

Learning Engineering by Building a Solar-Powered Autonomous Vehicle

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Abstract – *This study evaluates the impact of an ambitious project-based learning (PBL) experience implemented in a first-year engineering course, where students designed and built a hybrid semi-autonomous vehicle integrating Internet of Things (IoT) technologies and solar energy. Seventy-four students with no prior experience in programming, electronics, or renewable energy participated in an eight-week challenge involving obstacle avoidance, wireless control, and sustainable power management. A mixed-methods approach was applied using Likert-scale surveys and open-ended responses to assess technical learning, transversal competencies, motivation, creativity, and perceptions of curricular continuity. Results show very high interdisciplinary integration (97.3% agreement) and strong technical learning (88.3%), particularly in clean energy concepts (94.6%). Programming emerged simultaneously as the main learning outcome and the primary difficulty, reflecting a pattern of productive struggle consistent with the zone of proximal development. Significant positive correlations were observed between motivation, creativity, and students' desire for the project to remain in the curriculum, supporting predictions from Self-Determination Theory. Despite challenges related to workload and scaffolding, most students recommended the project and expressed interest in continued participation. These findings demonstrate that technology-rich PBL can effectively foster learning, motivation, and sustainability awareness in novice engineering students.*

Keywords-- *Project-Based Learning; First; IoT; Renewable Energy; Engineering Education; STEM Education*

I. INTRODUCTION

A. Context and Motivation

Engineering education faces critical retention challenges, with 30-40% of students leaving programs during their first year [1]. Traditional lecture-based approaches often fail to demonstrate disciplinary connections and real-world relevance, contributing to disengagement. Simultaneously, 21st-century engineering practice demands competencies beyond technical

knowledge: critical thinking, creativity, collaboration, and communication—competencies grouped into technical, methodological, social, and personal categories [2].

Project-based learning (PBL) addresses these challenges by engaging students in authentic problems requiring sustained inquiry and collaboration [2]. The PBL approach has gained significant attention as an effective teaching method that enhances students' creativity, empathy, and multiple competencies, particularly suitable for engineering disciplines where critical thinking and problem-solving skills are essential for professional careers [3]. Meta-analyses demonstrate PBL's effectiveness in improving learning outcomes, retention, and skill development compared to traditional instruction [4], [5], [6].

Contemporary engineering education must prepare students for increasingly complex, interdisciplinary problems characterizing modern engineering practice. University graduates must develop complex problem-solving abilities and capacity to address interdisciplinary challenges. Moreover, prospective engineers require "new ideas, technologies, perspectives and professional ethics to adapt to the changing world," including sustainability awareness. This imperative is particularly acute for first-year students who must transition from secondary education's compartmentalized learning to engineering's inherently integrative nature [7].

Emerging technologies—particularly Internet of Things (IoT), robotics, and renewable energy—offer compelling contexts for first-year PBL. These domains align with student interests, connect multiple STEM disciplines, and address global challenges aligned with UN Sustainable Development Goals (SDGs 7, 9, 12). The integration of IoT technologies and renewable energy systems provides authentic engineering contexts that prepare graduates for Industry 4.0 demands. Yet systematic evaluations of such integrative projects in first year remain limited.

B. Research Gap and Objectives

While a comprehensive scoping review found that most studies (n=49) reported PBL superiority in learning and

knowledge acquisition compared to traditional curricula, evidence also reveals complexity—19 studies found no significant difference, while three reported PBL inferiority [4]. This nuanced finding suggests that implementation quality and contextual factors significantly influence PBL outcomes.

Furthermore, research on PBL implementation in engineering departments identifies key challenges including incorporating the PBL approach into departments' overall instructional techniques, defining coordinator roles, and addressing characteristics of PBL problems in courses [3]. These considerations are particularly relevant for first-year programs where students lack prior disciplinary experience and require carefully scaffolded learning experiences.

This study addresses three research questions:

RQ1: What learning outcomes do students achieve across technical, transversal, and motivational dimensions in an ambitious first-year PBL project combining IoT and renewable energy?

RQ2: What relationships exist between motivation, creativity, and desire for PBL continuity?

RQ3: What implementation challenges emerge, and how can pedagogical design be improved?

C. Contribution

This work contributes: (1) empirical evidence for ambitious first-year PBL with IoT and renewable energy, (2) validated mixed-methods assessment framework, (3) identification of productive struggle in programming as a learning catalyst, (4) documentation of motivation-creativity-continuity nexus, and (5) practical recommendations for scalable implementation addressing identified challenges.

II. THEORETICAL FRAMEWORK

A. Project-Based Learning Foundations

PBL represents a student-centered pedagogical approach engaging learners in authentic, complex problems requiring sustained inquiry. The integration of design thinking with project-based learning (DT-PBL) has emerged as an innovative educational approach combining problem-solving methodology with experiential learning [2]. Essential PBL elements include: driving questions, student choice, iterative refinement, collaboration, and reflection.

Research indicates PBL effectiveness works with both experienced and novice learners, though implementation requires contextual adaptation as "a single educational practice is not suitable all of the time" [6]. Systematic reviews provide compelling evidence for PBL effectiveness: most comparative studies favor PBL over traditional instruction for knowledge acquisition and skill development. However, implementation quality significantly influences outcomes—structured approaches like the Maastricht Seven Step Model provide

scaffolding enabling students to navigate complex problems while developing autonomous learning capabilities.

B. First-Year Engineering Education

First-year engineering represents a critical juncture where students form foundational understandings and develop professional identities. Traditional engineering education has focused predominantly on theoretical knowledge, creating a need for innovative teaching methods that better engage students [8]. Research emphasizes the importance of hands-on, experiential learning in first-year courses to demonstrate relevance and build self-efficacy.

Contemporary frameworks for engineering education emphasize outcome-based education (OBE) principles with clearly defined learning objectives and aligned assessment strategies. Recent scholarship also emphasizes incorporating sustainability and ethical frameworks from the earliest stages. Bibliometric analysis spanning 1991-2022 demonstrates the need for sustained curriculum reform to successfully transform engineering education toward sustainability [9], supporting the integration of renewable energy systems into first-year projects as means of developing both technical competencies and sustainability awareness.

2.3 Productive Struggle and Zone of Proximal Development

The concept of productive struggle, rooted in Vygotsky's zone of proximal development (ZPD), provides theoretical grounding for understanding how challenging learning experiences promote deep understanding. In PBL contexts, students encounter difficulties that, when appropriately scaffolded, lead to meaningful learning outcomes. The integration of multiple challenging technologies creates what learning scientists term "desirable difficulties"—appropriately challenging tasks that enhance learning capabilities when calibrated to students' developing competencies [10].

The key lies in providing sufficient support structures while embracing appropriate challenge levels. Research demonstrates that scaffolding enables student success through productive struggle, where the most challenging aspects of learning experiences also produce the greatest learning gains.

C. Motivation and Self-Determination Theory

Self-Determination Theory (SDT) provides a robust framework for understanding motivation in PBL contexts. The theory posits that intrinsic motivation flourishes when learning environments support three basic psychological needs: autonomy (meaningful choices), competence (mastery experiences), and relatedness (social connection). PBL environments inherently support these needs through student choice in design, skill-building success experiences, and collaborative teamwork.

Research indicates that PBL approaches may positively affect instruction that novices enact, suggesting that autonomous learning experiences shape students' subsequent approaches to engineering challenges [6]. The motivational benefits of autonomous, meaningful learning experiences manifest in high

student recommendation rates and sustained engagement with engineering learning.

D. Technology Integration in Engineering Education

The integration of Internet of Things (IoT) technologies in engineering education presents significant opportunities [11]. Comprehensive reviews of IoT curriculum, pedagogy, and assessment emphasize three critical instructional design areas: curriculum development, assessment strategies, and pedagogical approaches. Contemporary STEM teaching practices must prepare students for Industry 4.0 demands, requiring curricula addressing IoT competencies alongside traditional fundamentals [7].

Microcontrollers such as ESP32 and Arduino platforms enable hands-on learning with authentic engineering tools. IoT technologies in control systems, particularly in applications involving motor drives and energy systems, contribute to improved monitoring capabilities while offering new teaching and research perspectives [12]. These experimental configurations upgrade laboratory infrastructure and provide students with industry-relevant technological experience.

Renewable energy systems integration, particularly solar power, addresses both technical competency development and sustainability education objectives. Project-based learning in renewable and sustainable energy education has been documented through case studies demonstrating methodologies for implementing PBL in renewable energy contexts, allowing students to develop technical competencies, labor skills, and soft skills simultaneously [9]. Emerging frameworks extend traditional engineering design by incorporating digital twin structures tailored to IoT applications, enabling real-time system feedback, simulation-based iteration, and hands-on experimentation [13] and [14].

III. METHODOLOGY

A. Context and Participants

This study was conducted with 74 first-year engineering students (Computer/Informatics track) at Universidad Autónoma de Chile during the 2024-01 semester. Participants had no prior formal experience in programming, electronics, or renewable energy systems. All students provided informed consent (100%) for anonymous data use in academic research.

B. Challenge Design and Implementation

The eight-week project centered on a driving question: "How can we design a mobile vehicle that integrates solar energy, obstacle avoidance, and remote control to demonstrate sustainable autonomous transportation?" This aligned with contemporary engineering education's emphasis on sustainability and interdisciplinary problem-solving. Students worked in teams of 4-5 to develop functional prototypes using NodeMCU microcontrollers, HC-SR04 ultrasonic sensors, DC motors with L298N drivers, 6V/2W solar panels, and rechargeable batteries. Communication was

implemented through the Blynk IoT platform. The technology stack provided hands-on experience with industry-relevant tools while maintaining accessibility for novices. Functional requirements included autonomous obstacle avoidance, WiFi remote control, hybrid power management, and robust creative structural design.

Evaluation employed multidimensional criteria: functionality (40%), energy efficiency (20%), creativity/design (20%), documentation (10%), and teamwork (10%), aligned with outcome-based education frameworks [8] and competency assessment across technical, methodological, social, and personal domains [2].

The implementation progressed through five phases following gradual release principles [15]: Weeks 1-2 focused on conceptualization and team formation with role assignments (technical leader, programmer, mechanical designer, energy manager, documentor). Weeks 3-4 provided structured workshops on Arduino/C++ programming, electronics fundamentals, sensor integration, WiFi/Blynk configuration, and solar energy systems. Weeks 5-6 emphasized development and integration with faculty consultation sessions and peer learning forums. Week 7 focused on testing, refinement, and technical poster preparation. Week 8 culminated in public demonstrations, peer evaluations, and post-project reflection.

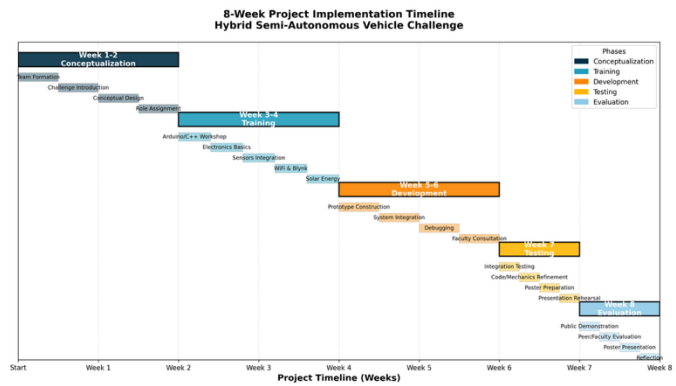


Fig. 1 Project Timeline.

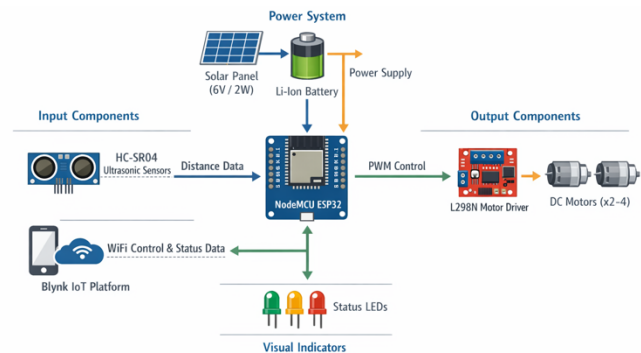


Fig. 2 Technical Architecture.

Pedagogical scaffolding incorporated gradual release of responsibility, just-in-time resources (video tutorials, annotated code, online Q&A forum), heterogeneous team composition, weekly formative assessment checkpoints, and faculty availability (professor plus two teaching assistants, 4 hours/week consultation). This approach aligned with research emphasizing that implementation quality significantly influences PBL outcomes.

C. 3.3 Data Collection and Analysis

Assessment employed mixed-methods approaches [3]. The survey instrument included 14 Likert-scale items (5-point scale) across six dimensions: Technical Learning (3 items: sensors/IoT, clean energy, math/programming application), Transversal Competencies (3 items: teamwork, autonomy, technical communication), Motivation & Creativity (2 items), Curricular Integration (1 item), Pedagogical Design (3 items: difficulty, support, materials), and Continuity Perception (2 items: curricular permanence, future participation). Five open-ended questions explored main learnings, difficulties, improvements, recommendations, and professional development impacts.

Survey administration occurred post-project via Google Forms with 100% completion rate (N=74). Quantitative analysis employed descriptive statistics (M, SD, median, IQR), agreement percentages (≥ 4 on Likert scale), Pearson correlations with significance testing ($\alpha=0.05$), and Shapiro-Wilk normality tests using Python 3.12. Qualitative analysis followed content analysis procedures with thematic coding, keyword frequency analysis, and pattern recognition. Triangulation between quantitative and qualitative data enhanced validity.

IV. RESULTS

A. Technical Learning and Transversal Competencies

All 74 students completed the survey with unanimous consent for data use. Technical learning averaged 4.28/5.0 (88.3% agreement), demonstrating successful competency development despite zero prior experience. Clean energy concepts achieved highest agreement (94.6%, M=4.54), indicating successful hands-on engagement with solar systems [11]. Math/programming application reached 89.2% agreement (M=4.23), validating experiential learning's role in consolidating abstract knowledge [2]. IoT/sensors learning achieved 81.1% agreement (M=4.07), consistent with qualitative data identifying programming as the primary challenge requiring productive struggle [10].

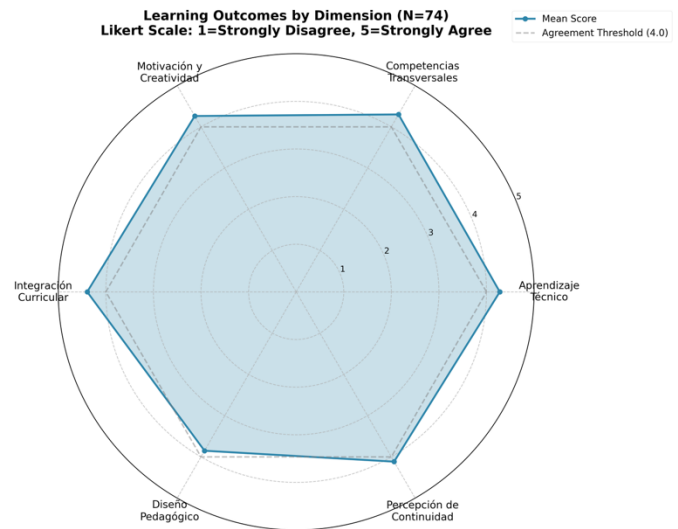


Fig. 3 Radar Chart – Learning Outcomes by Dimension.

Transversal competencies averaged 4.30 (85.1% agreement), demonstrating balanced professional skill development [2]. Teamwork scored highest (87.8%, M=4.38), validated by 28.4% of students explicitly mentioning it in open-ended responses. Technical communication (85.1%, M=4.26) and autonomy (82.4%, M=4.27) showed strong development through poster preparation, presentations, and independent problem-solving. Creativity stimulation achieved 91.9% agreement (M=4.41), substantially exceeding motivation (78.4%, M=4.12), though both correlated strongly ($r=0.615$, $p<0.001$), supporting Self-Determination Theory predictions [6].

B. Interdisciplinary Integration and Pedagogical Design

Interdisciplinary integration achieved the highest agreement across all dimensions at 97.3% (M=4.39, SD=0.54), revealing near-unanimous recognition that the project connected mathematics, programming, physics, and design into unified problem-solving experiences. This validates PBL's capacity for authentic disciplinary integration and addresses contemporary engineering education's imperative to prepare students for interdisciplinary challenges.

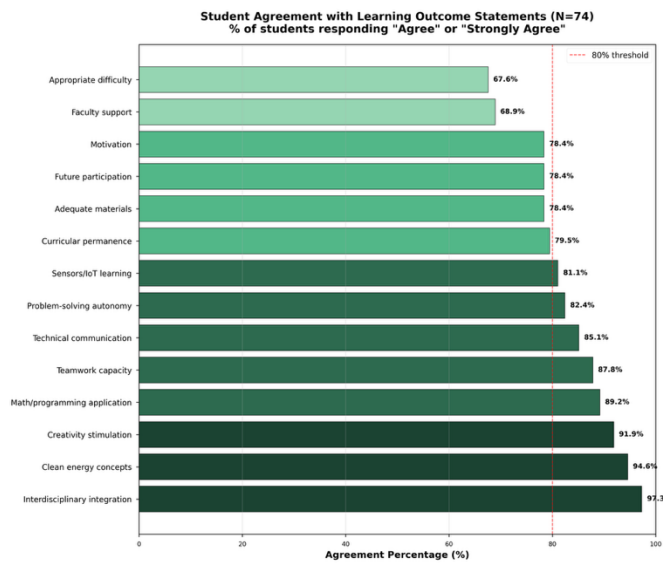


Fig. 4 Agreement Percentages

Pedagogical design averaged 3.85 (71.6% agreement)—lowest category yet still majority positive. Difficulty appropriateness (67.6%, $M=3.74$), faculty support (68.9%, $M=3.95$), and materials adequacy (78.4%, $M=3.86$) showed substantial variability, reflecting heterogeneous experiences and identifying improvement opportunities [3]. Despite lower scores, continuity perception remained strong: 79.5% believed projects should be permanent curriculum components, and 78.4% desired future participation. This paradox suggests students perceived high educational value despite implementation challenges [10].

C. 4.3 Correlation Analysis and Qualitative Findings

Pearson correlations revealed significant positive relationships between key dimensions. Motivation correlated most strongly with continuity ($r=0.640$, $p<0.001$), indicating motivated students became PBL advocates. Motivation-creativity correlation ($r=0.615$, $p<0.001$) supported SDT predictions about autonomy-supporting environments. All correlations were positive and significant (minimum $r=0.467$, $p<0.05$), suggesting synergistic effects where PBL dimensions mutually reinforce rather than compete.

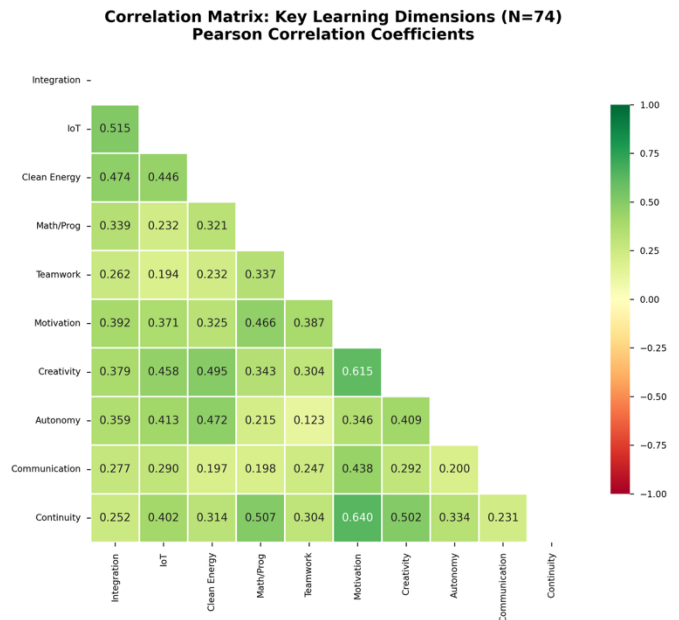


Fig. 5 Correlation Matrix Heatmap.

Content analysis revealed the productive struggle paradox: programming appeared as both main learning outcome (97.3% of students) and primary difficulty (98.6%). Representative quotes: "I learned programming isn't just applying knowledge, but having ingenuity, creativity, and critical thinking to solve problems"; "Lack of initial coding information was difficult, but classes during development helped us succeed." This validates productive struggle within the zone of proximal development—the challenge was sufficiently difficult to create effortful processing yet achievable through scaffolding (workshops, peer help, teaching assistants).

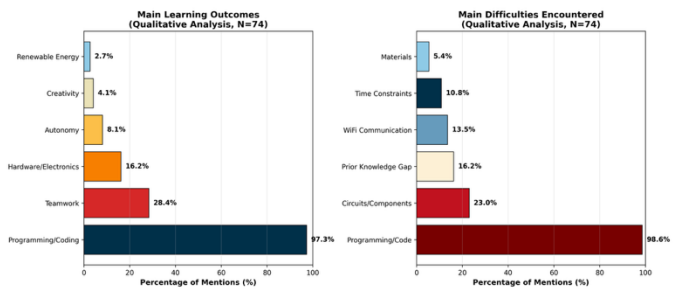


Fig. 6 Qualitative Themes – Learning & Difficulties.

Improvement suggestions distributed across better training (17.6%), better materials (17.6%), more support (14.9%), and more time (13.5%), with 18.9% satisfied with current format. Project recommendation reached 81.1% positive, 14.9% conditional, 4.1% negative, providing strong validation despite identified improvements. Conditional responses primarily suggested timing adjustments for better preparation.

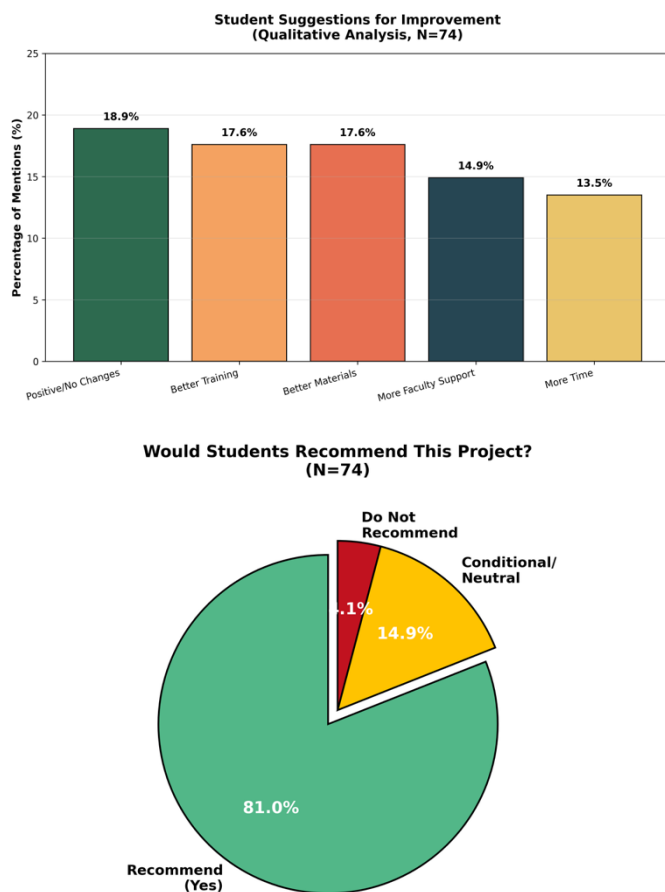


Fig. 7 Improvement Suggestions & Project Recommendation.

Shapiro-Wilk tests revealed non-normal distributions for all variables ($W=0.695-0.815$, all $p<0.001$), indicating ceiling effects with responses concentrated at upper scale values—typical in educational satisfaction surveys and reflecting genuine positive experiences.

V. DISCUSSIONS

A. PBL Effectiveness for Ambitious First-Year Projects

Results validate that first-year engineering students can successfully engage with complex, integrative projects combining IoT, robotics, and renewable energy despite zero prior technical experience. The 97.3% interdisciplinary integration agreement—the highest across all dimensions—demonstrates students clearly perceived authentic connections between mathematics, programming, physics, and design, mirroring real-world engineering practice where disciplinary boundaries blur. This finding extends systematic review evidence reporting PBL superiority for knowledge acquisition to technology-rich contexts involving Industry 4.0 competencies.

The 88.3% technical learning average occurred through constructivist learning-by-building processes [2], with clean

energy concepts achieving 94.6% agreement. This suggests hands-on experiences with tangible energy conversion systems create memorable learning moments, supporting integration of sustainability education from first year [9] rather than treating it as advanced content. The finding aligns with outcome-based education frameworks emphasizing integrated competency development [8] and validates the integration of design thinking with project-based learning as effective methodology [2].

The high achievement demonstrates that ambitious technical integration need not await advanced coursework when adequate scaffolding supports first-year implementation. This challenges traditional curriculum sequencing assumptions that reserve complex integrative experiences for senior capstone projects, suggesting earlier exposure may enhance retention and engineering identity formation through authentic practice experiences.

B. The Productive Struggle Paradox: Programming as Learning Catalyst

The programming paradox—appearing as both main learning outcome (97.3%) and primary difficulty (98.6%)—exemplifies productive struggle within Vygotsky's zone of proximal development [15]. This validates theoretical frameworks emphasizing desirable difficulties: optimal challenge levels with appropriate support maximize learning gains [10]. The challenge was sufficiently difficult to create effortful processing and memorable experiences, yet achievable through multi-layered scaffolding including workshops, peer assistance, teaching assistants, and just-in-time resources.

Critical insight: educators should not avoid challenging tasks in first year but rather design appropriate scaffolding while normalizing struggle as learning. The Maastricht Seven Step Model [15] provides frameworks for structuring such experiences through systematic problem clarification, analysis, solution development, and knowledge integration. Students developed resourcefulness extending beyond programming syntax—seeking help strategically, iterating solutions systematically, persisting through frustration, and debugging methodically. These metacognitive skills arguably provide greater professional value than specific technical content that evolves rapidly.

The finding explains why students rated technical learning highly (88.3%) despite identifying it as their greatest difficulty. The challenge created conditions for deep learning through active knowledge construction and persistent engagement with difficult material. This pattern supports research indicating appropriately challenging experiences generate strong outcomes even with execution imperfections, and that students experiencing productive struggle develop more robust understanding than those receiving only easily mastered material.

C. Motivation-Creativity-Continuity Nexus and Institutional Implications

Strong correlations between motivation↔creativity ($r=0.615$) and motivation↔continuity ($r=0.640$) reveal interconnected motivational constructs with important institutional implications. Through Self-Determination Theory lens [6], the project satisfied three psychological needs: autonomy through meaningful design choices within technical constraints, competence through functional prototype completion building self-efficacy, and relatedness through collaborative teamwork (87.8% agreement).

The motivation-continuity correlation demonstrates that motivated students become PBL advocates—a critical finding for curricular reform justification. Student advocacy based on positive experiences (81.1% recommendation rate, 79.5% desire for curricular permanence) provides powerful institutional justification for continued investment in active learning pedagogies. This creates positive feedback: creativity enhances motivation, which generates advocacy, which facilitates expansion, which provides more students with transformative experiences.

The finding suggests preserving creative freedom even when teaching specific technical content. Balancing structure (technical requirements ensuring learning objectives) with openness (design choices enabling autonomy) maximizes both technical competency development and intrinsic motivation. This challenges purely directive pedagogies that specify all design parameters, suggesting strategic openness enhances rather than compromises learning outcomes.

D. Pedagogical Design Improvements: From Challenges to Solutions

Lower pedagogical design scores (71.6% agreement) identify concrete improvement opportunities while aligning with research on PBL implementation challenges [3]. Three specific areas emerged with actionable solutions:

Differentiated Scaffolding: Heterogeneous prior knowledge created varied difficulty experiences (67.6% agreement). Solutions include diagnostic pre-assessment for strategic grouping, tiered challenges offering bronze/silver/gold requirement levels, advanced resources for experienced students (PID control, computer vision), and peer mentoring connecting novices with more experienced students. Research on PBL implementation emphasizes addressing problem characteristics as critical success factors.

Enhanced Support Infrastructure: Faculty support (68.9%) and materials (78.4%) improvements include monitored online forums enabling asynchronous Q&A, searchable video tutorial libraries organized by component and concept, extended lab hours with teaching assistant supervision, component lending systems enabling after-hours work, and pre-assembled starter kits reducing setup time and connection errors. These solutions address challenges documented across engineering departments

while aligning with scaffolding principles emphasizing just-in-time support.

Time Management: Qualitative feedback (13.5%) mentioned time constraints. Potential adjustments include maintaining eight-week duration while reducing scope, extending to ten or twelve weeks enabling more iteration, flexible milestone adjustments based on progress monitoring, or emphasizing rapid prototyping with earlier functional prototypes allowing more refinement time. Engineering curriculum reform research emphasizes aligning assessment with learning objectives—pacing adjustments could enhance this alignment.

The distributed improvement suggestions (no single overwhelming concern) validate pedagogical design as "good but improvable" rather than fundamentally flawed, supporting iterative refinement over wholesale redesign.

E. Technology Integration and Transferability Considerations

The integration of contemporary technologies—NodeMCU microcontrollers, IoT sensors, WiFi communication, and solar energy systems—provided authentic engineering contexts preparing students for Industry 4.0 demands. Solar energy integration (94.6% learning agreement) demonstrates that renewable energy concepts can be successfully embedded in first-year curricula, addressing bibliometric analysis findings emphasizing sustained curriculum reform toward sustainability.

IoT technologies in control systems translate effectively to educational contexts [12], with the vehicle challenge incorporating monitoring, control, and communication—core IoT competencies. Emerging frameworks on digital twin structures for IoT education [13] represent future extensions of this pedagogical approach, potentially enabling simulation-based design iteration alongside physical prototyping.

Transferability depends on multiple factors. The pedagogical framework (eight-week structure, gradual release) generalizes across PBL contexts. The technology stack (NodeMCU/Arduino ecosystem) offers affordability (~\$30-50/student), wide availability, and extensive documentation. Sustainability focus provides global applicability aligned with UN SDGs. However, implementation barriers include faculty interdisciplinary expertise requirements, initial hardware investment, institutional support needs (teaching assistants, lab space), and cultural PBL adoption variability.

Scalability strategies addressing these barriers include train-the-trainer professional development programs, open educational resource development (curriculum materials, code examples, tutorials shared publicly), institutional partnerships enabling resource pooling, and gradual implementation through pilot cohorts with iterative refinement before full-scale adoption. Research on PBL implementation challenges [3]

validates these as common across institutions, suggesting systematic approaches can facilitate broader adoption.

F. Alignment with Contemporary Engineering Education Frameworks

Results align with multiple contemporary frameworks validating the approach's comprehensiveness. Outcome-based education principles [8] manifest through clear learning objectives across technical, transversal, and motivational domains with aligned multidimensional assessments. Competency cluster frameworks [2] evidence development across technical (programming, electronics, energy systems), methodological (problem-solving, debugging, testing), social (teamwork, communication, peer learning), and personal (autonomy, persistence, creativity) domains simultaneously. Education for sustainable development objectives [9] integrate through renewable energy from first year, addressing UN SDG 7 (clean energy), 9 (industry and innovation), and 12 (responsible consumption). Industry 4.0 preparation occurs through IoT competencies, digital tools, and emerging technology exposure preparing graduates for contemporary practice. Design thinking integration combines problem-solving methodology with experiential learning through open-ended challenges requiring creative solutions within technical constraints.

These convergent alignments position the vehicle challenge as exemplar of contemporary best practices extending beyond traditional content delivery toward integrated competency development for twenty-first century engineering practice, validating the pedagogical approach while identifying specific areas for continued refinement.

G. Study Limitations and Future Directions

Several limitations warrant consideration. The single cohort from one institution ($N=74$, Universidad Autónoma de Chile) limits generalizability—multi-institutional replication would strengthen claims. The absence of control groups prevents isolating PBL effects from other factors including instructor enthusiasm and cohort characteristics. Self-reported Likert data risks social desirability bias—objective assessments through concept tests and code quality metrics would complement subjective measures. Post-test only design without baseline measurements prevents quantifying learning gains—pre/post designs would enable effect size calculation. Context-specific factors including Chilean university resources, faculty expertise, and first-semester timing may influence outcomes differently than other settings. Short-term outcome focus lacks longitudinal tracking—knowledge retention, skill transfer to subsequent courses, and career impacts remain unknown. Future research should address these through controlled comparisons with traditional instruction, multi-institutional studies validating findings across contexts, objective performance assessments complementing surveys, pre/post designs quantifying learning gains, and longitudinal tracking following cohorts through graduation and early career stages.

Additionally, investigations could explore disciplinary variations adapting the approach to mechanical, civil, or electrical engineering tracks, learning analytics integrating LMS data and code repository analysis, cost-benefit analysis examining return on investment compared to traditional instruction, and scalability model development for sustainable institutionalization [3].

Despite limitations, the convergence of high interdisciplinary integration (97.3%), strong technical learning (88.3%), documented productive struggle, significant motivation-continuity correlations, and high student recommendation (81.1%) provides compelling evidence for PBL effectiveness in first-year engineering with emerging technologies when appropriate scaffolding supports implementation.

VI. CONCLUSIONS

This study evaluated an eight-week hybrid semi-autonomous vehicle challenge with 74 first-year engineering students, demonstrating that ambitious project-based learning integrating IoT, robotics, and renewable energy achieves strong outcomes when appropriate scaffolding supports implementation. Results validate PBL effectiveness for developing interdisciplinary competencies, technical skills, and professional dispositions among novice engineering students despite zero prior technical experience.

A. Key Findings

Five principal findings emerged with theoretical and practical significance. First, interdisciplinary integration achieved 97.3% agreement—the highest across all dimensions—validating PBL's capacity to connect mathematics, programming, physics, and design into unified problem-solving experiences. Students experiencing engineering as integrated practice rather than disconnected subjects develop stronger professional identities and clearer understanding of authentic engineering work.

Second, the productive struggle paradox where programming emerged as both main learning outcome (97.3%) and primary difficulty (98.6%) exemplifies desirable difficulties within the zone of proximal development. Appropriately calibrated challenges with multi-layered support maximize learning gains through effortful processing that creates durable understanding extending beyond specific content to metacognitive capabilities including resourcefulness, persistence, and strategic help-seeking.

Third, strong correlations between motivation-creativity ($r=0.615$) and motivation-continuity ($r=0.640$) demonstrate synergistic effects consistent with Self-Determination Theory. Creative freedom within technical constraints enhanced intrinsic motivation, generating student advocacy for expanded PBL experiences—powerful institutional justification for continued investment.

Fourth, technical learning averaged 88.3% agreement with clean energy concepts reaching 94.6%, demonstrating successful competency development in previously unfamiliar

domains and validating sustainability integration from first year. The finding challenges assumptions that complex technology integration must await advanced coursework, showing that first-year students can engage successfully with Industry 4.0 technologies when adequate scaffolding supports implementation.

Fifth, pedagogical design scored lowest (71.6% agreement) while students strongly supported continuation (79.5% curricular permanence, 81.1% recommendation), indicating high perceived educational value despite implementation refinement opportunities in scaffolding, support infrastructure, and resource allocation. This pattern suggests students distinguish between valuable pedagogical approaches requiring refinement from fundamentally flawed approaches requiring abandonment.

B. Practical Implications

Results provide actionable guidance for engineering educators, curriculum designers, and administrators implementing or expanding project-based learning.

For Educators: Embrace controlled challenges developing both domain knowledge and learning-to-learn capabilities. Balance technical requirements with creative freedom to maximize motivation. Prepare for programming as both breakthrough and bottleneck requiring substantial scaffolding. Normalize struggle as productive learning process through psychological safety and growth mindset messaging. Leverage multi-layered support including peer learning, just-in-time resources, and strategic faculty intervention.

For Curriculum Designers: Prioritize integrative experiences connecting multiple disciplines over siloed content delivery. Embed sustainability authentically from first year through renewable energy and responsible design. Design differentiated pathways accommodating heterogeneous prior knowledge through tiered challenges and diagnostic assessment. Align assessments with outcome-based education frameworks emphasizing competency development across technical, methodological, social, and personal domains. Incorporate Industry 4.0 technologies with pedagogical intentionality ensuring authentic contexts support rather than distract from learning objectives.

For Administrators: Invest in professional development for faculty transitioning to PBL pedagogy through train-the-trainer programs and community of practice support. Provide institutional support structures including teaching assistants, equipment budgets, and adequate laboratory space with extended access hours. Recognize PBL as resource-intensive but high-impact for retention and competency development worthy of strategic investment. Use student satisfaction data (81.1% recommendation, 97.3% interdisciplinary integration) to justify expansion to stakeholders. Develop scalability strategies through pilot implementations, iterative refinement,

open educational resource sharing, and institutional partnerships enabling resource pooling.

C. Contributions to Engineering Education

This work contributes empirically and methodologically to engineering education research. Empirical contributions include documented evidence for technology-rich first-year PBL combining IoT and renewable energy, validation of productive struggle in programming as learning catalyst rather than barrier, demonstration of motivation-creativity-continuity nexus supporting Self-Determination Theory in engineering contexts, documentation of sustainability integration effectiveness from first year, and identification of specific implementation challenges with actionable solutions. Methodological contributions include a validated mixed-methods assessment framework employing Likert scales and open-ended questions for comprehensive outcome evaluation, triangulation procedures enhancing validity through convergent quantitative and qualitative findings, instruments adaptable to other PBL contexts with minor modifications, and detailed implementation protocols enabling replication across institutions. These contributions extend literature demonstrating PBL effectiveness while addressing implementation considerations and contemporary frameworks emphasizing outcome-based education, competency clusters, and Industry 4.0 preparation.

D. 6.4 Future Directions

Immediate research priorities include controlled comparisons with traditional instruction enabling causal inference, objective assessments through pre/post concept tests and code quality metrics complementing self-reported data, longitudinal tracking following cohorts through subsequent courses examining knowledge retention and skill transfer, and pedagogical refinements testing differentiated scaffolding, enhanced support infrastructure, and resource optimization. Medium-term investigations should pursue multi-institutional replication validating findings across universities and cultural contexts, disciplinary variations adapting the approach to mechanical, civil, and electrical engineering tracks, learning analytics integrating learning management system data and code repository analysis, and cost-benefit analysis examining return on investment compared to traditional instruction. Long-term studies examining career impact through graduate tracking, retention analysis correlating PBL participation with program completion rates, industry validation aligning competencies with employer needs and workforce readiness, and scalability model development for sustainable PBL institutionalization across programs would strengthen the evidence base for widespread adoption.

E. Final Reflections

As engineering education evolves to meet twenty-first century challenges—climate change, automation, global interconnection—experiential learning with emerging

technologies becomes imperative rather than optional. This study demonstrates that well-designed, scaffolded PBL experiences achieve strong learning outcomes in first-year engineering even with ambitious technical scope encompassing IoT, robotics, and renewable energy. However, effectiveness depends critically on execution quality: balancing challenge with support, structure with creative freedom, technical depth with accessibility.

The convergence of high interdisciplinary integration (97.3%), documented productive struggle, significant motivational correlations, strong student advocacy (81.1% recommendation), and identified improvement pathways (71.6% pedagogical design agreement) validates PBL as powerful pedagogical approach for contemporary engineering education while acknowledging implementation as iterative refinement process requiring sustained institutional commitment.

Future engineering educators can leverage these findings to design, implement, and refine PBL experiences that engage students, develop critical competencies, and prepare graduates for complex, interdisciplinary problems characterizing modern engineering practice, contributing to more diverse, capable, and professionally prepared engineering workforce addressing society's most pressing challenges.

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REFERENCES

- [1] B. N. Geisinger and D. R. Raman, "Why They Leave: Understanding Student Attrition from Engineering Majors*,"
- [2] L. Jia, N. A. Jalaludin, and S. Rasul, "Design Thinking and Project-Based Learning (DT-PBL): A Review of the Literature," *International Journal of Learning Teaching and Educational Research*, 2023, doi: 10.26803/ijlter.22.8.20.
- [3] M. Alarfaj, S. R. Mohamed, S. Chtourou, H. Enshasy, A. Aboulhaga, and M. Hassan, "Experience of Project-Based Learning: Challenges, Assessment, and Analysis," *International Journal of Engineering Pedagogy (Ijep)*, 2024, doi: 10.3991/ijep.v14i3.43849.
- [4] Y. Yustina, W. Syafii, and R. Vebrianto, "The Effects of Blended Learning and Project-Based Learning on Pre-Service Biology Teachers' Creative Thinking Skills Through Online Learning in the Covid-19 Pandemic," *Jurnal Pendidikan Ipa Indonesia*, 2020, doi: 10.15294/jpii.v9i3.24706.
- [5] C. Liu, W. Ouyang, X. Wang, C. Dan, and Z. Jiang, "Comparing Hybrid Problem-Based and Lecture Learning (PBL + LBL) With LBL Pedagogy on Clinical Curriculum Learning for Medical Students in China: A Meta-Analysis of Randomized Controlled Trials," *Medicine*, 2020, doi: 10.1097/md.00000000000019687.
- [6] M. Almulla, "The Effectiveness of the Project-Based Learning (PBL) Approach as a Way to Engage Students in Learning," *Sage Open*, 2020, doi: 10.1177/2158244020938702.
- [7] M. Lee, D. Chacón-Hurtado, and S. Hertel, "Engineers as Problem-Solvers for Sustainable Development?—Exploring Students' Learning Outcomes From Sustainability and Human Rights-Centered Approaches in Engineering Education," *Eur. J. Educ.*, 2025, doi: 10.1111/ejed.70137.
- [8] A. Hu, X. Mao, C. Fu, M. Wu, and S. Zhou, "Engineering Curriculum Reform Based on Outcome-Based Education and Five-Color Psychology Theory," *Sustainability*, 2023, doi: 10.3390/su15118915.
- [9] D. K. Narong and P. Hallinger, "Traversing the Evolution of Research on Engineering Education for Sustainability: A Bibliometric Review (1991–2022)," *Sustainability*, 2024, doi: 10.3390/su16020641.
- [10] S. Chakraborty and D. Galatro, "Incorporating Agile Methodologies Into the Chemical Engineering Curriculum," *Computer Applications in Engineering Education*, 2024, doi: 10.1002/cae.22805.
- [11] R. Muñoz, R. del Coso, F. Nuño, P. Villegas, D. O. Álvarez, and J. A. Martínez, "Solar-Powered Smart Buildings: Integrated Energy Management Solution for IoT-Enabled Sustainability," *Electronics (Basel)*, 2024, doi: 10.3390/electronics13020317.
- [12] M. G. Ioannides, A. P. Stamelos, S. A. Papazis, A. Papoutsidakis, and V. Vikentios, "IoT Monitoring System for Applications With Renewable Energy Generation and Electric Drives," *Renewable Energy and Power Quality Journal*, 2024, doi: 10.24084/repqj19.347.
- [13] A. Boltsi, D. Kosmanos, A. Xenakis, P. Chatzimisios, and C. Chaikalis, "Towards a Novel Digital Twin Framework Proposal Within the Engineering Design Process for Future Engineers: An IoT Smart Building Use Case," *Sensors*, 2025, doi: 10.3390/s25113504.
- [14] O. Loyola, B. Suarez, C. Sandoval, and E. Carrillo, "Integration of Cyber-Physical System and Digital Twin for Controlling a Robotic Manipulator: An Industry 4.0 Approach," 2024, pp. 141–152. doi: 10.1007/978-3-031-47372-2_14.
- [15] A. A. Funa and M. S. Prudente, "Effectiveness of Problem-Based Learning on Secondary Students' Achievement in Science: A Meta-Analysis," *International Journal of Instruction*, 2021, doi: 10.29333/iji.2021.1445a.