Data and Metadata. 2025; 4:685
doi: 10.56294/dm2025685

ORIGINAL

Use of mathematical modeling as a methodological proposal for the development of cognitive competences in the subject of differential equations

Uso de la modelación matemática como propuesta metodológica para el desarrollo de competencias cognitivas en la asignatura de ecuaciones diferenciales

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Cite as: Paz-León HH, Velasco-Arrellano MH, Orozco-Cantos LS, Castro-Cepeda L. Use of mathematical modeling as a methodological proposal for the development of cognitive competences in the subject of differential equations. Data and Metadata. 2025; 4:685. https://doi.org/10.56294/dm2025685

Submitted: 16-06-2024 **Revised:** 25-10-2024 **Accepted:** 12-04-2025 **Published:** 13-04-2025

Editor: Dr. Adrián Alejandro Vitón Castillo

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ABSTRACT

This study proposes to integrate mathematical modeling as an active methodology with a pedagogical approach oriented toward competency development. The objective is to use modeling activities as a bridge that connects problem-solving with the strengthening of cognitive competencies. The model contrasts with traditional methods, which typically focus on the execution of algorithms and the memorization of theorems and formulas, limiting mathematical learning to obtaining results without exploring their application to engineering problems or practical contexts. The research is conducted in an educational environment, where students could analyze, describe, formulate hypotheses, contrast them, reflect, argue, and communicate their ideas. The research design is quasi-experimental, descriptive-correlational, and the research employs scientific, inductive-deductive, and analytical-synthetic methods, basing the methodology on problem-solving in accordance with the progress of the Differential Equations course syllabus. To evaluate the proposal, techniques such as direct observation, teamwork, multiple-choice tests, and feedback were used with second-semester students. The results show that methodology promotes greater development of cognitive skills compared to the traditional approach based on mechanical problem-solving. It can be concluded that mathematical modeling allows students to develop cognitive skills such as critical thinking, creativity, and problem-solving through the analysis, synthesis, and evaluation of information.

Keywords: Mathematical Modeling; Cognitive Skills; Differential Equations.

RESUMEN

En este estudio se propone integrar la modelación matemática como una metodología activa con un enfoque pedagógico orientado al desarrollo de competencias. El objetivo es utilizar las actividades de modelación como un puente que conecta la resolución de problemas con el fortalecimiento de competencias cognitivas. El modelo contrasta con los métodos tradicionales, que suelen enfocarse en la ejecución de algoritmos y la memorización de teoremas y fórmulas, limitando el aprendizaje de la matemática a la obtención de resultados sin explorar su aplicación en problemas de ingeniería o contextos prácticos. La investigación se lleva a cabo en un entorno educativo, donde los estudiantes tienen la oportunidad de analizar, describir, formular hipótesis, contrastarlas, reflexionar, argumentar y comunicar sus ideas. El diseño de la investigación es cuasi experimental, de tipo descriptiva correlacional y durante la investigación se emplean los métodos Científico, inductivo deductivo y analítico sintético, fundamentando la metodología con la resolución de problemas de acuerdo con el avance del programa de la asignatura de Ecuaciones Diferenciales.

Para evaluar la propuesta, se emplean técnicas como observación directa, trabajos en equipo, pruebas de selección múltiple y retroalimentación con estudiantes de segundo semestre. Los resultados evidencian que la metodología promueve un desarrollo superior de las competencias cognitivas en comparación con el enfoque tradicional basado en la resolución mecánica de ejercicios. Pudiendo concluir que la modelación matemática permite que los estudiantes desarrollen competencias cognitivas como el pensamiento crítico, la creatividad y la resolución de problemas mediante el análisis, síntesis y evaluación de la información.

Palabras clave: Modelado Matemático; Competencias Cognitivas; Ecuaciones Diferenciales.

INTRODUCTION

In recent years, higher education institutions have asked themselves what is needed to improve education systems. To do this, the first thing we must understand is: What is education? According to Piaget, the primary goal of education is to create people who are capable of doing new things, not simply repeating what other generations have done; to train creative people who are interested in discovering, who have a series of abilities, skills that make them capable of easily integrating into social life and the workplace. Considering this concept and according to the study, a key factor for academic and professional success is the development of cognitive and analytical skills in students and the ability to apply knowledge in different contexts of life. The incorporation of mathematical modeling, in addition to strengthening these skills, contributes to improving students' motivation and interest in the exact sciences thanks to the fact that it promotes active learning and the applicability of mathematical laws, theorems, and mathematical definitions in real situations, which has a positive impact on academic performance and contributes to the modernization of the education system.[1]

The problem under study is framed within the field of mathematics education. It is focused on improving the teaching-learning processes by applying mathematical modeling as an active methodology that favors contextualized teaching oriented toward problem-solving.[2]

The study is carried out in a formal education environment and positively impacts several levels. At the educational level, it allows for the transformation of the teaching-learning processes of mathematics through an active methodology based on problem-solving that contributes to meaningful learning. At the social and professional level, it contributes to the training of students with skills in mathematical modeling, critical thinking, and creativity, which are essential competencies for facing new technological or professional challenges. At an institutional level, it contributes to reviewing and updating curricula and teacher training. On the other hand, at a global level, it must be considered that the implementation of mathematical modeling as an active method in education represents a challenge since it can be integrated with specialized software, simulators, and digital tools that enable its incorporation into virtual learning environments, which requires expanding research concerning curricular adaptations, teacher training, and education, among others, which opens multiple lines of research for the development of new study projects.[3]

As background to the research carried out, we can indicate that according to the evidence found in recent years, the traditional teaching of mathematics at a higher level is a subject of analysis and study that faces structural challenges concerning how to develop meaningful learning in students, the lack of effective teaching strategies to integrate active methodologies, the rigidity of the curriculum, the little or no application of knowledge to real contexts or situations, affect the ability of students to develop skills and competencies essential for their training, which is reflected in the statistics of a high rate of repetition and dropout of students taking basic science subjects in engineering degrees and particularly in the area of mathematics. This makes us reflect on various aspects, such as the teacher's role, the kinds of mathematics classes generally governed by methods and techniques that favor memorization, the repetition of processes, and the mechanical application of formulas to solve mathematical exercises. This is reflected in a deficit of learning achievements in students,[4] causing disinterest and demotivation to learn the subject. To address the problem, we will consider three fundamental aspects that we can work on that will allow us to improve an essential part of the educational system. We will focus on the student, the teacher, and the study programs to enhance teaching, making it more interesting, applied, innovative, and aligned with the professional profile of the degree. The objective is to implement mathematical modeling in formal education through an active methodological proposal based on problem-solving that allows the development of cognitive skills in students taking the subject of differential equations in engineering degrees.[5]

Problem statement

The implementation of mathematical modeling in formal education through an active methodological proposal based on problem solving has an impact on the development and achievement of cognitive skills of students taking the subject of differential equations in engineering degrees.

State of the Art

Mathematical modeling is the process by which a mathematical model is constructed. This model consists of a set of symbols and mathematical relationships that represent, in an abstract way, a specific phenomenon or problem. Beyond providing a particular solution, the model serves as a basis for developing other applications or theories, offering a structured framework for analyzing and understanding the problem at hand.[6]

Modeling, as a process, does not develop instantly or automatically. It requires time for the modeler to use their mathematical knowledge, their understanding of the context and the specific problem, and their skills to analyze, identify, and represent the relationships between the variables involved. This approach seeks to transform these relationships into a new mathematical construct, integrating advanced cognitive skills and technological tools to enrich the process.[7]

Table 1, based on Villa's work [2], highlights elements that reflect how mathematical modeling manifests itself as a scientific activity. This approach enables problem-solving and is used as a tool to promote the construction of mathematical concepts in the educational environment. It aligns with the principles of modern education by fostering active and collaborative learning in the classroom.

Table 1. Mathematical modeling as a scientific activity and as a tool

Criteria	As a scientific activity	As a tool in the classroom
Purpose of the model	The model is designed to address complex problems from various disciplines, such as the natural, social or human sciences, with an interdisciplinary approach or to advance theory or science.	The model is designed to facilitate the construction of meaningful mathematical concepts, promoting a deep understanding of mathematics. Its practical and applicable nature seeks to capture students' interest and stimulate their motivation, connecting learning to real-world situations.
Mathematical concepts	Mathematical concepts arise from the situation analyzed through a process of abstraction and simplification of the phenomenon under study.	The mathematical concepts involved must be selected and planned in advance by the teacher. This preparation includes choosing a suitable context that is relevant to the specific objectives of the class, ensuring that the activities are consistent with the educational purpose.
Contexts	It responds to novel problems or addresses previously unaddressed issues from innovative perspectives that have not been previously addressed or that require a different approach within the same discipline. This context allows for the exploration of new ways of interpreting phenomena, fostering innovation and the development of creative solutions.	The problems used as a basis for modeling must have been previously analyzed by the teacher, assessing their relevance and alignment with pedagogical goals. This ensures that the selected context is relevant and facilitates meaningful learning in the classroom.
Other factors	The development of the model typically occurs in an environment characteristic of the scientific discipline to which it is applied. These scenarios tend to be oriented towards rigorous analysis and experimentation, and in general are not influenced by considerations typical of traditional educational contexts.	It is presented in the classroom using everyday contexts or contexts related to other disciplines. This approach helps to connect abstract concepts with practical applications, fostering a more dynamic and accessible learning experience for students.

Source: Andrea C et al.[8]

Mathematical modeling is the fundamental activity derived from scientific activity that involves using mathematical models to represent, understand, and solve problems in various areas. It can also predict future behaviors or simulate different scenarios under controlled conditions. Mathematical modeling as a tool becomes a strategy that enables understanding a mathematical concept immersed in a "microworld" (a context endowed with relationships and meanings) that prepares the student to develop competencies while solving problems in contextualized reality.[9]

Hein et al.[2] emphasize that formal education presents certain challenges related to factors such as curriculum design, class duration, the number of students per group, and the time available for teachers to supervise student progress simultaneously. These aspects require specific adaptations in the use of mathematical modeling as a teaching methodology. For this reason, they propose a structured approach called mathematical modeling, which is designed to respond to these limitations while optimizing the teaching-learning processes.

Competencies in education are defined as "generic and specific competencies, understood as the set of knowledge, abilities, skills, aptitudes, and activities most appropriate for achieving long-term social objectives."[10]

Another perspective for understanding competencies classifies them in three dimensions: knowledge, which implies knowing necessary to carry out a task; know-how, which refers to the skills to apply that knowledge in practical contexts; and interpersonal skills, which encompass the attitudes, values, and behaviors appropriate to the context.[11]

The Alfa Tuning project[12] established that generic competencies seek to identify the shared attributes that could be generated in any degree and considered essential for society and common to all. On the other hand, specific competencies are directly linked to particular subject areas, highlighting their importance in each discipline as they are associated with specific and specialized knowledge.

Mathematical modeling improves mathematical skills and develops cognitive competencies, such as mental abilities, that allow a person to process information, develop creative capacity, make decisions, and adapt to new situations through problem-solving, which is fundamental for academic success and lifelong learning.[13,14,15]

METHOD

Type of study

The research design is quasi-experimental with a quantitative and longitudinal approach since it works with a group of students to improve their learning of differential equations, an area identified as complex, and data is collected at different times to analyze the changes resulting from the proposed methodology. This study evaluated the impact of mathematical modeling as a methodological strategy on the development of cognitive skills in students of this subject.[16]

This descriptive-correlational study seeks to identify the relationship between the independent variable, "Development of cognitive skills," and the dependent variable, "Use of mathematical modeling as a methodological proposal." This approach makes it possible to analyze how this teaching tool affects the development of cognitive skills within the teaching-learning process of the subject of differential equations.

Place and date of realization

The study was carried out in the Faculty of Engineering of the National University of Chimborazo, located in the city of Riobamba, Ecuador, during the academic period between April and August 2024.

Population and Sample

The population of this study was made up of all the students enrolled in the subject of Differential Equations in the Faculty of Engineering of the Information Technology Degree at the UNACH during the period of study.

Inclusion criteria

- Students enrolled in the Differential Equations course during the study period.
- Voluntary participation in the study.
- Availability to complete all the activities of the mathematical modeling program.

Exclusion criteria

- Students who have previously taken the course.
- Students with attendance of less than 75 % of the total number of sessions.
- Students who do not complete the assessments required for analysis.

Study variables

- Independent variable: use of mathematical modeling as a teaching methodology.
- Dependent variables: level of development of cognitive skills in solving differential equations (comprehension, analysis and application of mathematical concepts).

Methods and instruments for data collection

The following methods and instruments were used for data collection:

- Pre- and post-intervention evaluation tests to measure the development of cognitive skills.
- Structured surveys to gather students' perceptions of the mathematical modeling method.
- Systematic classroom observation using checklists to assess student participation.

Statistical techniques and procedures

A descriptive analysis of the data was carried out using measures of central tendency and dispersion. For the comparison of the pre- and post-intervention results, inferential statistical tests were applied, such as the

Shapiro-Wilk normality test, the F-test for equality of variances and the Student's t-test for related samples. (17)

A confidence level of 95 % was established, with a critical p-value of 0,05 to determine the statistical significance of the results obtained.

RESULTS

In this research, two groups of students are compared: one that was instructed using a traditional method and another that used the proposed mathematical modeling, that is to say, the analysis was carried out for independent groups.

Population size

N=24.

Table 2. Grades according to the traditional model and using the proposed model

Traditional	Modeling
6,84	9,70
7,03	8,78
7,10	8,37
8,02	8,87
6,31	7,68
6,58	7,71
5,58	7,78
6,34	9,41
8,26	8,64
8,79	9,80
7,23	7,81
5,71	7,66
7,32	8,37
4,35	6,26
7,45	9,03
5,67	7,19
6,09	6,91
7,56	8,13
7,02	8,77
6,99	7,65
5,00	6,66
6,94	8,87
6,38	8,65
5,52	7,66

Table 2 shows the scores according to the traditional model and the one that uses mathematical modeling through the proposed model. Table 3 shows the descriptive statistics for each population group.

Table 3. Descriptive statistics

Variable	Total count	Average	Est.Des.	Rank	CoefVar	Minimum	Maximum
M-Traditional	24	6,67	1,04	4,44	15,60	4,35	8,79
M-Modeling	24	8,18	0,92	3,54	11,26	6,26	9,80

The students who used the mathematical modeling method had an average of 8,18, while those who used the traditional method had 6,67. This suggests that the modeling method had better results on average. The dispersion of scores was slightly lower in the modeling method (0,92) compared to the traditional method (1,04). This indicates that the results in the modeling group were more consistent. The coefficient of variation (ratio between the standard deviation and the mean) is lower in the modeling method (11,26 %) than in the traditional method (15,60 %). This reinforces the idea that the scores in the modeling group were more homogeneous. The range of values is also lower in the modeling group (3,54 vs. 4,44), again indicating less variability in the scores. The minimum and maximum scores in the modeling method (6,26 - 9,80) are in a higher range than in the traditional method (4,35 - 8,79), which means that no student in the modeling group had scores as low as in the conventional group.

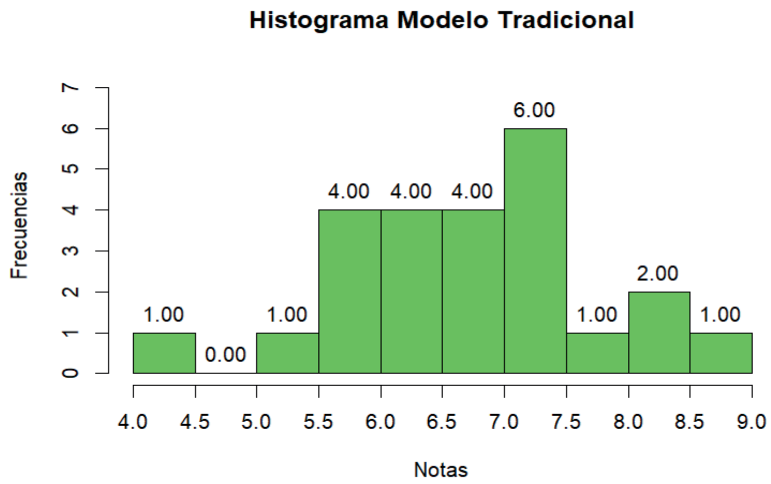

Figure 1. Histogram Traditional Model

Figure 1 shows the grade histogram for the traditional model, where it can be seen that the majority of students have grades between 6,5 and 7,5, with a peak at 7,0 - 7,5 (frequency = 6), there are few grades at the extremes (4,0 and 9,0), which indicates that the majority of students are grouped in the center of the scale. There appears to be a slight negative asymmetry (left-skewed), as there are more values towards the high marks. No extreme concentration at the low marks suggests that student performance in this model was not very poor. The most common mark is between 7,0 and 7,5, indicating that traditional teaching allowed several students to obtain grades in that range.

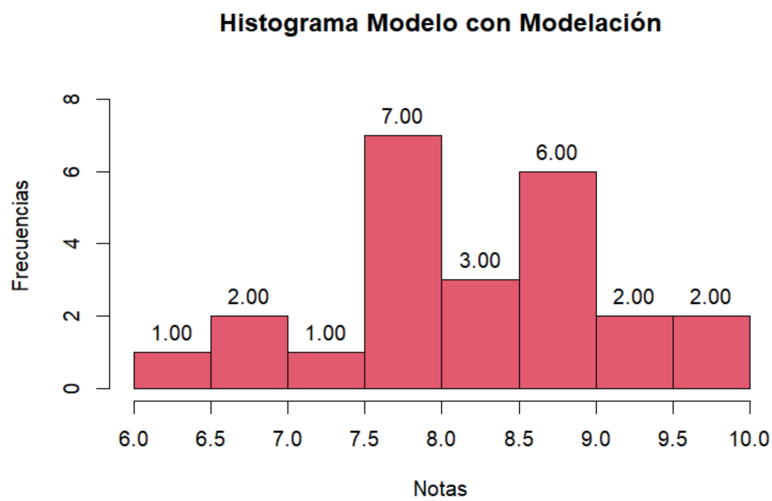

Figure 2. Histogram Model with Modeling

In figure 2, a histogram is presented with the grades with the modeling model, where it is verified that most students obtained grades between 7,5 and 9,0, with a peak at 7,5 - 8,0. An increase in the highest grades is observed compared to the traditional model. Unlike the conventional model, this histogram shows a trend towards high marks, with a higher frequency of values between 8,0 and 10. There are fewer low values (6,0 - 7,0) compared to the previous model, which suggests a performance improvement. Grades are concentrated in a higher range (6,0 - 10), whereas in the traditional model, they were lower. Dispersion is still present, but now, more students have outstanding grades. The most significant number of students have grades between 7,5 and 9,0, which indicates that mathematical modeling could be helping to improve results. More students have perfect scores (10) compared to the traditional model, which suggests better overall performance.

To perform the inferential analysis, we must carry out normality, homogeneity, and homoscedasticity tests to determine the most appropriate hypothesis test.

Proof of Normality

The normality of the data is verified using the Shapiro-Wilk hypothesis test.

- H0: the data follow a normal distribution.
- H1: the data do not follow a normal distribution.

For the scores of the traditional method, the following results are obtained:

Table 4. Results

Shapiro-Wilk normality test	
W	0,98678
p-value	0,9822

As the p-value (0,9822) is greater than the significance level of 0,05, H0 is not rejected and therefore the data from the traditional method follow a normal distribution.

For the scores from the method with modeling, the following results are obtained:

Table 5. Results

Shapiro-Wilk normality test	
W	0,97298
p-value	0,7405

As the p-value (0,7405) is greater than the significance level of 0,05, H0 is not rejected and therefore the data from the modeling method follow a normal distribution.

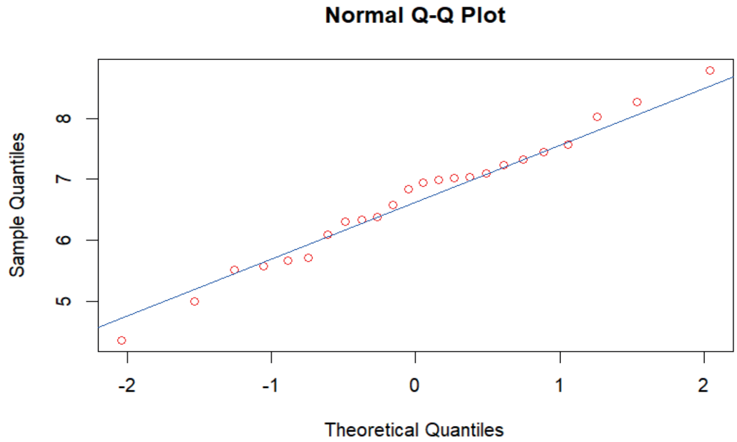

Figure 3. Proof of normality - Traditional Method

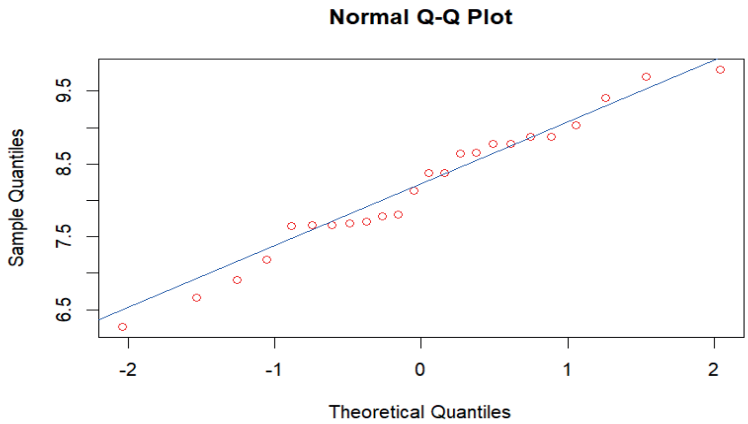

Figure 4. Proof of normality - Traditional Method

https://doi.org/10.56294/dm2025685

This can also be verified through figure 3 and figure 4, which evaluate whether the data set follows a normal distribution, where the blue line represents the expected theoretical normal distribution and the red dots represent the quantiles of the sample distribution. Most of the points align quite well with the blue line, which indicates that the data has a distribution close to normal. In addition, there are slight deviations at the extremes, which suggests the possible presence of outliers or a slight asymmetry.

After verifying normality, it is necessary to test for homoscedasticity. To do this, we can observe the behavior of the variable "grades" by comparing them in a boxplot and better visualize the difference in student performance between the two methods. In figure 5 we can see that the group that used the mathematical modeling method has a higher median and lower dispersion compared to the group that used the traditional method, which supports the previously analyzed statistical results.

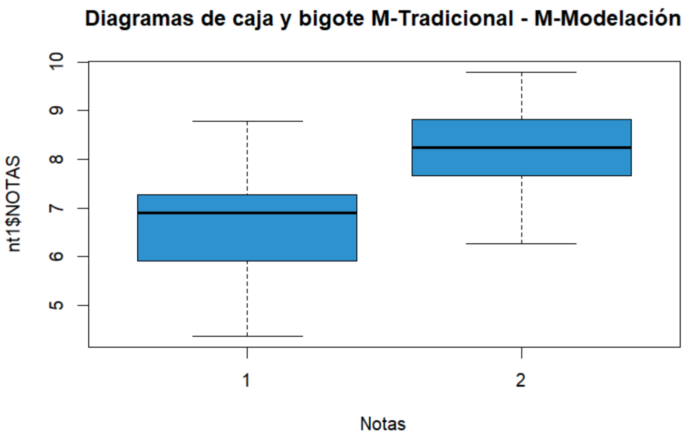

Figure 5. Box and whisker plots

Test for homoscedasticity

The F-test is used to check whether or not there is homoscedasticity, for which the following hypothesis is proposed.

$$H0: \frac{\sigma_1^2}{\sigma_2^2} = 1$$

$$H1: \frac{\sigma_1^2}{\sigma_2^2} \neq 1$$

Table 6. Results

F test to compare two variances	
F	0,97298
num df	23
denom df	23
p-value	0,5643

As the p-value (0,5643) is greater than the significance level of 0,05, H0 is not rejected and therefore the data meet the condition of homoscedasticity. Therefore, it meets the condition of normality and homoscedasticity, which allows a parametric hypothesis test to be carried out. Hence the formulation of the general hypothesis: Null Hypothesis (H0): there is no significant difference in the development and achievement of cognitive skills in students taking the subject of differential equations when implementing mathematical modeling as an active methodological proposal based on problem solving, compared to students who use the traditional method for teaching differential equations in formal education.

H0: μ_1-μ_2=0

Research Hypothesis (H1): there is a significant improvement in the development and achievement of cognitive skills in students taking the subject of differential equations when implementing mathematical modeling as an active methodological approach based on problem solving, compared to students who use the traditional method for teaching differential equations in formal education.

H1: μ_1-μ_2<0

For the analysis of hypotheses, the T-Test of independent samples will be used, for which the grades of each group will be used.

Control Group (Traditional Method)
Average: 6,67.
Standard Deviation: 1,04.

Test Group (Mathematical Modeling)
Average: 8,18.
Standard Deviation: 0,92.

The degrees of freedom are calculated

$v= n_1+ n_2 - 2 = 46$

Level of significance
α = 0,05

Table 7. Results

Two Sample t-test	
t	-5,3295
df	46
p-value	1,444e-06

The null hypothesis is rejected, as the p-value (1,444e-06) is much lower than the significance level of 0,05. Therefore, it can be inferred that there is a significant improvement in the development and achievement of cognitive skills in students taking the differential equations course when mathematical modeling is implemented as an active methodological approach based on problem solving, compared to those who used the traditional model.

DISCUSSION

After reviewing the specialized bibliography on how the development of cognitive competencies is produced through mathematical modeling, it can be seen that the results obtained are related to what they state:

María Brito[18] in her proposal for intervention in basic science programs and engineering degrees, she integrates mathematical modeling as an active methodology. Her objective is to use it as a bridge that connects the resolution of real-world problems with strengthening competencies that are fundamental in engineering degrees. This approach proposes to generate interactive processes that promote a deeper and more meaningful understanding of knowledge, aligning with the principles of modern education based on active and learning-centered paradigms.[19]

Carlos Márquez[20] in his findings, he emphasizes that mathematical modeling is a key tool in research and engineers' training. In his study on the development of competencies based on mathematical modeling, he expresses the need to improve the teaching-learning process in current education by recontextualizing the curriculum, considering three key categories: what to teach, how to prepare, and when. These categories must interact in permanent harmony so that the student learns in a meaningful way and, at the same time, develops cognitive competencies. Consequently, in today's education, the teacher becomes an organizer, guide, and mediator of knowledge, enhancing the critical and creative thinking of the learners. To this end, he states that teaching requires active methods. Mathematics problem situations allow dynamic learning since they give meaning to mathematical concepts, triggering cognitive activity. The main objective of the work is to evaluate the impact of modeling in experimental problem situations to achieve significant learning in students.[21,22]

The most relevant results of the study confirm that the teaching of mathematics and, in particular, of differential equations through the presentation of problems is fundamental in the training of an engineer since it allows the development of the ability to model mathematical concepts through a symbolic language, as well as developing cognitive skills, strengthening critical thinking, creativity, interest and teamwork in students. Consequently, the research hypothesis is accepted since there is a significant improvement in the development and achievement of cognitive competencies when implementing mathematical modeling compared to students taught using traditional teaching methods.[23,24]

CONCLUSIONS

The results obtained in the research allow us to accept the research hypothesis, showing that the implementation of a didactic intervention based on mathematical modeling contributes significantly to the development of cognitive skills, demonstrating a substantial improvement in the understanding, analysis, and application of mathematical concepts, in comparison with those students who were instructed using traditional teaching and learning methods.

Implementing the methodology in the classroom not only transforms science teaching by making maths classes more dynamic and meaningful but also contributes to the modernization of the curriculum and the training of students with better skills to strengthen their academic environment and face new professional challenges.

The present research proposes an intervention in the basic science programs of engineering degrees, incorporating mathematical modeling as an active methodological proposal for teaching. This approach promotes interactive learning processes that favor a deeper and more meaningful understanding of knowledge in coherence with the principles of modern education based on active and student-centered methodologies.

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FINANCING
The authors did not receive funding to carry out this research.

CONFLICT OF INTEREST
The authors declare that there is no conflict of interest.

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