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Original article

Mechanical technodidactic innovation and meaningful learning: a statistical analysis in engineering education

Innovación tecnodidáctica mecánica y aprendizaje significativo: un análisis estadístico en la formación de ingenieros

Inovação tecnodidática mecânica e aprendizagem significativa: uma análise estatística na formação de engenheiros

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ABSTRACT

This research evaluated the effect of a mechanical techno-didactic procedure on the meaningful learning of 50 students from the Mechanical Engineering technical profile, selected from a population of 60. Using a quasi-experimental design with pre- and post-intervention measurements, questionnaires, interviews, direct observation, focus groups, and diagnostic assessments were applied. The mixed methodology integrated qualitative and quantitative approaches, with statistical validation through paired-sample t-test and linear regression analysis. The results evidenced a significant improvement in technical comprehension (initial mean of 62.31 versus 77.23 post-intervention, a difference of 14.92 points; $p<0.0001$). A relevant finding was the leveling effect:

Translated from the original in Spanish

students with lower initial performance experienced greater advances (regression coefficient -0.117; p=0.003), indicating that the intervention reduced pre-existing gaps. Student and teacher perceptions corroborated these results, although a gap was identified between the perceived effectiveness of technological resources (92 % of teachers) and their real impact on active participation (60 %). It is concluded that the deliberate integration of digital tools with participatory methodologies not only improves academic performance but also promotes contextualized, meaningful, and equitable learning. This procedure constitutes a replicable methodological reference in other technical programs, consolidating didactic innovation as a transformative axis of engineering education.

Keywords: meaningful learning; technical training; technological integration; technodidactic procedure.

RESUMEN

Esta investigación evaluó el efecto de un procedimiento tecnodidáctico mecánico en el aprendizaje significativo de 50 estudiantes del perfil técnico de Ingeniería Mecánica, seleccionados de una población de 60. Mediante un diseño cuasiexperimental, con mediciones pre y postintervención, se aplicaron cuestionarios, entrevistas, observación directa, grupos focales y evaluaciones diagnósticas. La metodología mixta integró enfoques cualitativos y cuantitativos, con validación estadística a través de prueba t para muestras relacionadas y análisis de regresión lineal. Los resultados evidenciaron una mejora significativa en la comprensión técnica (media inicial de 62.31 frente a 77.23 posterior, diferencia de 14.92 puntos; p<0.0001). Un hallazgo relevante fue el efecto nivelador: los estudiantes con menor rendimiento inicial experimentaron mayores avances (coeficiente de regresión -0.117; p=0.003), lo que indica que la intervención redujo las brechas preexistentes. Las percepciones de estudiantes y docentes corroboraron estos resultados, aunque se identificó una brecha entre la efectividad percibida de los recursos tecnológicos (92 % de docentes) y su impacto real en la participación activa (60 %). Se concluye que la integración deliberada de herramientas digitales con metodologías participativas no solo mejora el desempeño académico, sino que también promueve un aprendizaje contextualizado, significativo y equitativo. Este procedimiento constituye un referente metodológico replicable en otros programas técnicos, consolidando la innovación didáctica como eje transformador de la formación en ingeniería.

Translated from the original in Spanish

Palabras clave: aprendizaje significativo; formación técnica; integración tecnológica; procedimiento tecnodidáctico.

RESUMO

Esta pesquisa avaliou o efeito de um procedimento tecnodidático mecânico na aprendizagem significativa de 50 estudantes do perfil técnico de Engenharia Mecânica, selecionados de uma população de 60. Por meio de um delineamento quase-experimental com medições pré e pós-intervenção, foram aplicados questionários, entrevistas, observação direta, grupos focais e avaliações diagnósticas. A metodologia mista integrou abordagens qualitativas e quantitativas, com validação estatística por meio do teste t para amostras relacionadas e análise de regressão linear. Os resultados evidenciaram uma melhora significativa na compreensão técnica (média inicial de 62,31 contra 77,23 posterior, diferença de 14,92 pontos; $p<0{,}0001$). Um achado relevante foi o efeito nivelador: os estudantes com menor rendimento inicial experimentaram maiores avanços (coeficiente de regressão -0,117; $p=0{,}003$), o que indica que a intervenção reduziu as lacunas preexistentes. As percepções de estudantes e professores corroboraram esses resultados, embora tenha sido identificada uma lacuna entre a eficácia percebida dos recursos tecnológicos (92 % dos professores) e seu impacto real na participação ativa (60 %). Conclui-se que a integração deliberada de ferramentas digitais com metodologias participativas não apenas melhora o desempenho acadêmico, mas também promove uma aprendizagem contextualizada, significativa e equitativa. Este procedimento constitui um referencial metodológico replicável em outros programas técnicos, consolidando a inovação didática como eixo transformador da formação em engenharia.

Palavras-chave: procedimento tecnodidático; formação técnica; aprendizagem significativa; integração tecnológica.

INTRODUCTION

The training of mechanical engineers at the higher education level requires constant updating of pedagogical approaches, in accordance with technological advances and the demands of the professional environment (Proaño *et al.*, 2025). In the mechanical engineering program, a persistent gap is evident between the theoretical knowledge taught in the classroom and its practical application in real-world scenarios, which limits students' ability to understand and effectively operate the complex mechanical systems that characterize their field of work (Alfonzo, 2023).

Several studies agree that meaningful learning and the constructivist approach are essential foundations for overcoming these limitations, provided they are combined with active methodologies and relevant technological resources (Ausubel, 2000; Vygotsky, 1978). In this sense, digital teaching strategies -such as simulators, interactive platforms, and virtual environments- are presented as effective tools for strengthening technical understanding and academic performance (Proaño *et al.*, 2025). However, their implementation at the higher education level remains partial and fragmented, revealing the need for integrative procedures that combine pedagogical innovation, technological updating, and methodological flexibility (Sánchez *et al.*, 2010; Sánchez & Pozo, 2017).

The theoretical foundation of this study rests on the need to link conceptual content with operational practices, promoting contextualized, collaborative, and meaningful learning (Alfonzo, 2023). The problematic situation lies in the insufficient articulation between theory and practice in mechanical engineering education, which creates gaps in professional training and limits the relevance of graduates to the current challenges of the mechanical engineering profile (Proaño *et al.*, 2025).

The literature review shows progress in the incorporation of digital resources and active methodologies, but also reveals gaps in the systematization of these innovations and their coherent integration with training objectives (Sánchez *et al.*, 2010; Qiu *et al.*, 2023). Therefore, a gap in the state of knowledge is identified, justifying the need for didactic procedures capable of overcoming fragmentation and guaranteeing a more comprehensive technical training (Alfonzo, 2023).

In this context, we propose to statistically analyze a mechanical techno-didactic procedure aimed at improving the academic performance of engineering students. The central purpose is to demonstrate, with empirical and verifiable evidence, the effectiveness of a procedure that integrates technological resources with participatory methodologies, highlighting its importance and scope as an innovative solution for technical education at the higher education level (Proaño *et al.*, 2025).

MATERIALS AND METHODS

The research adopted a mixed approach, combining quantitative and qualitative methods, with the purpose of analyzing the deficiencies in the ability of students with a mechanical technical profile to identify and visualize the operation of electrical and mechanical systems.

This design allowed for a comprehensive understanding of the phenomenon, facilitating data triangulation and validation of the results. The study was conducted as field research in an educational setting, specifically at the José Maceo higher education institution, over a period of three years. Its scope was descriptive and correlational, as it described the current state of the teaching-learning process and explored the relationship between the implementation of the mechanical technodidactic procedure and the improvement in students' skills.

Therefore, the unit of analysis consisted of 50 students from the mechanical engineering program, intentionally selected for their active participation in the training process from a total population of 60 students. Their grades, perceptions, and experiences related to the teaching intervention were considered.

Data collection instruments and techniques

Various techniques were used to collect information:

- Structured questionnaires applied to students and teachers (n=10 teachers from the area of mechanics), designed to collect perceptions on the ability to identify and visualize mechanical systems, as well as the effectiveness of digital teaching resources.
- Semi-structured interviews with the 10 teachers in the mechanics area, which allowed us to delve deeper into their experiences and opinions about the teaching-learning process.
- Direct observation in the classroom (50 observed class sessions), focused on analyzing the educational dynamics, the methodologies used, the teacher-student interaction and the use of technological resources.
- Focus groups with five groups of 10 students each, which facilitated discussion about their experiences, difficulties and suggestions to optimize the learning process.
- Diagnostic assessments applied before and after the intervention, with the aim of measuring the level of understanding of mechanical systems.

For the validation of the instruments, a process was implemented that ensured the reliability, validity, and objectivity of the instruments:

- Reliability: Cronbach's coefficient was calculated to assess the internal consistency of the questionnaires.
- Objectivity: clear criteria were defined for the administration and scoring of the instruments, minimizing bias in the interpretation of the results.

In the statistical analysis, the scores obtained before and after the intervention were compared using a paired Student's t-test, with a significance level of 0.05. A linear regression analysis was also applied to evaluate the relationship between initial performance and the academic improvement achieved after the intervention. To complement the quantitative analysis, box plots and scatter plots were created to visually illustrate the results and observed trends.

Ethical considerations were taken into account, and the procedures were carried out respecting the principles of impartiality and anonymity of the participants. The application of questionnaires, interviews, and assessments was conducted in accordance with the ethical standards established by the academic committee of the participating institutions, thus guaranteeing the confidentiality of the information and the informed consent of the students and faculty involved.

Finally, among the main limitations recognized was the small sample size, which restricts the generalizability of the results. Difficulties related to unequal access to technological resources and teachers' time availability to participate in interviews and focus groups were also identified.

RESULTS

Research on the teaching and learning process for the mechanical engineering profile at the higher education level showed significant results derived from the combined use of validated data collection instruments. The findings demonstrated improvements in students' ability to identify and visualize mechanical systems, as well as in their perception of the effectiveness of the digital teaching resources used.

In surveys administered to students, 26% rated their ability to identify and visualize mechanical systems as high, while 24% considered it moderate. The extreme categories were less represented, with 8% rating their ability as very low and 18% as very high. These results are presented in table 1, which shows a balanced distribution with a predominance of positive perceptions.

Table 1. Distribution of student perception on the ability to identify and visualize mechanical systems (n=50)

Perception category	Frequency (n)	Percentage (%)
Very low	4	8%
Low	12	24%
Moderate	12	24%
High	13	26%
Very high	9	18%
Total	50	100%

Source: Prepared by the author based on applied surveys

Statistical interpretation confirmed this trend: the mode corresponded to the "high" category (26%), the median was in the "moderate" category, and the skewness coefficient (+0.35) indicated a slight inclination toward higher perceptions. These values are shown in table 2, allowing us to conclude that the majority of students recognized improvements in their ability to identify and visualize mechanical systems.

Table 2. Measures of central tendency and shape (estimated with ordinal coding)

Statistical	Worth	Interpretation
Fashion	High (26%)	Most frequent category among students
Median	Moderate	Central point of the ordinal distribution
Asymmetry	+0.35 (slight)	Tendency towards higher perceptions; distribution slightly skewed to the right

Source: Prepared by the author based on applied surveys

In surveys administered to teachers, 92 % felt that the teaching resources used were effective for student learning. However, only 60% considered that the technology used in the classroom significantly contributed to improving student participation. This finding highlighted a gap between the perceived effectiveness of the resources and their impact on student motivation and active participation, which is a critical aspect for improving the traditional, techno-didactic approach.

The results provided empirical evidence on the relevance of the mechanical technodidactic procedure, confirming that its application fostered the understanding of mechanical systems and strengthened academic performance. At the same time, areas for improvement were identified related to the full integration of technological resources into the participatory dynamics of the classroom.

Semi-structured interviews with teachers in the field of mechanics allowed for a deeper understanding of their experiences. It was found that, although they recognized the usefulness of digital resources, they faced difficulties in their practical integration into the curriculum, as well as some resistance from students to actively participate in technological environments.

Systematic observation revealed a predominance of classes focused on theoretical exposition, with little incorporation of practical activities that would promote the visualization and understanding of mechanical systems (Table 3). This biased approach highlighted the need to implement more active and participatory methodologies, such as project-based learning, the use of digital simulators, and collaborative problem-solving in technical settings.

Table 3. Results of the systematic observation of class sessions (n=50 sessions observed)

Predominant type of activity	Frequency (n)	Percentage (%)
Theoretical explanation of concepts	40	80%
Practical activities with visualization of mechanical systems	10	20%
Total	50	100%

Source: Own elaboration

The supplementary analysis of the statistical measures (Table 4) confirmed that the mode corresponded to the theoretical explanation, while the negative skewness reflected a marked concentration on expository activities. The practical application index was estimated at 0.20, which evidenced the low frequency of activities that promoted the active visualization of mechanical systems.

Table 4. Complementary measures of systematic observation

Indicator	Estimated value	Interpretation
Fashion	Theoretical explanation	Most frequent activity in the observed sessions
Asymmetry	Negative (−0.85)	Marked focus on exhibition activities; low presence of practical activities
Practical application index	0.20	Proportion of classes that include active visualization of mechanical systems

Source: Own elaboration

Diagnostic assessments administered before and after the intervention showed that a high percentage of students had difficulty correctly identifying the components of a mechanical system. Following the implementation of innovative strategies, a significant improvement in understanding was observed, reflected in increased academic performance and the ability to visualize systems. The Student's t-test (Table 5) confirmed the statistical significance of this improvement.

Table 5. Descriptive statistics and Student's t-test for dependent samples

Variable	Average	Standard deviation	t-statistic	gl	p (bilateral)
Before	62.31	-	-	-	-
After	77.23	-	-	-	-
Difference	14.92	1.49	50.91	25	8.96×10^{-27} (< 0.0001)

Source: Own elaboration

The regression model (Table 6) confirmed the existence of a significant relationship between the initial grade and the improvement achieved. The negative slope indicated that students with lower initial performance tended to improve more.

Table 6. Regression model

Model	Non-standardized coefficients B	Standard error	Standardized Beta Coefficients	t	Sig.
(Constant)	21,842	4.215	-	5.182	0.000
Initial yield	-0.117	0.038	-0.421	-3.079	.003

Source: Own elaboration

The intervention resulted in a notable change in the variable studied. The initial mean, at 62.31 points, rose to 77.23 after the intervention, representing a difference of 14.92 points. This increase reflected an improvement in the participants' performance.

The consistency of the improvement was evidenced by the low dispersion of the data: the standard deviation of 1.49 indicated that most students progressed homogeneously, without large individual variations.

Inferential analysis reinforced these conclusions. The t-statistic reached a value of 50.91, with 25 degrees of freedom, confirming the robustness of the finding. The resulting p-value (8.96×10^{-27}) was less than 0.0001, ruling out any possibility that the observed improvement was due to chance.

Overall, the results showed a significant and consistent improvement in performance, corroborated by statistical evidence. The intervention not only raised the average level but also contributed to greater homogeneity within the group, a relevant finding for educational research.

DISCUSSION

The leveling effect observed -that is, that students with lower initial performance experienced a proportionally greater improvement- suggests a phenomenon that transcends mere empirical observation (Al-Khiami *et al.*, 2024). This finding is particularly significant because, as Bertozzi *et al.* (2022) point out, in the context of engineering education, interventions that succeed in reducing pre-existing disparities are exceptionally valuable, since technical training is often characterized by high variability in students' starting levels.

The consistency of the improvement observed across the entire performance spectrum is revealing. Bunjaku *et al.* (2024) documented that, in technologically integrated environments, there is a latent risk of amplifying educational gaps when digital tools are not accompanied by an inclusive pedagogical design. The opposite trend observed in the present study suggests that the design of the mechanical techno-didactic procedure incorporated scaffolding elements that facilitated equitable access to technical knowledge, which constitutes a central finding of this research.

Placing these results within the context of the contemporary state of the art reveals a fundamental convergence with the postulates of Wazlawick and Wazlawick (2024) on active learning methodologies in higher education. These authors demonstrated that pedagogical strategies that articulate conceptual knowledge with operational practice generate synergies that enhance the development of professional competencies. The mechanical technodidactic procedure, by integrating digital resources that allow for multiple forms of representation and access to content, appears to have operated under a similar logic: it offered alternative paths for understanding mechanical systems.

Aslanov and Bolshakov (2023) provide further evidence supporting this interpretation. In their study of virtual reality simulators for engineering education, they documented that immersive environments allow students to explore complex systems at their own pace, repeat operations as many times as necessary, and receive immediate feedback -features that are particularly beneficial for students with initial learning difficulties. The present research extends these findings by demonstrating that this benefit is not limited to the context of advanced simulators but also manifests itself in less technologically complex techno-didactic interventions.

However, it would be incorrect to claim that these findings align with all available research on educational technology. Strazzeri *et al.* (2024) found that implementing virtual reality in engineering requires careful usability considerations to be effective, and that without proper curriculum integration, the benefits may be marginal. This finding resonates with the observations of the present study, which demonstrated that the mere availability of resources does not guarantee their pedagogical effectiveness.

The discrepancy with the results of Motejlek and Alpay (2023) warrants analysis. These authors, in a study on information retention in virtual reality simulations, concluded that technology-mediated learning showed comparable -but not superior- results to traditional multimedia methods. However, the present study suggests that the crucial difference lies not in the technology *per se*, but in the accompanying pedagogical design. Canavesi and Ravarini (2024) argue along the same lines, noting that active methodologies mediated by technology develop competencies that transcend the purely technical, encompassing social, personal, and digital dimensions of learning.

From a theoretical perspective, the findings of this study contribute to the understanding of the mechanisms underlying technology-mediated meaningful learning. Angelis and Bailey (2025) demonstrated that educational interventions based on challenging experiences -the so-called "disorienting dilemmas"- can catalyze transformative learning processes when they connect with students' prior experiences. The mechanical technodidactic procedure, by presenting systems from interactive visual perspectives unavailable in traditional methods, appears to have operated under this logic.

Along these lines, research conducted by Guimarães and da Silva Lima (2023) on structural modeling of active learning methods in engineering education demonstrated a positive causal relationship between adherence to active methodologies and academic performance. Specifically, these authors documented an improvement in learning scores as a result of increased adherence to active methodologies. The present research complements this finding by demonstrating that this effect is not only significant on average but also benefits students with greater initial difficulties.

Some limitations are identified. The first relates to the sample size and the specific institutional context. Bunjaku *et al.* (2024) caution that generalizing findings on technology integration in education requires caution, given that the effects can vary significantly depending on the sociodemographic characteristics of the students and the institutional culture.

The second limitation concerns the duration of the study. Al- Khiami *et al.* (2024) noted that one of the methodological challenges in evaluating technological interventions in engineering is determining whether the improvements observed in the short term are sustained over time. In their study on virtual reality for civil engineering students, they documented that initially elevated motivation and performance tended to normalize after periods of prolonged exposure. The present study, being limited to immediate pretest- posttest measurements, cannot determine the sustainability of the observed effects.

The third limitation concerns uncontrolled intervening variables. Strazzeri *et al.* (2024) identified that factors such as system usability, prior experience with technology, and susceptibility to fatigue or simulation sickness can significantly influence the results. Although the quasi-experimental design employed allows us to attribute the changes to the intervention with reasonable confidence, it is not possible to completely rule out the influence of these factors.

Despite these limitations, there are reasons to consider the results valid. Canavesi and Ravarini (2024) argue that the consistency of the findings with the theoretical frameworks of active learning -particularly their coherence with the principles of scaffolding and continuous feedback- lends theoretical plausibility to the results. Similarly, Wazlawick and Wazlawick (2024) emphasize that methodological triangulation -combining quantitative measures of performance with qualitative perceptions from students and teachers- strengthens the internal validity of this type of study.

The preceding reflections lead to several lines of inquiry. Bertozzi *et al.* (2022) suggest that one of the remaining challenges in research on visible learning in engineering is determining which specific components of technodidactic interventions are the "active ingredients" responsible for the observed effects. Along these lines, future studies could break down the procedure into its constituent components -interactive visualization, immediate feedback, peer collaboration- using factorial designs that allow for isolating the contribution of each element.

Aslanov and Bolshakov (2023) point to another relevant direction: the need for longitudinal studies that assess learning retention over time. The question of whether the leveling effect observed in the short term persists once the intervention ceases has important practical implications for curriculum design. Motejlek and Alpay (2023) found that information retention in virtual environments can be comparable to that of traditional methods, but not necessarily superior, suggesting that the most substantial benefits might lie in dimensions not assessed in the present study, such as motivation or self-efficacy.

Finally, Angelis and Bailey (2025) propose exploring the transferability of these types of interventions to other areas of technical training. The question of whether the pedagogical principles that guided the mechanical technodidactic procedure are applicable to domains such as electrical engineering, automation, or thermodynamics constitutes a line of research of great practical and theoretical relevance.

This research has provided empirical evidence that the deliberate integration of interactive technological resources with participatory methodologies can significantly and equitably improve the learning of mechanical systems in engineering students. The magnitude of this improvement, its consistency, and its leveling effect constitute findings that transcend merely local interest to acquire theoretical and practical relevance, thus fulfilling the central objective of the research (Al- Khiami). *et al.*, 2024).

The significance of this work lies in having identified, beyond the overall effectiveness of the procedure, the mechanisms that likely explain it: the immediate feedback offered by interactive environments, the externalization of reasoning enabled by visualizations, and the implicit scaffolding that facilitates access to complex content (Bertozzi *et al.*, 2022). These mechanisms are not exclusive to mechanical engineering or the institutional context where the study was conducted; on the contrary, they constitute pedagogical principles of potentially general validity, as demonstrated by research in various domains of engineering education (Canavesi & Ravarini, 2024; Strazzeri *et al.*, 2024).

This opens up a research agenda, the development of which allows us to offer answers on how to design technical learning environments that are simultaneously rigorous, engaging, and equitable. Engineering education, like the technology it studies, is a constantly evolving field; pedagogical innovations should be no exception (Guimarães & da Silva Lima, 2023).

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Conflict of interest

Authors declare no conflict of interests.

Authors' contribution

The authors participated in the design and writing of the article, in the search and analysis of the information contained in the consulted bibliography.