examples of the criteria applied to measure proficiency

Competency (ABET SO)	**Assessment Criterion (Rubric Example)**	**Excellent Performance Indicator (Score 9–10)**
Problem Solving (SO 1)	Application of engineering and mathematical principles.	The project demonstrates accurate mathematical modeling and correct application of control algorithms on real hardware.
Engineering Design (SO 2)	Development of a solution under technical constraints.	The prototype meets all technical requirements, with careful selection of sensors and actuators.
Teamwork (SO 5)	Collaboration and an inclusive environment.	All members participate actively; there is clear leadership, task division, and ethical conflict resolution.
User Experience (UX)	HMI interface and usability.	The interface is intuitive, provides clear process feedback, and complies with safety and ergonomics standards.

Data Collection and Analysis Procedures

Quantitative data consisted of aggregated rubric scores collected annually for each competency dimension and curricular axis. Mean values were calculated to characterize overall performance and to identify longitudinal trends.

Qualitative data were derived from systematic instructor observations during project milestones, laboratory sessions, and final demonstrations. These observations were used to contextualize quantitative results, particularly regarding student engagement and interdisciplinary integration.

Data analysis emphasized descriptive statistics and longitudinal interpretation, without inferential testing.

Ethical Considerations and Limitations

All data analyzed in this study were collected as part of standard academic assessment procedures. Student identities were anonymized during data aggregation, and participation in the research did not affect individual academic outcomes beyond regular course evaluation.

The study presents inherent limitations. The absence of a control group restricts causal inference, and rubric-based evaluations may be subject to evaluator bias despite the use of unified criteria. Furthermore, the findings reflect a single institutional context, which may limit their generalizability to other engineering education programs.

Results

This section presents the empirical results obtained from the aggregated analytical rubric scores collected throughout the implementation of the Integrative Project model. The results are reported using mean values on a 0–10 scale, corresponding to the competency dimensions defined in the assessment instruments.

The analysis focuses on two complementary perspectives:

i. current performance levels across competency dimensions, and
ii. longitudinal trends observed over the implementation period, particularly in relation to the transition from optional to mandatory curricular integration.

Performance by Competency Dimension

Table 2 presents the current average performance levels for each assessed competency dimension, aligned with ABET Student Outcomes and national curriculum guidelines.

Table 2. Detailed Analysis of Current Performance Compared to International Metrics

Competency	Description and ABET Alignment	Current Average (0–10)	Observed Evolution

C1 – Teamwork	SO 5: Effective functioning on teams.	8.6	Greatest growth observed after the implementation of mandatory integration.
C2 – Technical Knowledge	SO 1: Identify and solve complex engineering problems.	8.4	Consolidation of the practical application of theory.
C3 – Critical Thinking	Related to SO 1 and SO 2.	8.2	Improvement in the ability to diagnose failures.
C4 – Effective Communication	SO 3: Communicate effectively with diverse audiences.	8.1	Refinement in scientific reports and posters.
C5 – Project Management	Related to SO 5 and transversal outcomes.	7.9	Stabilization in meeting project schedules.
C6 – User Experience (UX)	SO 2: Design focused on specific needs.	7.3	Point of attention: lowest average in the cycle.

Overall, the results indicate higher performance in technical and collaborative competencies, with comparatively lower performance observed in human-centered design aspects.

- C1 – Teamwork (SO 5) achieved the highest mean score (8.6), indicating strong student performance in collaboration, task distribution, leadership, and ethical interaction within multidisciplinary teams.
- C2 – Technical Knowledge and Problem Solving (SO 1) presented a mean score of 8.4, reflecting students' ability to identify, model, and solve complex engineering problems involving real systems and constraints.
- C3 – Critical Thinking, related to both SO 1 and SO 2, reached a mean score of 8.2, suggesting improved diagnostic skills, iterative reasoning, and evaluation of alternative solutions.
- C4 – Effective Communication (SO 3) achieved an average score of 8.1, indicating satisfactory performance in technical reports, oral presentations, and visual documentation of project outcomes.
- C5 – Project Management, associated with transversal outcomes and teamwork-related competencies, presented a mean score of 7.9, reflecting relative stabilization in planning and schedule compliance as project complexity increased.
- C6 – User Experience (UX – SO 2) obtained the lowest mean score (7.3), highlighting persistent challenges related to usability, interface clarity, and ergonomic considerations.

These results demonstrate an uneven distribution of maturity across competency dimensions, with human-centered aspects lagging behind technical and collaborative skills.

Longitudinal Trends and the Impact of Mandatory Integration

Analysis of the aggregated scores over time reveals progressive improvement across most competency dimensions, particularly after the implementation of mandatory curricular integration starting in 2022.

Before mandatory integration, performance gains were inconsistent, and student engagement with multidisciplinary requirements varied significantly between teams. Following the transition to mandatory integration, the data indicate:

- Greater consistency in teamwork performance, reflected in higher mean scores and reduced variability.
- Improved alignment between system design and implementation, especially in Axis II projects involving PLCs, industrial communication, and actuation systems.
- More stable project management performance, despite increased technical complexity and integration demands.

These trends suggest that compulsory integration across multiple course units played a central role in consolidating the intended pedagogical effects of the Integrative Project model.

Evolution of Project Complexity and Student Outputs

In addition to quantitative performance metrics, qualitative analysis of project artifacts indicates a clear evolution in technical complexity throughout the implementation period.

Early projects developed within Axis I typically involved basic sensor monitoring, signal conditioning, and single-loop control applications. In later cycles, particularly within Axis II, student teams produced high-fidelity prototypes featuring dynamic behavior, industrial communication networks, sequential logic, and coordinated multi-actuator systems.

This progression reflects not only increased technical sophistication, but also students' growing ability to manage interdependencies between hardware, software, and control logic within integrated engineering systems.

Comparative Visualization of Competency Development

To facilitate a comparative interpretation of performance across competency dimensions, Figure 3 presents a visual comparison of the mean scores aligned with ABET and DCN metrics.

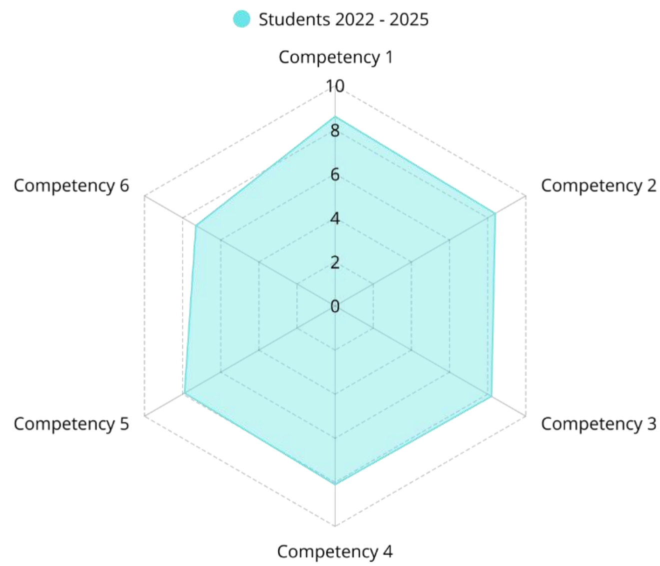

Figure 3. Performance Comparison: ABET and DCN Metrics

The figure highlights the relative maturity of teamwork, technical knowledge, and problem-solving competencies, as well as the consistently lower performance associated with user experience. This visualization reinforces the quantitative findings presented in Table 2 and provides an integrated view of strengths and weaknesses within the current implementation of the model.

Summary of Key Results

The results indicate that the Integrative Project model is associated with:

- High performance in teamwork and technical problem solving;
- Progressive improvement in critical thinking and communication skills;
- Increased consistency following the adoption of mandatory curricular integration;
- A persistent performance gap in user experience and human-centered design.

These findings establish a clear empirical basis for the discussion presented in the following section, where the implications of these results are examined in relation to Engineering 5.0 and multidisciplinary engineering education frameworks.

Discussion

The results presented in this study provide empirical support for the effectiveness of a mandatory, multidisciplinary Integrative Project model in fostering the development of both technical and transversal competencies in Control and Automation Engineering education. When interpreted in light of existing literature on Project-Based Learning (PjBL) and the CDIO framework, several relevant insights emerge.

First, the consistently high performance observed in teamwork (SO 5) aligns with prior studies that identify collaborative project environments as a key mechanism for developing interpersonal and professional skills in engineering education [3,6]. The longitudinal nature of the model appears to have amplified this effect, as students were repeatedly exposed to team-based problem solving across multiple curricular stages. Unlike short-term or isolated PjBL implementations, the present model required sustained collaboration under increasing technical complexity, which may explain the progressive stabilization and maturation observed in teamwork-related outcomes.

Second, the strong performance in complex problem solving and technical knowledge (SO 1) supports the argument that integrative, hands-on projects enhance students' ability to transfer theoretical knowledge to real systems. The alignment of project stages with the CDIO life cycle contributed to reinforcing this transfer, as students were required to conceive, design, implement, and validate functional prototypes rather than merely simulate solutions. This finding is consistent with previous research emphasizing the role of authentic engineering tasks in promoting deep learning and systems thinking [3,4].

The transition from optional to mandatory curricular integration represents a critical element in understanding the observed trends. Prior to this transition, performance gains were uneven, and student engagement with interdisciplinary requirements varied significantly. Following mandatory implementation, the results indicate greater consistency across teams and competency dimensions. This suggests that structural curricular decisions, rather than pedagogical strategies alone, play a decisive role in the success of multidisciplinary PjBL initiatives. Similar observations have been reported in studies highlighting the limitations of voluntary or peripheral project experiences within otherwise fragmented curricula [5].

Despite these positive outcomes, the persistently lower performance observed in user experience (UX) highlights an important limitation of the current model. While UX-related criteria were formally included in the assessment rubrics, the results suggest that students tended to prioritize functional and technical requirements over human-centered considerations. This imbalance reflects a broader challenge in engineering education, where human factors, usability, and ergonomics are often treated as secondary to technical performance. From an Engineering 5.0 perspective, this finding underscores the need to more explicitly integrate human-centered design methodologies, such as Design Thinking and usability testing, into the early stages of project conception.

Finally, it is important to acknowledge the contextual nature of these findings. The observed improvements cannot be attributed solely to the Integrative Project model, as factors such as instructor experience, institutional culture, and cohort characteristics may also have influenced outcomes. Nevertheless, the convergence between quantitative trends and qualitative observations strengthens the credibility of the interpretations presented.

Conclusions

This study examined the longitudinal implementation of a multidisciplinary Integrative Project model grounded in Project-Based Learning and structured around the CDIO framework within a

Control and Automation Engineering program. By employing unified analytical rubrics aligned with ABET Student Outcomes, the study provided a direct assessment of student competency development over a five-year period.

The results indicate that mandatory curricular integration is associated with high levels of performance in teamwork, technical problem solving, and engineering design, as well as progressive improvements in critical thinking, communication, and project management skills. These findings suggest that sustained, curriculum-wide PjBL experiences can effectively mitigate the fragmentation traditionally observed in engineering education and support the development of integrated professional competencies.

At the same time, the identification of a persistent gap in user experience and human-centered design highlights an important area for curricular enhancement. Addressing this gap will require not only refining assessment criteria but also embedding human factors methodologies as explicit technical requirements within the project lifecycle. Such adjustments are essential for aligning engineering education with the principles of Engineering 5.0, which emphasize the integration of technological excellence with social and human considerations.

The study is subject to limitations, including the absence of a control group and the reliance on rubric-based assessments within a single institutional context. Future research should seek to expand this approach by incorporating comparative studies, inter-institutional collaborations, and more granular analyses of individual competency trajectories. Additionally, extending the integrative model to emerging areas such as digital twins and artificial intelligence represents a promising direction for further investigation.

In conclusion, the findings support the view that the education of contemporary engineers requires more than the inclusion of advanced technologies; it demands intentional curricular structures, sustained interdisciplinary integration, and continuous faculty mediation. Within these conditions, integrative project-based models can serve as powerful catalysts for preparing engineers capable of addressing the complex technical and human challenges of modern society.

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References

[1] C. Pacher, M. Woschank, B. M. Zunk e E. Gruber, “Engineering education 5.0: a systematic literature review on competence-based education in the industrial engineering and management discipline,” Production & Manufacturing Research, vol. 12, no. 1, 2024, https://doi.org/10.1080/21693277.2024.2337224.

[2] E. Jiménez López, F. Cuenca Jiménez, G. Luna Sandoval, F. J. Ochoa Estrella, M. A. Maciel Monteón, F. Muñoz e P. A. Limón Leyva, “Technical considerations for the conformation of

specific competences in mechatronic engineers in the context of Industry 4.0 and 5.0," Processes, vol. 10, no. 8, art. no. 1445, 2022, https://doi.org/10.3390/pr10081445.

[3] K. Edström e A. Kolmos, "PBL and CDIO: complementary models for engineering education development," European Journal of Engineering Education, vol. 39, no. 5, pp. 539–555, 2014, https://doi.org/10.1080/03043797.2014.895703.

[4] E. F. Crawley, J. Malmqvist, S. Östlund, D. R. Brodeur e K. Edström, Rethinking Engineering Education: The CDIO Approach, 2ª ed., Cham, Switzerland: Springer International Publishing, 2014. https://doi.org/10.1007/978-3-319-05561-9.

[5] R. Graham, The Global State of the Art in Engineering Education, Cambridge, MA, USA: Massachusetts Institute of Technology, Mar. 2018. Available: https://www.rhgraham.org/resources/Global-state-of-the-art-in-engineering-education---March-2018.pdf.

[6] J. Chen, A. Guerra, X. Du e A. Kolmos, "Guest Editorial Project- or Problem-Based Learning (PBL) in Engineering Education: Variations and Prospects," International Journal of Engineering Education, vol. 38, no. 4, pp. 876–878, 2022. [Online]. Available: https://www.ijee.ie/editorials/02_Guest_Editorial38-4.pdf.