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ORIGINAL

Application of Systems Thinking in Scientific Research in Engineering and Science: an Interdisciplinary Approach

Aplicación del Pensamiento Sistémico en la Investigación Científica en Ingeniería y Ciencias: un Enfoque Interdisciplinario

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ABSTRACT

This study analyzes the integration of systems thinking with the quantitative scientific method in the teaching of research in engineering and applied sciences. It demonstrates that systems thinking enables a better understanding of complex problems by considering the interrelation between variables, facilitating system modeling in various fields. The results obtained through statistical analysis indicate a significant improvement in students' academic performance after implementing the systems approach. The Wilcoxon test showed a p-value of $5{,}539 \times 10^{-10}$, confirming that grades significantly improved in the second evaluation. Additionally, the Shapiro-Wilk normality test revealed that the analyzed variables (nota-1, nota-2, dt1, dt2) do not follow a normal distribution, justifying the use of non-parametric methods. Overall, systems thinking-based teaching reduces learning variability, helping students acquire a more structured knowledge. The findings suggest that this approach can be a valuable tool for teaching research methodology in engineering and applied sciences.

Keywords: Systems Thinking; System Dynamics; Scientific Research; Engineering Education.

RESUMEN

Este estudio analiza la integración del pensamiento sistémico con el método científico cuantitativo en la enseñanza de la investigación en ingeniería y ciencias aplicadas. Se demuestra que el pensamiento sistémico permite comprender mejor problemas complejos al considerar la interrelación entre variables, facilitando la modelización de sistemas en diversos campos. Los resultados obtenidos mediante análisis estadístico indican una mejora significativa en el rendimiento académico de los estudiantes tras la implementación del enfoque sistémico. La prueba de Wilcoxon mostró un p-valor de $5{,}539 \times 10^{-10}$, lo que confirma que las calificaciones mejoraron notablemente en la segunda evaluación. Además, la prueba de normalidad de Shapiro-Wilk reveló que las variables analizadas (nota-1, nota-2, dt1, dt2) no siguen una distribución normal, justificando el uso de métodos no paramétricos. En términos generales, la enseñanza basada en el pensamiento sistémico reduce la variabilidad en el aprendizaje, logrando que los estudiantes adquieran un conocimiento más estructurado. Los hallazgos sugieren que este enfoque puede ser una herramienta valiosa para la enseñanza de la metodología de la investigación en ingeniería y ciencias aplicadas.

Palabras clave: Pensamiento Sistémico; Dinámica de Sistemas; Investigación Científica; Educación en Ingeniería.

INTRODUCTION

Systems thinking and dynamics have been fundamental to understanding and modeling complex systems in various disciplines. Since its origins in the work of Jay W. Forrester in the 1950s, systems dynamics has been applied in fields such as engineering, economics, risk management, and higher education. This approach has allowed problems to be analyzed not in isolation but in their global context, considering the interconnections and dynamic relationships between the components of a system.[1]

On the other hand, the quantitative scientific method has been the basis for developing knowledge in science and engineering since the Scientific Revolution. Its evolution has allowed the application of mathematical approaches, computational models, and simulations in research, which has improved the ability to analyze complex phenomena and design innovative solutions.[2,3]

In this context, combining systems thinking and the scientific method has become a powerful tool for problem-solving in engineering and applied sciences. The need to address contemporary challenges, such as climate change, energy sustainability, and optimizing industrial processes, has driven the development of methodologies that integrate these approaches.[4]

History and evolution of systemic thinking and system dynamics

Systems thinking emerged as a response to the growing complexity of social, technological, and environmental systems. Ludwig von Bertalanffy introduced General Systems Theory in the 1940s, establishing principles that have been applied in multiple disciplines, from biology to software engineering. This theory highlighted the importance of studying systems as interrelated wholes rather than focusing solely on their individual parts.[5,6]

Subsequently, Jay W. Forrester developed systems dynamics, a methodology based on differential equations and computer simulations that allowed the behavior of complex systems to be modeled over time. His first significant contribution was the industrial dynamics model, which was used in supply chain management at General Electric to optimize inventories and production. This approach was later extended to urban and environmental problems, giving rise to models such as Urban Dynamics (1969) and World Dynamics (1971), which were the basis of the influential report The Limits to Growth by the Club of Rome.[1,7]

Systems thinking continues to evolve and is applied in various areas, such as higher education, risk management, and industrial safety. It has been identified as a key competence for preparing students to solve unstructured problems, promoting interdisciplinary and project-based learning.[8] In safety management, it has enabled the development of new accident analysis models, such as the Interaction Theory of the Hazard-Target System (ITHTS), which incorporates human, organizational, and technological factors within the same analytical framework.[9]

The quantitative scientific method in engineering research

The quantitative scientific method has its roots in Cartesian rationalism and Newtonian empiricism. It establishes a framework based on experimentation, data analysis, and empirical validation. Over time, it has evolved with approaches such as Francis Bacon's inductivism and Karl Popper's falsificationism, which emphasizes the refutability of hypotheses as a fundamental criterion of scientific knowledge. In engineering, this method has been essential for developing mathematical models and the experimental validation of physical phenomena.[10,11]

One recent approach to applying the scientific method in education has been integrating artificial intelligence and active learning methodologies. Recent research has shown that combining traditional methods with artificial intelligence tools can improve the teaching of complex thinking and students' analytical capacity.[12,13]

The scientific method has incorporated specific engineering variations, such as the iterative development cycle, which allows for the improvement of models and experiments through successive adjustments.[14,15] Another relevant approach is model-based research, where the formulation and testing of computational models complement traditional experimentation. This approach has been widely used in systems engineering to analyze complex interactions in infrastructure networks and industrial processes.[16]

Interdisciplinary applications of systems thinking in scientific research

Various disciplines have adopted systems thinking to address complex problems with multiple interconnected variables. In education, the integration of systems thinking has improved the teaching of science and mathematics through the implementation of innovative methodologies, such as model-based learning. In industrial safety, applying systems thinking has led to the development of advanced accident analysis methods. Likewise, in entrepreneurship and innovation, a strong correlation has been identified between systems thinking and entrepreneurs' ability to make strategic decisions.[2,17]

The teaching of scientific research involves a process in which the student must develop criteria for tackling complex problems. The trend in engineering programs is to consider scientific research as an initiatory subject in training in such a way that it is located at the beginning of the curriculum. This is a problem because if the teaching of this subject does not generate a different way of thinking, what is learned tends to dissipate over time. On the other hand, the fact that the subject of scientific research is at the beginning of engineering training provides an opportunity for students to learn tools that can be applied throughout the rest of their degree.

The present work addresses this particular issue by applying systems thinking and systems dynamics to teaching scientific research in engineering and science. The impact on resolving interdisciplinary problems is highlighted, not by appealing to rote mechanisms but by a methodology that becomes natural to the student. The integration of this approach is initially carried out using the quantitative scientific method.

As challenges in engineering and science become more complex, adopting systemic approaches becomes fundamental for designing sustainable and efficient solutions. This study provides a conceptual and methodological framework that can guide future research in these areas, contributing to developing new methodologies in education and applied research.

METHOD

The development of engineering and applied sciences knowledge is based on the rigorous application of the scientific method, which allows for the structured generation of hypotheses, experimental validation, and the generalization of results. This work considers a variant of the scientific method adapted to engineering research, consisting of five fundamental steps: Observation, Definition, Experimentation, Generalization, and Dissemination. Each of these steps contributes to the construction of knowledge, from the identification of a problem to its dissemination in the scientific and professional community.(18)

Stages of the Scientific Method in Engineering

Observation

Observation is the starting point of the scientific method in engineering and applied sciences. Its purpose is to identify relevant phenomena that require analysis and understanding. This process relies on two fundamental elements:

The senses: direct sensory perception is one of the most basic observation forms. In engineering, this can include the visual inspection of a structure, the temperature measurement in a thermal system, or the acoustic evaluation of mechanical equipment. Knowledge: In addition to empirical observation, the literature review, theoretical background, and previous experiences contribute to contextualizing the problem under study.

Problem definition

In the present approach, the existence of a problem that can be defined as a mathematical functional relationship is considered. This is reflected in the principle of causality between one or more independent variables, “xi,” and a dependent variable, “y.” Within this conception of the problem is also the domain and range of the research.

Once a phenomenon of interest has been identified, the research problem is defined by analyzing the variables involved. At this stage, the following key elements are formulated:

Research variables: these factors influence the phenomenon under study, and they can be quantified (measurable, evaluable, or categorizable). They are classified as dependent variables (those sought to be explained or predicted) and independent variables (manipulated or studied as possible causes). The relationship between independent and dependent variables can include feedback relationships in the case of complex systems. Establishing these types of relationships in models corresponds to the deepest level in terms of investigative scope. In figure 1, n independent variables are shown, and from variable n+1 onwards, variables affected by the dependent variable “y” are displayed.

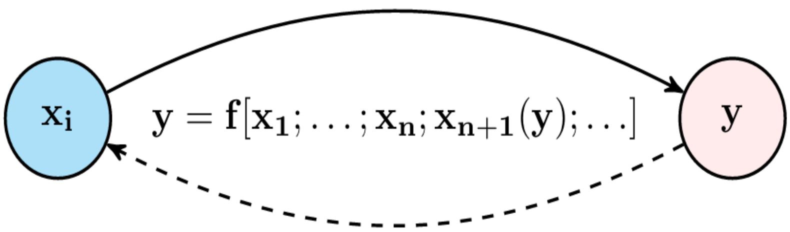

Figure 1. Functional relationship related to a research problem

Research question: based on the identified variables, an open and transparent question is formulated to guide the study.

Hypothesis: a well-founded assumption is made about the relationship between the variables. This

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relationship reflects the hypothesis, and the principle can be assigned a positive or negative value, as shown in figure 2.

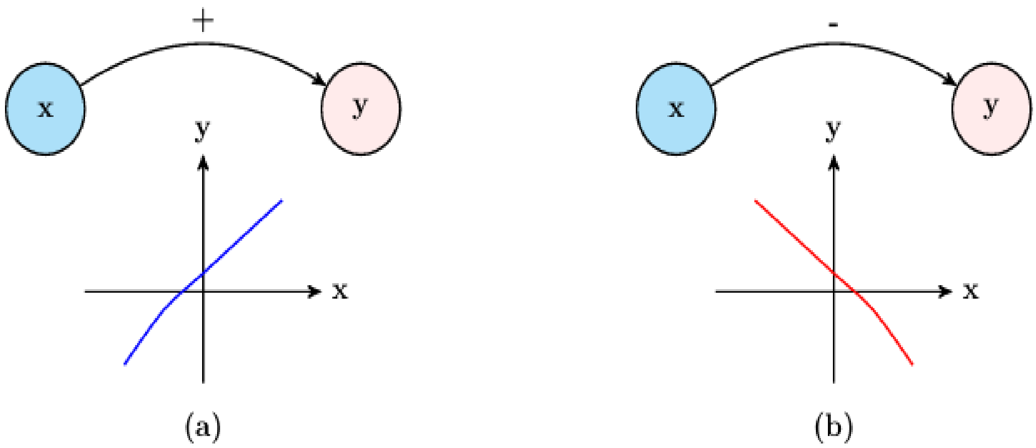

Figure 2. Research hypothesis as causal relationships

General Objective: the purpose of the study is defined, and it usually involves validating the hypothesis through models, experimentation, or data analysis.

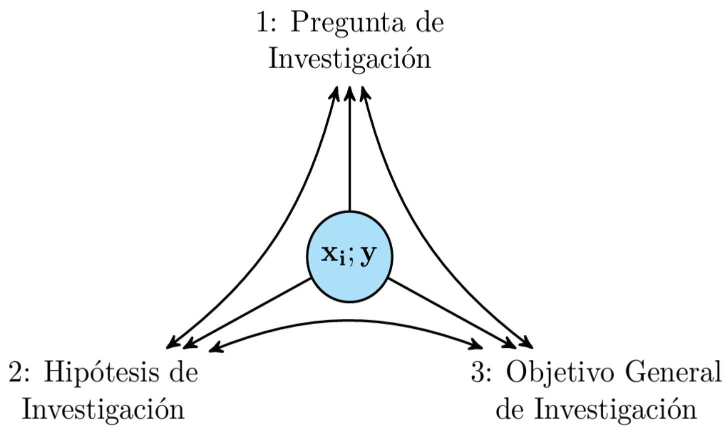

Figure 3. Scientific Method in Engineering

The research question, the research hypothesis, and the general objective contain the previously defined research variables within their structure. Figure 3 shows the relationship between these three tools for defining the research problem. This work proposes that these three concepts have the same structural foundation analyzed from a systemic thinking perspective.

Experimentation

In this phase, tests are designed to validate the proposed hypothesis. In the context of engineering, experimentation can take various forms. The experimental design must guarantee the reproducibility of the results, minimize sources of error, and ensure the validity of the conclusions.

Generalization

Once the experimental results have been obtained, evaluating the extent to which they can be extrapolated to other conditions within the same field of study is necessary. The scope and possible limitations of the study must also be considered.

Dissemination

The final step in the scientific method is disseminating the generated knowledge.

Figure 4 shows a flowchart that summarizes the structure of the scientific method in engineering and applied sciences.

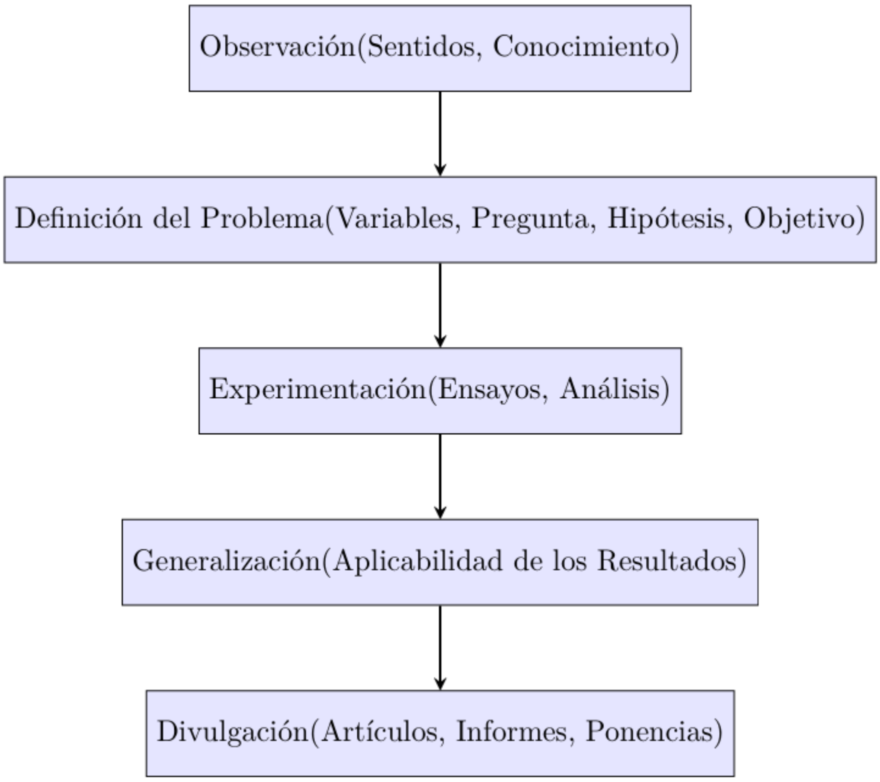

Figure 4. Scientific Method in Engineering

Causal diagram in system dynamics and its application in scientific research

In systems dynamics, a causal diagram is a fundamental tool for representing the relationships between variables within a system. It is based on the idea that systems are composed of multiple interconnected elements whose relationships can influence each other directly or indirectly. These types of diagrams are widely used in the modeling of complex problems in engineering, environmental sciences, economics, and systems management.[19,20]

A causal diagram consists of nodes that represent the system's variables. Directed arrows indicate the direction of the causal influence between the variables. Positive (+) or negative (-) signs indicate whether the relationship between two variables is direct or inverse. These diagrams allow us to understand the feedback structure of a system and are the basis for modeling more advanced dynamics with differential equations in system dynamics.

The scientific method and causal diagrams in systems dynamics share a conceptual structure based on the relationship between variables, hypotheses, and inference processes. In this sense, an analogy can be established between the elements of a causal diagram and the phases of the scientific method, which allows the research process to be visualized from a systemic perspective.

Causal diagram variables and research variables

In the scientific method, a hypothesis is formed by identifying independent and dependent variables. In a causal diagram, these variables appear as nodes connected by arrows representing causal relationships.

Independent variables (x*i*): these are the factors that the researcher manipulates or measures to analyze their effect on a dependent variable. In a causal diagram, these variables are at the ends of the structure and point towards other variables. Dependent variable (y): this is the response or effect we are trying to explain. In the causal diagram, it is the node where the arrows of the independent variables arrive. There may be intermediate variables mediating the relationship between an independent and a dependent variable, as well as exogenous variables, which affect the system but are not affected by it. Just as in scientific research, it is essential to identify these variables to formulate a hypothesis; in a causal diagram, their correct arrangement defines the system's structure being analyzed.

Research hypothesis and arrows in the causal diagram

In the scientific method, a hypothesis establishes a relationship between variables, generally regarding cause and effect. In a causal diagram, these relationships are represented by arrows, indicating how one variable affects another.

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Figure 5 shows the analogy between concepts of system dynamics and scientific research.

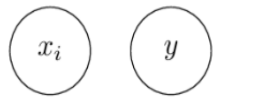
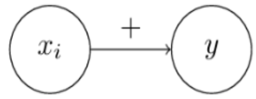
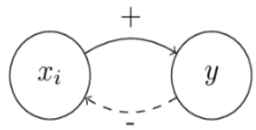
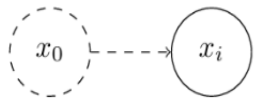
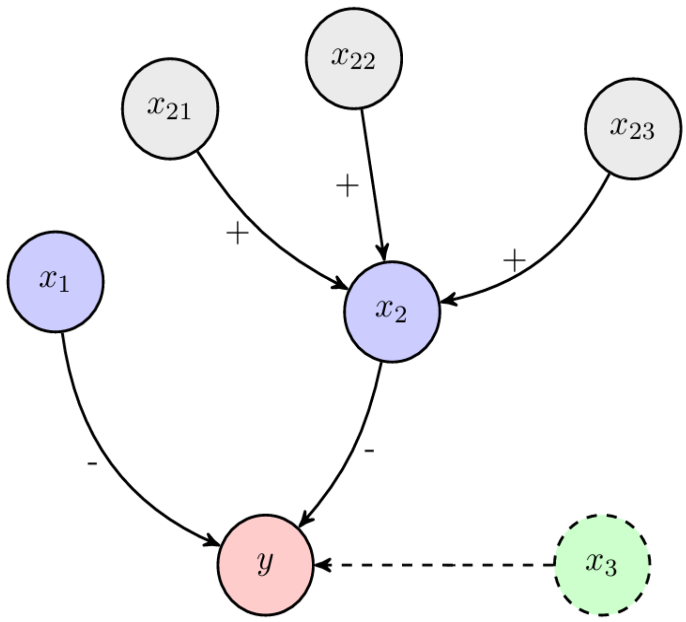
Investigación	**Analogía en DS**
Variables: Conceptos susceptibles de medición, evaluación o categorización. (x_i, y).	
Hipótesis de Investigación: Relación entre una variable independiente y la dependiente.	
Retroalimentación: Cuando la variable dependiente afecta a la independiente.	
Variable Exógena: Variable que influye en el sistema pero no es afectada por él.	

Figure 5. Analogy between system dynamics concepts and scientific research

With these tools, the following example of an application is shown:

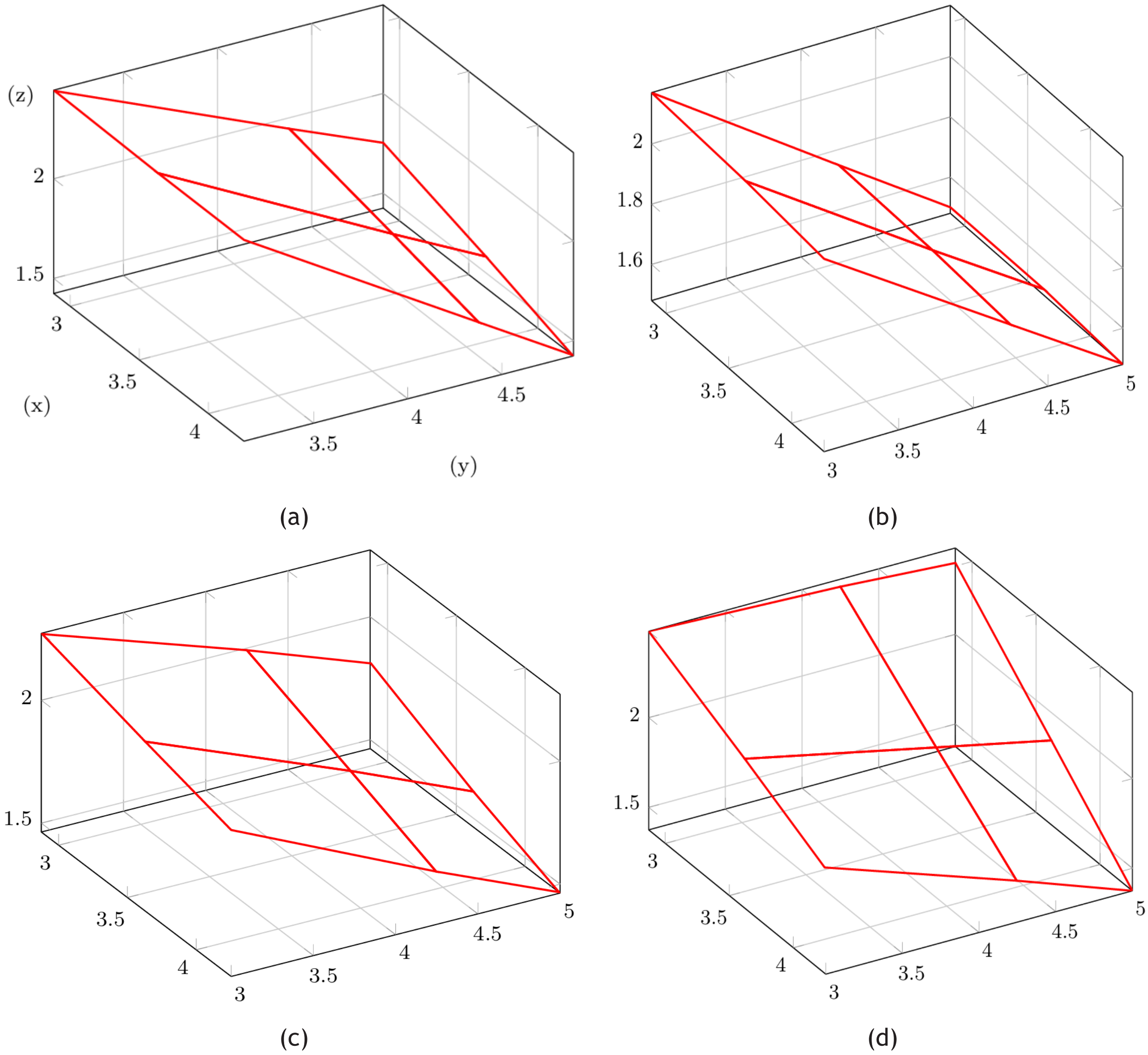
Article: emotional intelligence and suicidal ideation in adolescents: the mediating and moderating role of social support.[21] Where y is suicidal ideation, x1 is emotional intelligence, and x2 is social support, which in turn is measured through family support (x21), peer support (x22), and teacher support (x23). In addition, there is a variable that can be interpreted as exogenous: the adolescent's age (x3).



Fuente: Galindo-Domínguez et al.[21]

Figure 6. Causal representation of the article: Emotional intelligence and suicidal ideation in adolescents: the mediating and moderating role of social support

Figure 6 shows the basic systemic structure of the article: Emotional Intelligence and suicidal ideation in Adolescents: the Mediating and Moderating Role of Social Support. The variables are represented by nodes with their corresponding codings and the probable relationships by arrows. These probable relationships make up the research hypothesis on which the work is based and which is finally validated.



Fuente: Galindo-Domínguez et al.[21]

Figure 7. Emotional intelligence towards suicidal ideation when family support is a moderator. The axes (x), (y) and (z) represent emotional intelligence, social support and suicidal ideation respectively

Figure 7 shows the experimental results of the study, which are represented causally in figure 6. The axes (x), (y), and (z) represent emotional intelligence, social support, and suicidal ideation, respectively. Figura 7 (a) does not consider the age of the sample as an independent variable, while graphs 6 (b), (c), and (d) show results for samples aged 12, 13, and 15 years, respectively. Based on the experimentation, the hypotheses relating to the variables are confirmed. In this way, a direct application of systemic thinking is shown in a complex research project, which has been validated and can be correctly represented through a causal diagram.

Once the theoretical basis has been shown as a tool in teaching basic systems dynamics in the approach and definition of research problems, this methodology is applied to a group of engineering students at a public university in Ecuador.

Application of the systemic approach in the teaching of scientific research

This experiment has been carried out over a full semester to analyze the effect of this methodology. The application does not involve exclusive treatment for any specific group of students since it has been designed to evaluate the groups before and after using the systemic approach as a teaching strategy to measure its effect on learning.

Figura 5 shows the topics covered in the Research Methodology course. This information covers an average course of research at the university level to train students in methodology.

To apply the approach proposed in this paper, in the first phase, the subject whose content is in figura 5 has been covered traditionally, using a methodology of lectures with student participation and examples of analysis of scientific articles through the application of ICTs. To evaluate the results of this first phase, a tool has been designed with 59 questions about examples of scientific articles, their titles, abstracts, and conclusions. Each question provides the student with a title, abstract, and findings and asks the student to identify elements such as research variables, scope, and general objective. Examples:

Question: given the title, identify the research variables: Title: effect of probiotic consumption on gastrointestinal health in patients with irritable bowel syndrome.

A. Probiotic consumption.
B. Gastrointestinal health.
C. Type of diet.
D. Hours of sleep.
E. Level of physical activity.

In this case, the correct answers are options A and B.

Question: given the summary of the research article, identify the research objective:

Summary: this study investigates how regular physical exercise impacts psychological well-being in older adults. Data was collected from 300 participants, divided into two groups: those who engage in regular physical exercise and those who do not. Ryff's Psychological Well-Being Scale was used to measure levels of well-being. The results indicate a significant improvement in the psychological well-being of older adults who engage in regular physical exercise compared to those who do not.

A. Determine if regular physical exercise improves psychological well-being in older adults.
B. Compare the sleep quality between older adults who exercise and those who do not.
C. Evaluate the relationship between physical exercise and cardiovascular health in older adults.
D. Investigate the effects of physical exercise on reducing work-related stress in older adults.
E. Analyze the differences in blood pressure between older adults who perform different types of exercise.

The correct answer is option A.

Question: given the abstract of the research article, identify the scope of the research:

Abstract: "This study examines how consuming fruit and vegetables affects adult digestive health. Four hundred adults were included and were evaluated in terms of their daily consumption of fruit and vegetables and their digestive health using specific questionnaires. The results showed a positive correlation between higher consumption of fruit and vegetables and better digestive health.

A. Exploratory.
B. Descriptive.
C. Correlational.
D. Explanatory.

The correct answer is C.

Table 1. Topics covered in Research Methodology for the application of the scientific method

Curricular Unit	Contents
1. Knowledge, Science and Research	1.1 Epistemology, knowledge and science. 1.2 Scientific research, research paradigms. 1.3 Ethics and research, Code of Institutional Ethics and/or Academic Unit. 1.4 Citation standards and scientific writing.
2. Research Methods and Techniques	2. Research Methods and Techniques 2.1 Quantitative vs. qualitative research. 2.2 Methods or types of quantitative and qualitative research. 2.3 Techniques and instruments of scientific research. 2.4 Population and sample. Probabilistic and non-probabilistic sampling.
3. The Research Plan	3. The Research Plan 3.1 The topic and the research problem. 3.2 Justification and background. 3.3 Research questions and/or hypotheses. Objectives. Methodology. 3.4 Materials and methods, schedule and resources.
4. Research Results Report (Scientific Article)	4. Report of Research Results (Scientific Article) 4.1 Importance of reporting the results of a scientific investigation. 4.2 Materials and methods. 4.3 Results and discussion. 4.4 Conclusions, summary, abstract, key words (keywords).

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This tool has been used to assess the knowledge of 90 students from various branches of engineering. All the topics used in the assessment tool were generated using AI and are structured by one or two independent variables and one dependent variable without feedback. This way, a basic structure of title and abstract, commonly presented in scientific databases, is reproduced.

Once these results were obtained, called the purpose "Score-1" to the score achieved and "dt1" to the time in minutes it took each student to respond, a second phase was carried out, which involved teaching the basics of system dynamics to the group of students. This knowledge affects the contents shown in table 2. The teaching methodology continues to be master classes with student participation and analyzing scientific articles using ICTs. Once the basic knowledge of systemic thinking has been imparted, which is necessary to apply in research methodology, applying a structurally identical tool to that applied in the first phase is repeated. This way, the results "Score-2" and "dt2" are obtained, with the score and time corresponding to this second evaluation.

Table 2. Fundamentals of Systemic Thinking and Causal Diagrams

Unit	Contents
1. Introduction to Systemic Thinking	Definition of systems and systems thinking.
	Differences between linear and systems thinking.
	Basic principles of systems thinking.
2. Elements of a System	Components of a system: elements, relationships and purpose.
	Types of systems: open, closed, dynamic, complex.
	Feedback and its importance in systems.
3. Causal Diagrams	Introduction to causal diagrams.
	Identification of causal relationships.
	Feedback loops: positive and negative.
	Construction and interpretation of causal diagrams.

The results do not follow a normal distribution (Shapiro-Wilk), so the following analysis will be done with non-parametric statistics. In this case, the Wilcoxon test is used.

Variable	Mín	Q1	Mediana	Media	Q3	Máx	Desv. Est.	W (Shapiro)	p-Valor
Nota 1	15	26.75	55.50	53.06	78.00	95	26.34	0.89247	1.89×10^{-6}
Nota 2	22	65.50	76.00	73.10	86.75	98	18.73	0.90171	4.83×10^{-6}
dt1	3	22.25	34.00	35.09	40.50	197	26.92	0.61429	5.03×10^{-14}
dt2	4	22.25	34.00	37.79	45.75	174	25.65	0.82770	7.45×10^{-9}

Figura 8. Descriptive Statistics and Normality Test (Shapiro-Wilk)

Figure 9 shows the graphical analysis of the variables' normality: Note-1 and Note-2 at the top, dt1 and dt2 at the bottom. It can be seen that there are apparent deviations from normal behavior in all four graphs. Figure 8 confirms the graphical observation; all the p-values of the analyzed variables are significantly less than 0,05, meaning that none of the variables (Score 1, Score 2, dt1, dt2) are typically distributed. Therefore, for future statistical analyses (such as comparisons of means or correlations), it is recommended to use non-parametric methods, such as the Wilcoxon test for paired samples or Spearman's correlation.

The results obtained from the descriptive statistical analysis and the Wilcoxon test allow us to evaluate the behavior of the grades (grade 1 and grade 2) and the resolution times (dt1 and dt2).

The analysis of the grades shows that the average grade 1 is 53,06, while grade 2 is 73,10, which indicates an improvement in academic performance. This trend is also reflected in the median, which went from 55,5 in grade 1 to 76,0 in grade 2, and in the interquartile range, Q1 increased from 26,75 to 65,50 and Q3 from 78,00 to 86,75. The standard deviation decreased from 26,33 in grade 1 to 18,73 in grade 2, which suggests a lower dispersion in the grades of the second evaluation; the students showed a more uniform performance.

Analysis of the resolution times indicates that the average time in dt1 was 35,09 minutes, increasing slightly to 37,79 minutes in dt2. The median remained constant at 34,0 minutes, but the values of the third quartile (Q3) increased from 40,50 to 45,75 minutes, indicating that some students spent more time on the second evaluation. The standard deviation in dt1 was 26,91, while in dt2, it was 25,65, suggesting that response times were more homogeneous in the second evaluation.

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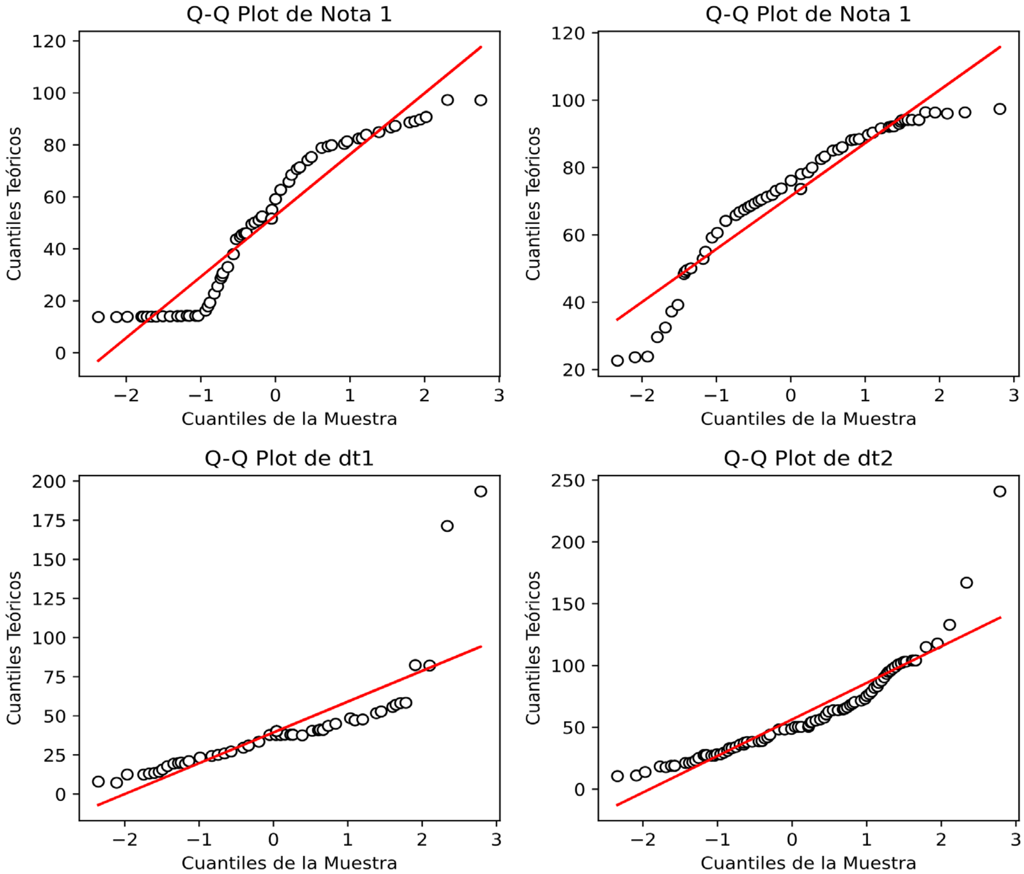

Figure 9. Normality analysis of the parameters analyzed

These results are supported by the Wilcoxon test, which yielded a p-value of $5{,}539 \times 10^{-10}$, indicating that the difference between grade 1 and grade 2 is statistically significant. The null hypothesis of no change in grades is rejected, and the alternative hypothesis is accepted, confirming that the students improved in the second assessment.

In general terms, the data reflect a significant improvement in the student's grades in the second evaluation, with a reduction in the variability of the scores, which suggests a consolidation of learning. Although the average time to solve the problem increased slightly, the difference is not statistically relevant.

CONCLUSIONS

The present study shows that integrating systems thinking in the teaching of research methodology significantly impacts students' academic performance. The grades obtained in the second of two assessments carried out through the application of a teaching strategy based on systems dynamics improved, as confirmed by the statistical analysis performed.

The Shapiro-Wilk normality test revealed that none of the variables analyzed follow a normal distribution, leading to non-parametric tests for the statistical analysis. The mean of the first grade was 53,06, and the second increased to 73,10. The median increased from 55,5 to 76,0, and the interquartile range shifted towards higher values, indicating a generalized progress in understanding the evaluated contents.

The results of the Wilcoxon test with a very low p-value confirm that the difference in grades between the first and second evaluations is statistically significant. The decrease in the standard deviation from 26,33 to 18,73 between the two assessments suggests that the student's performance was more homogeneous after implementing the methodology. This indicates that teaching based on systems thinking improves individual results and reduces learning dispersion, favoring a more structured understanding of concepts.

No significant change was evident regarding resolution times, from 35,09 to 37,79 minutes. The median remained at approximately 34,0 minutes, while the third quartile increased from 40,50 to 45,75 minutes, indicating that some students spent more time on the second assessment. This trend suggests that learning based on systems thinking led to more excellent reflection and analysis when answering the assessment rather than simply repeating knowledge.

Further research is needed on the effect of the systems approach in different areas of engineering and applied sciences education and to assess its long-term impact on training professionals with strengthened analytical and critical skills.

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