Bridging Conceptual Gaps in Applied Statics through ChatGPT-Supported Learning

Prof. Hector Buyones-Gonzalez, Universidad Andres Bello

Hector Buyones Gonzalez is a professor in the School of Engineering's Construction Engineering program at Universidad Andres Bello and Universidad Autonoma de Chile in Santiago, Chile. He earned his degree in Civil Engineering and Civil Construction, as well as a Master's degree in Construction Management. With extensive experience coordinating and executing construction projects across diverse sectors—including the oil industry (refineries), retail, and high-rise building construction—Professor Buyones brings a wealth of practical knowledge to his teaching. His primary research interests are focused on education and innovation in construction, the application of artificial intelligence within the construction industry, and construction management.

Dr. Monica Quezada-Espinoza, Universidad Andres Bello, Santiago, Chile

Monica Quezada-Espinoza is a professor and researcher at the School of Engineering at Universidad Andrés Bello in Santiago, Chile, where she collaborates with the Educational and Academic Innovation Unit (UNIDA) as an instructor in active learning methodologies and mentors engineering faculty in educational research. She is the Secretary of the Women in Engineering Division (WIED) of the American Society for Engineering Education (ASEE) and an associate researcher in the STEM Latin America Network, specifically in the STEM + Gender group. Her research interests are diverse and focus on university education in STEM fields, faculty and professional development, research-based methodologies, and the use of evaluation tools and technology for education. She is also passionate about investigating conceptual learning in abstract physics topics, developing strategies to improve the retention of first-year engineering students, and enhancing skills and competencies in higher education. Additionally, Monica is dedicated to exploring gender issues in STEM education, with a particular emphasis on studying and proposing improvements for the inclusion of women in highly male-dominated fields. For more information on her work, visit her ORCID profile.

Bridging Conceptual Gaps in Applied Statics through ChatGPT-Supported Learning

Abstract

Applied Statics, a foundational Construction Engineering course, shows high failure rates tied to weak prerequisite skills in trigonometry, vectors, and linear equations. This mixed-methods study asks whether ChatGPT-supported leveling activities can narrow those gaps. Two cohorts at a private Chilean university were compared: a control group (Spring 2024, $n = 33$) and an experimental group (Spring 2025, $n = 23$). The experimental group completed two instructor-designed activities: first, students solved problems by hand, then entered the same exercises into ChatGPT to compare procedures, check intermediate steps, and correct errors under instructor oversight. A 15-item pretest–posttest adapted from the TUV and CCI instruments produced a normalized gain of $\langle g \rangle = 0.67$. Pass rates rose from 72.7% to 82.6% (mean grades 4.3 → 4.9; Mann–Whitney U, $p = 0.060$, not significant). Between 87% and 96% of students reported that ChatGPT clarified concepts, supported self-paced review, and encouraged autonomous reasoning. Together, these findings show that when generative AI is embedded with clear didactic criteria, hand-first practice, AI-assisted verification, and instructor oversight, it can measurably strengthen prerequisite skills in gateway engineering courses and offer a replicable model for addressing the math-readiness gap in STEM programs.

Keywords: Applied Statics, ChatGPT, Construction engineering education, Generative AI, Learning gain, Mathematical prerequisites

Introduction

The construction sector is one of the fundamental pillars of the Chilean economy, accounting for an average of 6.5% of the national gross domestic product (GDP) over the past 10 years. Additionally, according to data from the National Institute of Statistics, in 2023 the construction sector accounted for 7.9% of national employment, making it one of the country's main sources of jobs [1]. By 2026, investment in construction is expected to increase by 4.8%, driven primarily by growth in infrastructure and housing [2]. Within this context of expansion and high labor demand, the need to educate professionals with strong technical competencies is reinforced, particularly those capable of meeting the sector's requirements for productivity, safety, and quality. Consequently, strengthening the education of future construction engineers is essential to ensure that graduates possess the skills and competencies currently demanded by the industry, facilitating a rapid and successful transition into the workforce.

In this context, the Applied Statics course is included in most Construction Engineering curricula due to its fundamental role in developing competencies in equilibrium analysis and the behavior of isostatic structural systems. This course addresses the study of loads acting on structures, support reactions, and the determination of internal forces in structural elements. Mastery of these principles is essential for addressing the technical challenges involved in the safe and efficient execution of building and infrastructure projects [3].

Applied Statics is a course that involves abstract and complex concepts, and many students struggle to relate structural models, free-body diagrams, and mathematical language to realworld scenarios [4]. These difficulties are often associated with insufficient foundational skills in algebra and trigonometry, gaps that instructors frequently identify. For example, Liu et al. [5, p. 1] note: *"My students can't do the math. They need to know math, then they would do better on the exams."* Such deficiencies negatively affect students' academic performance and their ability to apply fundamental principles of mechanics in Applied Statics and in more advanced engineering courses.

Globally, there is growing concern about the decline in students' mathematical competencies entering higher education, particularly with respect to essential concepts that should have been mastered in secondary education. For instance, in Malaysia, Mahat et al. [6] reported results from diagnostic assessments administered to first-year engineering students, identifying strengths in vector operations but significant weaknesses in trigonometric functions and calculus. These gaps delay academic progress and limit students' preparation for entering the engineering profession [6]. In line with these foundational gaps, international evidence indicates that difficulties are not confined to trigonometry and calculus but also extend to fundamental modeling skills in physics and engineering, such as vector concepts [7]. A study conducted with science and engineering students completing an introductory physics course identified persistent difficulties in key vector concepts, particularly in the representation and use of unit vectors, two-dimensional vector addition and subtraction, and the interpretation of dot and cross products [7]. These concepts constitute direct prerequisites for courses in Civil Engineering and Construction Engineering.

Similarly, Barniol and Zavala [8] designed and validated the Test of Understanding of Vectors (TUV) based on an analysis of errors made by 2,067 students and subsequently administered it to 423 students at the end of an introductory physics course. Their results showed that, even after passing the course, students continued to exhibit substantial difficulties with vectors, particularly in the vector cross product, as well as errors in the representation of unit vectors and in two-dimensional vector subtraction [8]. These findings confirm that vector-related gaps are not automatically resolved in introductory courses and may persist into subsequent engineering coursework.

In a similar vein, European research has addressed this issue, which some scholars refer to as the "mathematics problem" [9]. Nortvedt and Siqveland [9] report that the Norwegian Mathematical Council developed and implemented an assessment to measure mastery of basic mathematical skills among students entering higher education programs in engineering, mathematics, and economics. The results indicated that students did not demonstrate sufficient mastery of content covered in lower secondary mathematics curricula, including basic arithmetic principles, simple algebra, and algebraic language. Notably, an exercise that proved surprisingly difficult involved ordering fractions by magnitude. Additionally, evidence from Ireland reported by Hyland and O'Shea [10], based on diagnostic assessments across 11 institutions, indicates that the transition to higher education remains marked by persistent gaps in basic mathematics. This finding reinforces an international and long-standing concern, as the authors note: *"In any case, it seems that worries about the lack of basic mathematical proficiency among school leavers are prevalent internationally"* [10, p.45].

Research conducted in the United States similarly indicates that a large proportion of students enter university with deficiencies in mathematical knowledge, particularly in algebra and precalculus, which significantly affects their retention in STEM programs. Consequently, early identification and support are considered essential strategies for reducing these gaps [11]. Other studies in the U.S. higher education context also acknowledge that many students lack a solid foundation in mathematical skills upon entry, which substantially hinders their academic progress [12].

In the Chilean context, a study conducted with first-year engineering students identified significant gaps in foundational content, particularly in trigonometry, highlighting errors in the use of trigonometric identities and inappropriate application of algebraic properties. In their discussion, the authors argue that these errors are primarily related to insufficient prior knowledge in trigonometry and algebra [13].
The 2022 PISA results reported by the OECD further highlight this issue, showing that Chile performed below the OECD average in mathematics, reading, and science. In mathematics, only 44% of students reached at least Level 2 (compared to 69% across OECD countries), a threshold indicating the ability to recognize and interpret how a simple situation can be represented mathematically. At the same time, only 1% of students achieved high performance levels (Levels 5–6), compared to 9% in the OECD. These indicators suggest deficits both in minimum expected learning outcomes and in the development of advanced skills, with direct implications for the transition into university courses that require strong mathematical reasoning, particularly in engineering programs [14]. Evidence from school-level assessments (PISA) and studies involving first-year university students converges in showing that a substantial proportion of students enter higher education with weaknesses in fundamental mathematical competencies and prerequisite content, especially algebra and trigonometry. These gaps become particularly evident in “gateway” courses within engineering curricula, where prior mathematical mastery is critical for understanding, modeling, and solving engineering problems.

Within this context, recent evidence from a Chilean Construction Engineering program identifies the set of courses in the structures area as a historical “bottleneck,” concentrating the highest failure rates in the curriculum. Specifically, Applied Statics, the first course in this area, shows an approval rate of approximately 54%, reinforcing the presence of conceptual and procedural gaps that hinder progression to subsequent courses [15].

Recent work in engineering education has also advanced pedagogical approaches specifically within Statics and Applied Statics. In particular, assessment-oriented studies have emphasized that evaluating students’ ability to construct free-body diagrams (FBDs) requires more than checking procedural correctness, prompting the development of competency-based models that identify common conceptual errors in authentic Statics tasks [16]. Complementing this line of work, research on representational competence has highlighted the importance of helping students interpret, coordinate, and reason with visual representations, suggesting that explicit scaffolds can strengthen learning in engineering problem-solving contexts [17].

In addition, metacognitive approaches, such as self-explanation, have been investigated in Statics as knowledge-building activities that can promote conceptual change and make students more aware of their reasoning during problem-solving [18]. Taken together, these studies show that recent innovation in Statics pedagogy has focused on improving assessment, representational scaffolding, and metacognitive support. However, less is known about course-embedded interventions that explicitly remediate prerequisite mathematical gaps—such as trigonometry, vectors, functions, and systems of linear equations—through instructor-mediated adaptive scaffolding within Applied Statics courses. This gap provides a clear rationale for the present study.

In response to this situation, generative artificial intelligence tools such as ChatGPT have emerged as potential supports for personalized and adaptive learning, offering effective feedback mechanisms to address diverse learning styles. A systematic review of ChatGPT in higher education analyzed 57 articles published between 2023 and 2024 and reported applications focused on academic tutoring, automated feedback, and the generation of study resources, highlighting its potential to provide frequent and accessible learning support [19].

Complementarily, another systematic review of 44 articles identified eight primary uses of ChatGPT to support student learning, ranked from most to least frequent: 24/7 support and accessibility, explanation of difficult concepts, conversational partner, personalized feedback and learning materials, writing support, self-assessment, student engagement, and self-determination. These findings reinforce the idea that ChatGPT can help reduce educational gaps, provided its implementation is guided by explicit pedagogical and ethical criteria [20].

Along the same lines, a systematic review with meta-analysis of experimental studies identified 69 articles published between 2022 and 2024 across five databases and found that ChatGPT-based interventions are predominantly implemented at the university level, integrated into regular classroom practices, and, in most cases, involve students directly using ChatGPT. This context is particularly relevant, as it suggests that adoption is occurring in authentic instructional settings and at an accelerated pace. Unlike traditional chatbots based on predefined responses and limited interactions, ChatGPT's generative capabilities enable more dynamic, context-sensitive conversations and personalized feedback, thereby supporting timely and adaptive learning assistance [21].

Consistent with this evidence, empirical research in higher education suggests that integrating ChatGPT can yield measurable benefits in completing complex tasks that require reasoning and creativity. Specifically, its value can be described across three dimensions: (i) cognitive support during problem-solving, including step-by-step explanations, concept clarification, and procedural organization; (ii) strategic support for comparing and selecting solution pathways through the evaluation of alternatives; and (iii) motivational support by increasing students' confidence in their ability to solve problems. When incorporated as a learning companion, ChatGPT has been associated with improved student performance. However, these benefits depend on students' self-regulation, as responses may appear correct even when they are not, potentially leading to overconfidence. Consequently, its use requires the strengthening of metacognitive skills such as verifying procedures, cross-checking results, and justifying decisions, that is, adopting a critical and reflective stance, since perceived usefulness does not guarantee correct solutions.

Within this framework, the objective of this study is to evaluate the extent to which a ChatGPT-supported learning intervention contributes to reducing conceptual gaps in Applied Statics, particularly in foundational mathematical skills, including trigonometry, vectors, functions, and systems of linear equations.

Methodology

This study adopted a mixed-methods approach, integrating quantitative and qualitative methods to examine both the impact and the student experience associated with the use of ChatGPT as a complementary learning resource in the Applied Statics course. The quantitative component followed a quasi-experimental design with non-equivalent groups, consisting of a control group (CG) from the Spring 2024 semester that completed the course without any AI-based intervention, and an experimental group (EG) from the Spring 2025 semester that participated in an instructional intervention supported by ChatGPT.

In the experimental group, a conceptual pretest and posttest were administered. These assessments were adapted from validated instruments reported in the literature, specifically the *Test of Understanding of Vectors* (TUV) [8] and the *Calculus Concept Inventory* (CCI) [22]. Learning gains were subsequently calculated using Hake's normalized gain method [23]. In the control group, no pre–post measurements were conducted; therefore, this group was used as a comparative reference based on institutional academic indicators, including final course grades and pass/fail rates.

In addition to the quantitative measures, a perception survey was implemented to capture students' views regarding the educational innovation involving ChatGPT as an assistive technology. The survey consisted of eight items measured on a five-point Likert scale assessing levels of agreement, as well as four open-ended questions aimed at eliciting students' reflections on their experience using ChatGPT. These open responses enabled the collection of qualitative data on perceived benefits, limitations, and implementation recommendations. This instrument was administered exclusively to the experimental group.

A. Participants

The sample comprised students enrolled in the *Applied Statics* course within a Construction Engineering program at a private university in Chile.

- Control Group (CG): Spring 2024 semester, n = 33 (32 male students and 1 female student).
- Experimental Group (EG): Spring 2025 semester, n = 23 (22 male students and 1 female student).

Context and procedure

The *Applied Statics* course is offered in the fourth semester of the Construction Engineering curriculum and requires prior completion of an introductory mechanics course. It constitutes a core component of the program and serves as a prerequisite for subsequent courses in the structural engineering area. The course aims to develop students' abilities to analyze isostatic structures by applying principles of equilibrium, mechanics of materials, and the determination of internal forces. The instructional approach traditionally combines lectures, problem-solving sessions, and written assessments focused on quantitative reasoning and the development of discipline-specific analytical skills. Table 1 presents an overview of the instruments and instructional activities implemented during the study, including the specific weeks of the semester in which each activity was conducted.

The instruments implemented in this study are described below.

- Conceptual Test (Pretest and Posttest – EG only):
  A 15-item multiple-choice conceptual diagnostic test was administered in a pretest format (at the beginning of the semester, prior to the intervention) and a posttest format (at the end of the intervention) to estimate learning gains in prerequisite content for *Applied Statics*. The instrument assessed foundational mathematical competencies, including vectors, trigonometry, linear equations, and functions.

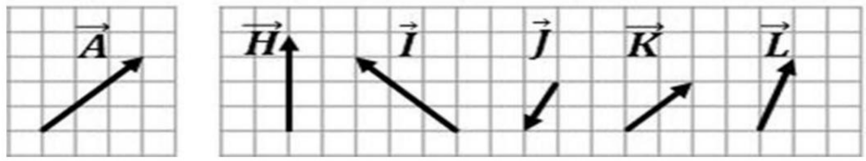
Table 1. Timeline of activities and assessments incorporating ChatGPT in the Applied Statics course.

Time of the semester	**Content**	**Week of the semester (out of 17)**
Beginning	Pre-conceptual test	Week 2
Activity 1	Part 1: The students solve exercises traditionally (manually) using a calculator. Part 2: The same exercises are entered into ChatGPT to compare results, reflect on the generated responses, and validate the calculations.	Traditional method: Week 4 Using ChatGPT: Week 5
Activity 2	Part 1: The students solve exercises traditionally (manually) using a calculator. Part 2: The same exercises are entered into ChatGPT to compare results, reflect on the generated responses, and validate the calculations.	Traditional method: Week 12 Using ChatGPT: Week 13
Final	Post-conceptual test	Week 16
	Survey about students' perceptions and reflections regarding using ChatGPT.	Week 17

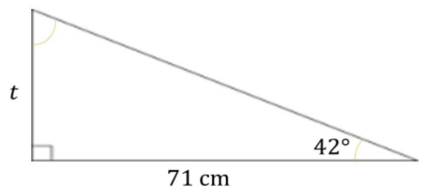
The test was developed based on validated instruments reported in the literature, specifically the *Test of Understanding of Vectors* (TUV) and the *Calculus Concept Inventory* (CCI). It comprised six items on vectors, four on trigonometry, and five on linear equations and functions. Examples of the test items for each dimension are presented in Table 2.

Table 2. Dimensions and sample items.

Dimensions (No items)	**Items examples**

<table>
<tr><td>Vectors (6)</td><td>The figure below shows vector $\overrightarrow{A}$ and a list of vectors. Which vector(s) has/have the same direction as vector $\overrightarrow{A}$?[8]


(A) $\overrightarrow{K}, \overrightarrow{L}$
(B) $\overrightarrow{I}, \overrightarrow{K}$
(C) $\overrightarrow{K}$
(D) $\overrightarrow{H}, \overrightarrow{K}, \overrightarrow{L}$
(E) No vector has the same direction as vector $\overrightarrow{A}$

Correct answer: option (A)</td></tr>
<tr><td>Trigonometry (4)</td><td>Which is the correct method to work out side t?


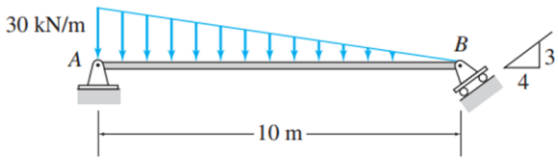
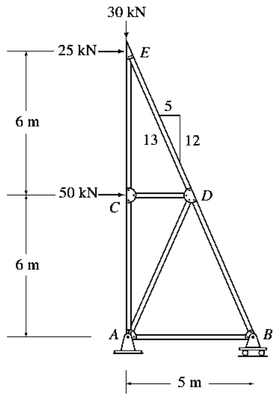
(A) $\frac{cos\ (42)}{71}$
(B) $sin\ (42) * 71$
(C) $\frac{tan\ (42)}{71}$
(D) $tan\ (42) * 71$

Correct answer: option (D)</td></tr>
<tr><td>Functions and systems of linear equations (5)</td><td>Values at a few points are given below for two functions f(x) and g(x) that are defined for all real values of x. [22]
<table><tr><th>x</th><th>f(x)</th></tr><tr><td>1</td><td>101</td></tr><tr><td>2</td><td>102</td></tr><tr><td>3</td><td>103</td></tr><tr><td>4</td><td>104</td></tr></table><table><tr><th>x</th><th>g(x)</th></tr><tr><td>2</td><td>101</td></tr><tr><td>4</td><td>102</td></tr><tr><td>6</td><td>103</td></tr><tr><td>8</td><td>104</td></tr></table>Which of the following relations can be correct?

(A) g(x) =2 f(x)
(B) $g(x) = f(2x)$
(C) $g(x) = \frac{f(x)}{2}$
(D) $g(x) = f\left(\frac{x}{2}\right)$
(E) $g(x) = \frac{f(2x)}{2}$
Correct answer: option (D)</td></tr>
</table>

Two practical activities were implemented throughout the semester. Each activity was designed to align with the course learning outcomes and conducted in a group-based format to promote peer collaboration. Table 3 presents the content areas addressed in each activity, along with a representative question for each.

Table 3. Sample questions and content covered by the activity.

<table>
<tr><th>Activity and Sample Question</th><th>Topics Covered</th></tr>
<tr><td>Activity 1
Given the proposed structural system, determine the external reactions at each support.

</td><td>Decomposition of forces, calculation of support reactions, and resultant force.</td></tr>
<tr><td>Activity 2
Determine the forces in each member of the truss shown using the method of joints.

</td><td>Trigonometry, linear equations, and the determination of forces in truss structures.</td></tr>
</table>

Perception survey on the use of ChatGPT

The purpose of this survey was to collect information on students' perceptions regarding the use of generative artificial intelligence tools in problem-solving activities within *Applied Statics*. The instrument consisted of eight Likert-scale items designed to measure students' perceptions, along with four open-ended questions that allowed students to reflect on their experiences and provide recommendations based on their use of ChatGPT.

Data analysis and ethical considerations

The collected data were analyzed using Microsoft Excel to synthesize and effectively visualize the results, and JASP was employed to conduct inferential statistical analyses. Regarding ethical considerations, the study adhered strictly to ethical guidelines applicable to educational research. All participants were fully informed about the purpose, objectives, and scope of the study prior to participation. Confidentiality was ensured through the use of anonymous identifiers and the secure storage of all collected data. In addition, written informed consent was obtained, ensuring that participants understood their right to withdraw from the study at any time without any negative consequences.

Results

This section presents the results of the study. First, the findings related to the normalized learning gain (⟨g⟩), calculated following Hake [23] using Equation (1), are reported. According to this author, learning gains are categorized as follows: low-g < 0.3; medium-g 0.3–0.7; high-g > 0.7.

$$\langle g \rangle = \frac{\%\langle Sf \rangle - \%\langle Si \rangle}{(100 - \%\langle Si \rangle)} \quad (1)$$

After entering the pretest and posttest data into the model proposed by Hake [23], a normalized learning gain of ⟨g⟩ = 0.67 was obtained, indicating a medium-to-high learning gain. Dimension-level analysis shows comparable normalized gains across the conceptual domains assessed, with g = 0.65 for vectors, 0.68 for trigonometry, and 0.66 for functions and systems of linear equations, suggesting consistent learning gains across topics. Item-level learning gains for individual test questions are presented in Table 4.

Table 4. Item-level learning gains on the conceptual test.

Item	Dimension	Gain ⟨g⟩
1	Vectors	0.63
2	Vectors	0.62
3	Vectors	0.54
4	Vectors	0.64
5	Vectors	0.75
6	Trigonometry	0.50
7	Trigonometry	0.73
8	Vectors	0.72
9	Trigonometry	0.67
10	Trigonometry	0.83
11	Functions and systems of linear equations	0.75
12	Functions and systems of linear equations	0.53
13	Functions and systems of linear equations	0.79
14	Functions and systems of linear equations	0.71
15	Functions and systems of linear equations	0.54

Regarding final course grades, an increase of approximately 10% in the pass rate was observed between the control group (72.7%) and the experimental group (82.6%), along with an increase in the overall course average (see Table 5). Differences in means between the control and experimental groups were examined using the Mann–Whitney U test (95% confidence level).

The results indicated that the observed differences were not statistically significant (p = 0.060). Table 6 presents the test results along with the corresponding descriptive statistics.

Table 5. Course pass rates and average final grades.

	Spring 2024	Spring 2025
% Pass rate	72.7%	82.6%
% Fail rate	27.3%	17.4%
Course average grade	4.3	4.9

Table 6. Descriptive Statistics.

	Grades	
Group	1	2
Valid	33	23
Mean	4.3	4.9
Std. Deviation	1.15	1.15
Minimum	2.2	2.1
Maximum	6.7	6.4

Finally, the results of the perception survey regarding the use of ChatGPT are presented. The survey was administered at the end of the leveling activities. Table 7 summarizes the results of the instrument, in which the response categories were regrouped into three levels: Disagree (combining *Strongly disagree* and *Disagree*), Neutral (corresponding to *Neither agree nor disagree*), and Agree (combining *Agree* and *Strongly agree*).

Table 7. Students' perceptions of the use of ChatGPT in leveling activities in Applied Statics.

Question	Disagree	Neutral	Agree
The activities supported by ChatGPT helped me better understand the concepts of trigonometry, vectors, and systems of equations required for Applied Statics.	0.0%	13.0%	87.0%
The step-by-step explanations provided by ChatGPT helped me identify and correct errors in my problem-solving approach.	0%	8.7%	91.3%
I feel that the activities supported by ChatGPT helped reduce the gaps in prior knowledge I had at the beginning of the course.	4.3%	8.7%	87.0%
During the activities, I was able to progress at my own pace and request additional clarification from ChatGPT when I did not understand a procedure.	0%	8.7%	91.3%
Working with ChatGPT made me feel more motivated and engaged in my learning process.	4.35%	4.35%	91.3%
I consider it useful to continue using generative AI tools such as ChatGPT as academic support in other courses within the curriculum.	4.35%	4.35%	91.3%
Overall, my experience using ChatGPT in the leveling activities was positive and contributed significantly to my learning.	0%	8.7%	91.3%
I believe that the use of ChatGPT complements, rather than replacing, the instructor's explanations in class.	0%	4.3%	95.7%

The following section presents the open-ended questions administered at the end of the intervention, along with the categories derived from the analysis of students' responses, including their corresponding frequencies and a representative example. The categorization process was conducted through qualitative analysis of the collected responses, first identifying key ideas, then defining recurring themes, and subsequently grouping them into emergent categories. See Table 8.

Question 1. How did your perception of artificial intelligence tools change (if at all) after participating in these activities? Please comment using concrete examples or specific situations.

Table 8. Emergent categories and response frequency for question 1.

Categories emerged (frequency)	**Description (an example of response)**
No change (5)	This category includes responses indicating that students' perceptions of artificial intelligence did not change, as they had already been using AI tools as academic support prior to the intervention. Example: *"It did not change because I have always used ChatGPT as a complementary tool for studying."*
Positive change (15)	This pattern reflects a positive shift in students' perceptions of AI tools, moving from viewing them primarily as "machines that provide answers" to recognizing them as resources that support reasoning and learning. Example: *"I stopped seeing AI only as machines that give answers and started using them as support for reasoning."*
Change with reservations (3)	Responses in this category acknowledge that ChatGPT can provide useful support, while also highlighting perceived risks and limitations. Example: *"Even though ChatGPT can help in many ways, it does not always provide correct results, which can sometimes lead to confusion when studying."*

Question 2. Thinking about your learning in Applied Statics, to what extent do you feel that using ChatGPT helped you study more autonomously? Please describe a concrete example (e.g., a situation, exercise, or study moment).
The emergent categories identified for Question 2 are presented in Table 9.

Table 9. Emergent categories and response frequency for Question 2.

Categories emerged (frequency)	**Description (an example of response)**
Formative feedback (14)	This category reflects students' perceptions of ChatGPT as a support tool for problem solving by providing detailed procedures and explanations of underlying reasoning, as well as guidance aimed at understanding the solution process. Example: *"When I made a mistake, the AI explained in detail where I went wrong, helped me solve the problem step by step, and recommended additional study materials."*
Autonomy (7)	This category highlights that the tool supports autonomous learning by allowing students to study at their own pace without relying on instructors or peers. Example*: "Using ChatGPT helped me study Applied Statics more autonomously because it allowed me to identify and correct my own mistakes without always depending on a professor or a classmate…"*

Limited usefulness (2)	This category acknowledges that ChatGPT provides general guidance; however, students expressed limited trust in its use for calculation-intensive exercises due to perceived errors and inconsistencies. Example: *"This semester ChatGPT did not help me study Applied Statics because I don't trust the answers it gives; when it comes to calculations, it often provides different results."*

Question 3. When an exercise did not work out for you, what type of help did you request from ChatGPT (e.g., hints, analogies, intermediate steps, result verification), and which aspects of that support helped you understand the prerequisite concept you were missing (trigonometry, vectors, or systems of equations)?
The emergent categories identified for this question are presented in Table 10.

Table 10. Emergent categories and response frequency for Question 3.

Categories emerged (frequency)	**Description (an example of response)**
Step-by-step guidance and explanation of underlying reasoning (12)	This category reflects students' requests for detailed, step-by-step procedures accompanied by explanations of *why* a problem should be solved in a particular way. The emphasis is on understanding the reasoning process rather than receiving the final solution. Example: *"I asked it to explain everything step by step, but without giving me the final answer. This helped a lot, especially with trigonometry."*
Guided hints and error correction (9)	This group is characterized by requests for more targeted support, such as hints, intermediate steps, and review of the student's own procedure to identify mistakes. The focus is on detecting and correcting errors within the solution process developed by the student. Example: *"When a statics problem didn't work out, I mainly asked ChatGPT for guided hints, verification of my free-body diagrams and equations, and sometimes intermediate steps without giving the final result. This type of help allowed me to identify exactly where my mistake was without solving the entire problem for me."*
Result verification and comparison (2)	In this category, students used ChatGPT primarily to verify their results and compare their answers with alternative solution methods. Example*: "I asked it to verify my results and to show whether there were different ways to reach the answer."*

Question 4. Please write at least four prompts that you used during your interaction with ChatGPT.
The emergent categories identified for this question are presented in Table 11.

Table 11. Emergent categories and response frequency for Question 4.

Categories emerged (frequency)	**Description (an example of response)**
Learning companion tool (14)	The prompts written by students reflect an intentional use of ChatGPT as a learning support tool, prioritizing step-by-step guidance rather than direct access to the final answer. This pattern is evident in explicit requests for feedback without revealing the solution. Example: *"Take the role of a statics instructor and help me resolve my questions and review the exercises without giving the correct final answer."*
Result verification and error correction (4)	This category includes prompts primarily focused on verifying and validating results, as well as identifying potential errors in students' solutions. Example: *"Verify the results I obtained, compare them with yours, and correct me."*

Personalized materials and resources (5)	In this category, prompts request that ChatGPT generate additional practice problems and complementary study materials (e.g., videos, personalized resources, platforms) to help reduce learning gaps. Example: *"Propose exercises targeting the areas where I show the most difficulties when solving problems and recommend materials and videos so I can study the topic more effectively."*

Discussion

In line with the objective of this study, to evaluate how a ChatGPT-supported instructional intervention may contribute to reducing learning gaps in *Applied Statics*, particularly in foundational mathematical skills such as trigonometry, vectors, functions, and systems of linear equations, this section discusses the main findings of the research.

Regarding students' learning of trigonometry, vectors, functions, and systems of linear equations, the normalized learning gain obtained was $\langle g \rangle = 0.67$, which falls within the medium-gain range according to Hake's classification (low-g < 0.3; medium-g 0.3–0.7; high-g > 0.7), while also being very close to the upper threshold of this range. This finding is particularly relevant because normalized gain allows learning progress to be interpreted relative to students' initial knowledge levels (pretest), providing a comparative metric for discussing the effects of instructional strategies on conceptual learning rather than solely on final performance.

This result is consistent with other interventions reported in higher education. For instance, Huesca et al. [24] integrated ChatGPT into programming courses and found that its impact was associated with learning gains when embedded within a structured instructional design. Specifically, in a university-level flipped learning course, the ChatGPT group achieved a normalized gain of $\langle g \rangle = 0.53$, compared to the control group's $\langle g \rangle = 0.41$. The comparison between groups revealed a statistically significant difference in normalized gains in favor of the ChatGPT-supported flipped learning group (Wilcoxon–Mann–Whitney, $p = 0.000584$), supporting the idea that ChatGPT can enhance learning gains when integrated into a well-designed instructional strategy.

Complementarily, Masriyah et al. [25] reported evidence from mathematics education (integral calculus), where ChatGPT was incorporated as a support tool within a flipped classroom approach. Their results showed a normalized gain of $\langle g \rangle = 0.89$ in the experimental group, compared with $\langle g \rangle = 0.76$ in the control group, further supporting the potential of AI-based tools to strengthen conceptual understanding of mathematical content.

Regarding final course grades, the experimental group (4.9) had a higher average than the control group (4.3), along with a higher pass rate (72.7% in the control group and 82.6% in the experimental group). However, as no statistically significant differences were identified between the two groups, these variations cannot be conclusively attributed to the ChatGPT-based intervention.

These findings are consistent with those reported by Abdulla et al. [26], who, in a study with similar characteristics, also found no statistically significant differences between experimental and control groups. The authors attributed this result to the highly specific nature of the second exam administered, which was designed for a particular context and may have required more specialized prompting strategies, as well as more precise contextualization of the tool, to reveal measurable advantages in academic performance.

In the present study, the absence of statistically significant differences in overall performance may be associated with the fact that the ChatGPT-supported intervention focused specifically on strengthening foundational mathematical competencies, vectors, trigonometry, functions, and linear equations, rather than addressing the full range of content covered in the *Applied Statics* course. From this perspective, it is plausible that the intervention's impact would be more clearly reflected in indicators directly related to these competencies, whereas the final course grade, which integrates multiple assessments and heterogeneous content, may partially dilute the intervention's effect, despite the favorable trend observed in the experimental group.

Regarding students' perceptions, the quantitative results indicate strong acceptance of the ChatGPT-supported intervention. As shown in Table 8, students highlighted the usefulness of step-by-step explanations for identifying and correcting errors (91.3%), which aligns with qualitative responses describing ChatGPT as a support tool for understanding procedures and receiving immediate feedback during problem-solving. Similarly, the opportunity to progress at their own pace by requesting additional clarifications (91.3%) is consistent with responses emphasizing increased autonomy, as students were able to study outside the classroom without constant reliance on others.

Additionally, students reported that the intervention contributed positively to their learning process (91.3%). This perception is reinforced by the analysis of prompts, which show that students oriented their interactions toward reviewing steps, identifying errors, and contrasting procedures rather than simply obtaining the correct final answer. Along the same lines, the near-unanimous agreement that ChatGPT "complements, but does not replace" the instructor (95.7%) suggests that, from the students' perspective, the tool functions as an academic support resource rather than a substitute for instructional mediation—an important consideration for the responsible use of AI in education. This pattern aligns with findings in higher mathematics education reported by Fardian et al. [27], who describe ChatGPT as a tool that provides step-by-step explanations and makes learning more accessible and motivating, while emphasizing that the instructor's role as a mediator or facilitator remains essential.

However, responses also revealed concerns about the tool's reliability, particularly the possibility of incorrect or inconsistent results. These findings underscore the importance of integrating ChatGPT use with explicit criteria for validation and critical thinking. Zhuang [28] notes that ChatGPT may produce calculation errors, highlighting the need for instructor supervision to evaluate and validate AI-generated outputs. Similarly, Fardian et al. [27] emphasize that the reliability of the information provided depends on both problem complexity and prompt quality, reinforcing the importance of human oversight to minimize errors.

Overall, the qualitative evidence supports the conclusion that, under guided implementation, ChatGPT can function as an effective tool for strengthening conceptual understanding and supporting autonomous learning, while maintaining the instructor's role as the central mediator in the learning process.

Conclusions

The objective of this study was to evaluate the extent to which a ChatGPT-supported learning intervention contributes to reducing conceptual gaps in *Applied Statics*, particularly in trigonometry, vectors, functions, and systems of linear equations. Using a mixed-methods approach that combined a conceptual pre–post test and a perception survey, the results revealed a normalized learning gain of $\langle g \rangle = 0.67$, corresponding to a medium-to-high gain, with consistent values across the assessed dimensions (vectors, trigonometry, and equations/functions). These findings suggest that a guided implementation of ChatGPT can contribute to strengthening foundational knowledge that is essential for problem-solving in applied statics.

Regarding students' experiences, the perception survey indicates a broadly positive evaluation of ChatGPT use, particularly highlighting its usefulness in providing step-by-step explanations that help identify and correct errors, ultimately fostering greater student autonomy. The open-ended responses and prompt analysis further reinforce that ChatGPT was predominantly used in a formative manner, oriented toward understanding procedures through immediate feedback, verifying solution steps, and accessing additional materials and practice exercises to complement learning. At the same time, some reservations emerged about ChatGPT's reliability for calculation-intensive tasks, underscoring the need to incorporate explicit validation criteria and to adopt a critical stance when using the tool.

Overall, the convergence of quantitative and qualitative findings indicates that ChatGPT, when incorporated as a complementary tool within a pedagogically guided framework, can function as an effective instructional support mechanism by providing formative feedback that enhances autonomous learning and helps reduce mathematical gaps relevant to *Applied Statics*, while preserving the instructor's role as the central mediator of the learning process.

In this regard, the results of this study provide evidence that ChatGPT can strengthen existing pedagogical strategies in higher education, provided it is integrated with clear didactic criteria and used to promote a more personalized learning process aligned with the educational demands of twenty-first-century learners.

Limitations and Future Work

This study presents methodological and contextual limitations related to the sample, which was drawn from a single institution and a specific academic program (Construction Engineering), and showed limited gender diversity. In addition, the absence of pre–post measurements in the control group restricts the ability to compare learning gains across cohorts. Furthermore, access conditions to ChatGPT (free versus paid versions) were not controlled, which may have influenced the number and nature of student interactions with the tool.

Given these limitations, future research could extend this study by including larger samples from multiple institutions and engineering programs, thereby enhancing the generalizability of the findings and accounting for greater diversity in educational contexts and student profiles. Additionally, the implementation of quasi-experimental designs with pre–post measurements in both experimental and control groups is recommended to enable more robust analyses of learning gains and to strengthen causal inferences.

In line with the present findings, future studies could also examine the impact of ChatGPT on specific competencies and content areas within *Applied Statics*, using more targeted indicators that allow for a more precise assessment of intervention effects. Finally, it is recommended that future research control for and analyze the type of access to the tool (free versus paid versions), as well as the frequency and characteristics of student interactions, in order to better understand how these variables moderate the impact of generative artificial intelligence on learning.

Acknowledgments

The authors acknowledge the institutional and financial support of the School of Engineering at Universidad Andrés Bello, Chile, as well as the Educational Research and Academic Development Unit (UNIDA) for its mentorship and guidance in strengthening research capabilities in higher education.

References

[1] H. de Solminihac and J. Almendra Dagá, "Productividad y especialización local en la construcción de Chile: Análisis y propuestas de mejora **[**Productivity and local specialization in Chile's construction industry: Analysis and improvement proposals**]**," CLAPES UC, Pontificia Univ. Católica de Chile, Santiago, Chile, Working Paper No. 155, Apr. 2025. [Online]. Available: https://assets.clapesuc.cl/Productividad_y_Especializacion_Construccion_d87c6bdcc2.pdf

[2] A. Echavarría F. and N. León R., "Inversión en construcción: Análisis y perspectivas [Investment in Construction: Analysis and Perspectives]", CChC, Gerencia de Estudios y Políticas Públicas, Dec. 22, 2025. [Online]. Available: https://cchc.cl/documents/431409/539255/Prensa_MACh69_22diciembre2025.pdf/bc7427b2-9307-8127-4b36-7c5ebd1ad3dd

[3] H. Buyones-Gonzalez and M. Quezada-Espinoza, "Using ChatGPT to Improve Learning in Applied Statics for Construction Engineering Students," in *Proc. 2025 ASEE Annual Conference & Exposition*, Montreal, QC, Canada, Jun. 2025. [Online]. Available: https://doi.org/10.18260/1-2--57297

[4] G. Navas, G. Navas-Reascos, G. E. Navas-Reascos, and S. Guaño, "Innovating engineering education with AI: a case study on ChatGPT 4.0's role in statics-physics," *Cogent Education*, vol. 12, no. 1, Art. no. 2539545, Aug. 2025. [Online]. Available: https://doi.org/10.1080/2331186X.2025.2539545

[5] Q. Liu, H. Moni Prakash, and A. F. Heckler, "Algebra and other relevant physics skills: The effectiveness of mastery practice on skills accuracy and exam grade in introductory physics," *Physical Review Physics Education Research*, vol. 21, art. no. 010121, Mar. 2025. [Online]. Available: https://doi.org/10.1103/PhysRevPhysEducRes.21.010121

[6] A. Mahat, Z. M. Nopiah, S. M. Maat, and N. Razali, "An Early Detection of Students Mathematical Competency in Engineering Mathematics Courses," *Jurnal Kejuruteraan*, vol. 37, no. 4, pp. 1683–1689, Jul. 2025. [Online]. Available: https://doi.org/10.17576/jkukm-2025-37(4)-07

[7] S. Sabah, "Science and engineering students' difficulties in understanding vector concepts," *Eurasia Journal of Mathematics, Science and Technology Education*, vol. 19, no. 8, Art. no. em2310, 2023. [Online]. Available: https://doi.org/10.29333/ejmste/13431

[8] P. Barniol and G. Zavala, "Test of understanding of vectors: A reliable multiple-choice vector concept test," *Physical Review Special Topics – Physics Education Research*, vol. 10, Art. no 010121, Jun. 2014. [Online]. Available: https://doi.org/10.1103/PhysRevSTPER.10.010121

[9] G. A. Nortvedt and A. Siqveland, "Are beginning calculus and engineering students adequately prepared for higher education? An assessment of students' basic mathematical knowledge," *International Journal of Mathematical Education in Science and Technology*, vol. 50, no. 3, pp. 325–343, 2019. [Online]. Available: https://doi.org/10.1080/0020739X.2018.1501826

[10] D. Hyland and A. O'Shea, "The nature and prevalence of diagnostic testing in mathematics at tertiary-level in Ireland," *Teaching Mathematics and its Applications: An International Journal of the IMA*, vol. 41, no. 1, pp. 32–50, 2022. [Online]. Available: https://doi.org/10.1093/teamat/hrab006

[11] C. N. Watson, P. Duran, A. Castillo, E. Fuller, G. Potvin, and L. Kramer, "The supportive role of active learning in a calculus course on low precalculus proficiency students," *International Journal of Mathematical Education in Science and Technology*, published online Sep. 22, 2023. [Online]. Available: https://doi.org/10.1080/0020739X.2023.2255189

[12] M. A. Dagley and R. Ait Maalem Lahcen, "Accelerating Student Success in Mathematics through Personalized Adaptive Learning," in *Proc. 2025 ASEE Annual Conference & Exposition*, Montreal, QC, Canada, Jun. 22–25, 2025, Paper ID #47521. [Online]. Available: https://doi.org/10.18260/1-2--55422

[13] T. Castro and A. Cárcamo, "Errores en la Resolución de Ecuaciones Trigonométricas: un Estudio Exploratorio con Estudiantes de Primer Año de Ingeniería" [Errors in Solving Trigonometric Equations: An Exploratory Study with First-Year Engineering Students], *Bolema*, vol. 37, no. 75, pp. 336–351, Apr. 2023. [Online]. Available: https://doi.org/10.1590/1980-4415v37n75a16

[14] OECD, PISA 2022 Results (Volume I): *The State of Learning and Equity in Education*. Paris, France: OECD Publishing, 2023. [E-book] [Online]. Available: https://doi.org/10.1787/53f23881-en

[15] C. P. Muñoz and M. Quezada-Espinoza, "Remedial Courses Effectiveness on Timely Graduation Rates and Degree Progression within Construction Engineering Students," *in Proc. 2023 ASEE Annual Conference & Exposition*, Baltimore, MD, USA, Jun. 25–28, 2023, Paper ID #38444.[Online]. Available: https://peer.asee.org/remedial-courses-effectiveness-on-timely-graduation-rates-and-degree-progression-within-construction-engineering-students

[16] A. Vázquez-Sánchez and F. Delgado, "A Competency Assessment Model for Free-Body Diagrams Construction in Mechanical Engineering Students: A Case Study," *European Journal of Engineering Education*, vol. 50, no. 5, pp. 1094–1125, 2025. [Online]. Available: https://doi.org/10.1080/03043797.2025.2526831

[17] J. Rho and M. A. Rau, "Supporting engineering students' representational competencies in individual and collaborative learning settings," *Journal of Engineering Education*, vol. 114, no. 2, 2025. [Online]. Available: https://doi.org/10.1002/jee.20631

[18] J. L. De La Hoz, C. Vieira, and C. A. Arteta, "Self-explanation activities in statics: A knowledge-building activity to promote conceptual change," *Journal of Engineering Education*, vol. 112, no. 3, pp. 741–768, 2023. [Online]. Available: https://doi.org/10.1002/jee.20531

[19] M. I. Baig and E. Yadegaridehkordi, "ChatGPT in the higher education: A systematic literature review and research challenges," *International Journal of Educational Research*, vol. 127, art. no. 102411, 2024. [Online]. Available: https://doi.org/10.1016/j.ijer.2024.102411

[20] H. Crompton and D. Burke, "The Educational Affordances and Challenges of ChatGPT: State of the Field," *TechTrends*, vol. 68, pp. 380–392, 2024. [Online]. Available: https://doi.org/10.1007/s11528-024-00939-0

[21] R. Deng, M. Jiang, X. Yu, Y. Lu, and S. Liu, "Does ChatGPT enhance student learning? A systematic review and meta-analysis of experimental studies," *Computers & Education*, vol. 227, no. 105224, 2025.[Online]. Available: https://doi.org/10.1016/j.compedu.2024.105224

[22] J. Epstein, "The Calculus Concept Inventory—Measurement of the Effect of Teaching Methodology in Mathematics," *Notices of the American Mathematical Society (Notices of the AMS),* vol. 60, no. 8, pp. 1018–1025, Sep. 2013. [Online]. Available: http://dx.doi.org/10.1090/noti1033 [Accessed: Jun. 4, 2025].

[23] R. R. Hake, "Interactive-Engagement Versus Traditional Methods: A Six-Thousand-Student Survey of Mechanics Test Data for Introductory Physics Courses," *American Journal of Physics*, vol. 66, no. 1, pp. 64–74, Jan. 1998. [Online]. Available: https://doi.org/10.1119/1.18809

[24] G. Huesca, Y. Martínez-Treviño, J. M. Molina-Espinosa, A. R. Sanromán-Calleros, R. Martínez-Román, E. A. Cendejas-Castro, and R. Bustos, “Effectiveness of Using ChatGPT as a Tool to Strengthen Benefits of the Flipped Learning Strategy,” *Education Sciences*, vol. 14, no. 6, Art. no. 660, 2024. [Online]. Available: https://doi.org/10.3390/educsci14060660

[25] Masriyah, N. Indrawatiningsih, S. Hartono, M. Sa’diyah, U. Hanifah, and A. S. L. Sari, “The effectiveness of a ChatGPT-supported flipped classroom in enhancing preservice mathematics teachers’ understanding of integral calculus,” *Multidisciplinary Science Journal*, vol. 8, Art. no. e2026331, Nov. 2025. [Online]. Available: https://doi.org/10.31893/multiscience.2026331

[26] S. Abdulla, S. Ismail, Y. Fawzy, and A. Elhaj, “Using ChatGPT in Teaching Computer Programming and Studying its Impact on Students Performance,” *Electronic Journal of e-Learning*, vol. 22, no. 6, pp. 66–81, 2024. [Online]. Available: https://doi.org/10.34190/ejel.22.6.3380

[27] D. Fardian, D. Suryadi, S. Prabawanto, and A. Jupri, “Integrating Chat-GPT in the Classroom: A Study on Linear Algebra Learning in Higher Education,” *International Journal of Information and Education Technology*, vol. 15, no. 4, pp. 732–751, Apr. 2025. [Online]. Available: https://doi.org/10.18178/ijiet.2025.15.4.2279

[28] Y. Zhuang, “Lessons from Using ChatGPT in Calculus: Insights from Two Contrasting Cases,” *Journal of Formative Design in Learning*, vol. 9, pp. 25–35, 2025. [Online]. Available: https://doi.org/10.1007/s41686-025-00098-2.