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PAPER

Validation of an Instrument to Assess Deductive Reasoning in Solving Types of Problems

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ABSTRACT

The accelerated pace of knowledge generation requires engineering students to develop different types of reasoning during their education. Deductive reasoning is essential to establishing self-regulated judgments based on reasoned argumentation. This paper aims to describe and illustrate the process by which a test of multiple-choice, open-response verbal mathematical problems was designed, applied, and validated to assess the deductive reasoning of second-semester students of two engineering degrees from a university in a region of southern Chile. The research used a non-experimental, cross-sectional approach focused on psychometric aspects. The evaluation instrument was developed on the basis of a typology of mathematical problems and a model of deductive reasoning. The resolutions of types of problems are classified according to their nature, routine and non-routine, and according to their context, real, realistic, fantasy, and purely mathematical, while the deductive argumentative model comprises the phases of data, claim, and warrant. The results guarantee sufficient content and construct validity, item discrimination, and reliability; therefore, they represent a useful tool for measuring the level of deductive reasoning among first-year engineering students during the process of solving a type of mathematical problem.

KEYWORDS

deductive reasoning, problem solving, validity, reliability, engineering programs

1 INTRODUCTION

The scientific literature agrees that engineers need to develop skills that enable them to solve problems. To do so, the basic cognitive process called reasoning is used, through which the acquired knowledge is applied [1–2]. But empirical evidence from various analyses of engineering programs establishes that training is not focused on activities that precisely involve reasoning and abstraction skills [3–4].

Nowadays, reasoning plays a very important role both in educational contexts and in the workplace, and some reasoning skills are considered essential components of

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these 21st century skills [5]. Several researchers have pointed out that reasoning is an important dimension of science and mathematics education [6].

It is also recognized that reasoning skills can help students understand and evaluate the scientific and technological society, as reasoning will enable them to analyze new situations that they face in all aspects, make logical assumptions, explain their thoughts, come to conclusions, and defend their conclusions. However, according to [7], despite the need to develop students' reasoning skills proposed by researchers and educators in the last four decades, there is great difficulty in defining and, consequently, assessing them.

Peirce, cited in [8], establishes the existence of three types of reasoning or argumentation in mathematics: abductive, inductive, and deductive. Mathematics education has had a great deal of research development around these three types of reasoning or argumentation that may be involved in teaching-learning processes [9–10]. However, research on reasoning by deduction is scarcer, and studies on inductive reasoning prevail. The slightly more explored area associated with these types of reasoning is geometry. In this regard, it is worth noting that several researchers have shown how open problems solved in dynamic geometry environments favor inductive, abductive, and deductive argumentative processes [11] [10]. However, they do not make explicit how the structure of the problem statement can favor the production of different types of reasoning, keys for the elaboration of conjectures, and, eventually, the production of their proof.

The authors [12] are categorical in stating that deductive reasoning is the only one that allows validating mathematical knowledge, but they recognize that abductive and inductive reasoning play a relevant role in producing demonstrations. As indicated by [8], abductive reasoning helps to find possible hypotheses or data to initiate deductive reasoning, and inductive reasoning helps to increase the conviction of the certainty of the conclusion or to refute it if a counterexample is found. For many students, the first university courses constitute the occasion of their encounter with formal proofs in mathematics, and the forms of reasoning associated with them. However, the deductive structures underlying them are not often the object of attention in teaching.

Engineering thinking involves both inductive and deductive reasoning. This means that, in engineering education, case-based descriptive examples are important for the student as analogous and deductive sources for problem solving. Recent studies have shown that deductive reasoning skills (including their specificities: transitive and conditional inferences) are related to mathematical skills. However, the links between mathematical skills and these two forms of deductive inference have so far not been investigated in a single study [13]. So far, the link between transitive deductive reasoning and mathematical skills has only been investigated for children [14] and adolescents [15]. These studies have found a relationship between mathematical skills and transitive deductive reasoning ability in typical populations [15], as well as when comparing groups of children with exceptionally low, medium, and high mathematical ability [14]. The authors [16] establish that people argue with respect to inferences only with the initial information, without thinking about different alternatives that allow the resolution of the problem posed.

On the other hand, [2] states with respect to the training of engineers that, despite being trained in the mastery of logical arguments as part of mathematical reasoning, they do not make use of them, which may lead them to make erroneous decisions that may have a negative impact on society once they graduate from the programs. In this regard, [17] states that common sense is not effective at complex levels of abstraction and highlights that people do not distinguish between logical and conventional implications. This is also supported by [18], who point out that young people have difficulties generating argumentative texts with the greatest number of arguments in order to favor the validity of the text. In his research, he point out that students, for the most part, elaborate arguments based on their personal experience; however, they do not master the theoretical concepts, so the data do not acquire great relevance.

According to the literature reviewed, no studies were found that relate the resolution of types of problems and deductive reasoning in the education of engineers, even though the explanatory framework of problem solving is deductive. We are certain of the importance of having relevant and reliable assessment instruments that have been subjected to statistical tests and have a high scientific rigor [19]. In this context, the objective is to design, apply, and validate a verbal mathematical problem-solving test to assess the level of deductive reasoning that emerges when a group of engineering students are involved in solving a type of mathematical problem that can be solved in various contexts.

2 THEORETICAL FRAMEWORK

In mathematics, based on the PISA 2021 theoretical framework, students learn that, with appropriate reasoning and assumptions, they can arrive at results that they can fully trust as true in a wide variety of real-life contexts. It is also important that these conclusions are unbiased, without the need for validation by an external authority [20].

Intense competition between people who have deductive, critical, systematic, logical, and creative thinking skills and the ability to communicate creative ideas will be part of the 21st century, the era of globalization, increasingly sophisticated technological products, and the diffusion of the flow of information. Subjects that meet the aforementioned characteristics require education, and more specifically, mathematics education. Studying mathematics as a whole implies achieving, among others, the ability to solve problems, to reason deductively, to reason logically, to achieve critical thinking, logical thinking, systematic thinking, and creative thinking. This is because mathematics is a means of thinking [21].

Theories on deductive reasoning can be found in the current literature. The theoretical and experimental model of mental logic assumes that reasoning employs and handles finite semantic representations by applying rules of inference analogous to the deductive rules of logic. The theory of mind models is a rival theoretical framework to mental logic and is based on specific semantic simulations or interpretations [22].

On the basis of argumentation and in contrast to theories based on mental logic and mental models, the model of [23] emerges, which can be applied in inductive, abductive, and deductive reasoning.

2.1 Deductive reasoning

A characterization of deductive reasoning that is still very common holds that they are those that "go from the general to the particular or specific", or those that go "from the whole to a part." The authors [24] argued that such a conceptualization is nowadays inconsistent in light of contemporary findings in logical science. The authors indicate that the popular tradition has distorted the concept and offer an improved version of deductive argument, which can be useful for conceptualizing deductive reasoning, insofar as they define deductive argument as that in which the conclusion necessarily follows from the premises. If this claim is achieved, the reasoning is valid, and if not, it is invalid.

All mathematical reasoning is associated with a type of argument that can be typified by any of the following forms: inductive, abductive, or deductive, and constitutes the model of [23], on which the theoretical framework of this study is based.

2.2 Toulmin's deductive argumentative model

According to [23], in Toulmin's basic Model, an argument is an oral or written statement, with a ternary structure, that relates particular propositions (data and claim) and a general one (warrant), which are defined as follows:

Data (D) corresponds to the facts or grounds on which the reasoning is based.
Claim (C) or affirmation is the statement to be justified or whose veracity is to be convinced.
Warrant (W) or justification is the principle or proposition that links the data to the assertion.

Schematically, Toulmin's basic argumentative model is related as follows:

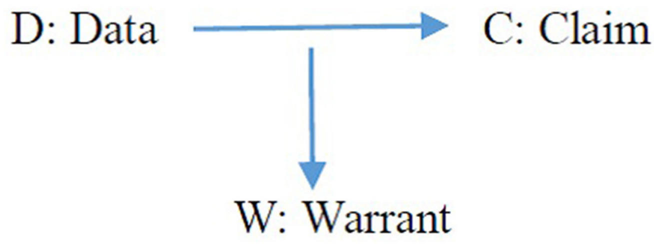

Fig. 1. Toulmin's basic model

The warrant, which can be expressed as a principle or a rule, acts as a bridge between the data and the assertion. The propositions may not be explicit, but to formalize what is expressed it must be possible to identify them. The way in which particular propositions (*p* and *q*) and the general proposition (*r*) are related defines the type of argument: deductive, inductive, or abductive. In a deductive argument, a known general proposition (r: $p \rightarrow q$) is applied to some existing data (p_1: particularization of *p*), to necessarily obtain the assertion (q_1: particularization of *q*). The scheme of the argument is: $(p_1 \Lambda r) \rightarrow q_1$. This type of argument occurs primarily in the process of proving a conjecture.

In general terms, according to this model, in an argument, an affirmation or claim can be established on the basis of data obtained or observed phenomena justified in accepted scientific knowledge. This type of reasoning makes it possible to validate knowledge in mathematics, which is irrefutable unless the initial axiomatic system is changed.

2.3 Problem solving

Although the term 21st century skills may sound modern, some of these skills are not new; they are just newly important. Vital capacities such as critical thinking and problem solving have always been essential. However, today, due to the emerging demand for knowledge-based economies, these capabilities have become increasingly important [25].

It is generally accepted that the work of engineers consists fundamentally of detecting, recognizing, and solving problems, and may even be the core of their practice [2]. In order to meet these requirements, engineering education must maintain continuous communication with reality, with the aim of preparing future professionals to perform adequately when it is their turn to experience it. This objective has a basic characteristic: the need to develop logical-deductive thinking and an adequate abstract interpretation in order to achieve an efficient and effective resolution of these problems. In the training of engineers for the 21st century, this need is a basic component because their performance will be largely governed by an adequate interpretation of the problem before they are presented with a solution. Therefore, engineering education, as a scientific area, must include reasoning, abstraction, mathematics, and problem solving at all levels, and as professionals, they are expected to master and apply types of reasoning. Paradoxically, few programs in the world adequately address this training need [12].

2.4 Types of mathematics problems

Problem solving as a high-level skill that orchestrates a complete set of cognitive, metacognitive, and behavioral processes [26] can be applied in diverse areas, situations, and contexts; therefore, it is also known as a 21st century skill [27].

Due to the importance of the contexts associated with the problems, we opted for the classification of types of problems by the authors [28] [29] and [30] [31], who have worked in different areas of mathematics, which form part of the theoretical framework.

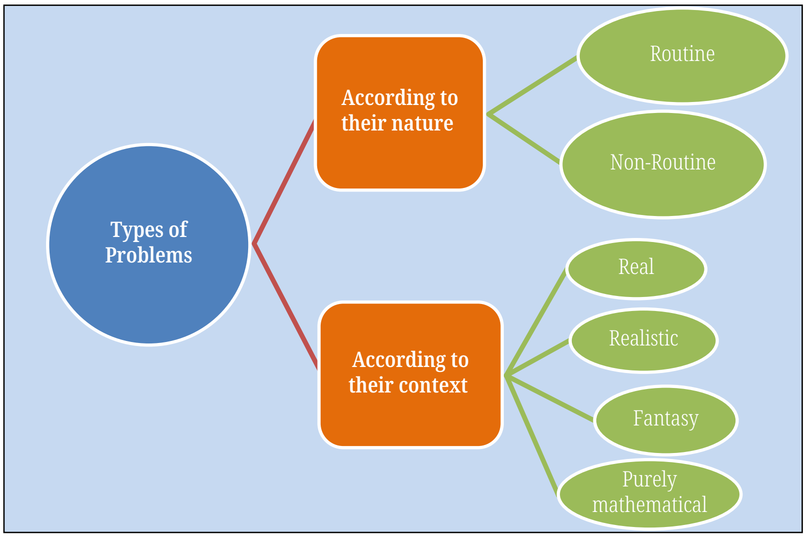

Fig. 2. Types of mathematics problems

- Nature of the problem

Based on their nature, problems are defined as routine and non-routine. (1) Routine problems are similar to those solved during instructional courses; the student follows a sequence that involves understanding concepts and algorithms to reach valid solutions. (2) A problem will be non-routine when a student does not know an answer or a previously established procedure or routine to find it.

- Context of the problem

a) Real context problem: A context is real if it is produced in reality and compromises the actions of the student in it.
b) Realistic context problem: A context is realistic if it is susceptible to being produced. It is about a simulation of reality, or a part of it.
c) Fantasy context problem: A context is fantasy if it is fruit of imagination and is unfounded in reality.
d) Purely mathematical context: A context is purely mathematical if it makes exclusive reference to mathematical objects: numbers, relations and arithmetic operations, geometric figures, etc.

3 METHODOLOGY

The present study is descriptive, non-experimental, cross-sectional, and focused on psychometric aspects, as it aims to validate a measurement instrument [32]. This instrument was developed in four stages: Stage 1 curriculum design, Stage 2 development of constructs, Stage 3 construction of the evaluative instrument, Stage 4 procedure used and participants, and Stage 5 pilot study.

3.1 Stage 1: Curriculum design

The first stage consisted of a review of the curricular designs of existing engineering majors in state universities in Chile in order to extract the relationship between the type of reasoning and problem-solving skills. The competencies and skills considered indispensable for engineers were also reviewed in relation to the curricular designs of other latitudes and with similar training. From this, we can indicate that the description of engineering degrees or programs has as a common denominator to train professionals who are equipped with the necessary knowledge and skills to address multidisciplinary problems from the science of engineering, in tune with the pattern of thinking required to solve a problem.

3.2 Stage 2: Constructs development

At this stage, a literature review was conducted in Wos, Scopus, and Scielo of the constructs "deductive reasoning" and "problem solving", both in engineering programs, and selected in the first instance according to title and abstract from the year 2000 onwards. Articles related to aspects of design and the conduct of studies in relation to both constructs were included.

3.3 Stage 3: Construction of the evaluation instrument

Mathematics test. To measure the levels of deductive reasoning evidenced in the resolution of types of mathematical problems, a mathematical test was designed and elaborated. During its construction stages, it required a conceptual definition of deductive reasoning and the types of problems, operationalizing the conceptual definitions through indicators expressed in the problems elaborated, with questions to which the student must give an answer. The mathematical test called "Test of Deductive Reasoning" was structured based on the types of problems classified according to their nature as routine and non-routine and according to their context as real, realistic, fantasy, and purely mathematical [28] and on the three stages of data, conclusion, and guarantee of the model [23], to characterize the deductive argument produced by the students.

The test as a whole consists of six problems. Each problem in turn consists of a mathematical problem situation with alternative answers plus an open answer. Each of the proposed problems has implicit data (D) as the first component of the deductive argumentation, and the student is expected to use all the information given in the statement of the type of problem. The answer options are multiple choice with 4 or 5 alternatives, and their purpose is to demonstrate the second component of assertion or claim (C), insofar as students associate the problem statement with the most assertive statement or assertion based on the information or data contained in the problem. To record the third component of assurance or warrant (W), in an open response to the proposed problem, students are expected to support their response to the resolution of the type of problem, that is, to provide a justification argument derived from the chosen conclusion.

Problem number three of the test, which is of a routine nature and has a fantasy context, is presented below.

Instructions. Read each statement and answer the problems, according to the indication given in each statement. Attach your responses on a separate sheet of paper.

A factory employing robot, manufactured one thousand spaceships in the last month and eleven hundred in the previous month. Therefore, increasing the wages of the robots helped to improve the productivity of the factory.

What assumption underlies the above argument?

a) Spaceships factories produce around a thousand spaceships every month.
b) Two months ago, the factory was producing twelve hundred spaceships.
c) Increasing robot wages always increases productivity.
d) The factory used to make less than a thousand spaceships a month.
e) The factory produced a thousand spaceships last month.

- Choose the conclusion that you think is best supported by the data of the problem posed (circle the selected option).
- Argue why you chose the conclusion: ....

Rubric. According to [33], rubrics constitute a set of quality criteria that are related to the competence or competencies to be evaluated and determined by descriptors or indicators. It assume different levels of achievement or performance.

In order to obtain the classification of students into different levels with respect to their deductive reasoning ability and associated with the Toulmin model, an assessment rubric for deductive reasoning skills was developed and validated as an evaluative instrument for the interpretation of the test score.

The basic structure of the rubric for the validation process contains: informative data, performance criteria, a progressive rating scale (high, medium, and low), the weighting of each criterion, and space for suggestions for improvement. Next, the final rubric is presented in Table 1.

Table 1. Assessment rubric for deductive reasoning skills

Propositions	Valuation Level		
	High	Medium	Low
Data	Use all the information given to solve the type of problem	Partially uses the information given to solve the type of problem	Does not use the information given to solve the type of problem
Claim	Associates the statement with the most assertive response based on the information provided by the type of problem	Partially associates the statement with the most assertive response based on the information provided by the type of problem	Does not associate the statement with the most assertive response based on the information provided by the type of problem
Warrant	You fully support your answer to the resolution of the type of problem	Partially supports your response to the resolution of the type of problem	You fail to support your response to the resolution of the type of problem

3.4 Stage 4: Procedure and participants

A non-probabilistic selection of state universities with engineering degrees in Chile was used. After selecting and getting permission from the university, permission was obtained from the corresponding faculty, and data collection was carried out directly on each campus at a time determined by each faculty, with students in the second semester of two engineering degrees who are studying Calculus I during the second semester of 2022.

The students who were the subjects of the study correspond to groups already constituted and with different teachers in the subject of Calculus I, which is nearing the end of the second semester. The students were informed about the nature of the study and explained how to answer the mathematics test. All participants were also presented with the informed consent form before completing the assessment, and the assessment instrument was applied to those who voluntarily agreed to participate. In this way, the sample consisted of 105 students from two engineering courses taught at a university in southern Chile. This group was made up of 84 men and 21 women, with an average age of 18 years.

3.5 Stage 5: Pilot study

The deductive reasoning test was applied to a pilot sample of engineering students in order to identify and correct, on one side, terms that are difficult to understand for the students at whom the assessment instrument is oriented, and on the other side, to analyze its psychometric properties relative to validation. The application was administered individually in person. The suggestions and modifications proposed by the specialists and by the students were considered, which allowed the elaboration of the definitive version of the deductive reasoning test, which will be applied in the future research stage to a definitive sample.

4 RESULTS

The results and analyzes presented below address the validation process of the instrument, ensuring face, content, and construct validity, problem discrimination, and reliability.

4.1 Apparent validity

The validation process started with the face validity of the mathematics test. Face validity refers to the degree to which an instrument reflects a specific content domain of what it measures. It is the degree to which the measure represents the concept or variable being measured [32].

Face validity made it possible to assess the clarity and comprehensibility of the evaluative instrument without ambiguity. In this study, the analysis of face validity was carried out taking into account the assessment criteria: length and wording. The experts agreed that the types of problems, according to nature and context, met the levels of deductive reasoning tested. Students also agreed that the purpose and direction of the questions were clear.

4.2 Content validity

The content validity of the deductive reasoning test was established according to the evaluation criteria of relevance, pertinence, clarity, and accuracy and was carried out [4] through the judgment of nine experts in the subject [33]. The collaboration of professionals with extensive experience in solving mathematical problems, in the deductive reasoning construct, and in the evaluation of measurement instruments was sought through an expert evaluation guideline, which contained the problems, definitions, and criteria of the aspects to be evaluated [35]. It was established whether the sample of problems was representative and sufficient for each of the categories of deductive reasoning that the instrument assesses.

Once the concepts of the expert judges had been received, each of the problems was modified in accordance with the suggestions given. After making the pertinent modifications to the problems in accordance with the recommendations in the wording of some of the problems and the elimination of others, the final version was obtained with six problems. In the validation of relevance, pertinence, clarity, and accuracy, an average content validity index of 0.97 was obtained, which indicates that this instrument evaluates the levels of deductive reasoning in engineering students when they solve a type of mathematical problem classified according to nature and context into routine and non-routine.

On the same lines, the content validity of the assessment rubric for deductive reasoning skills was evaluated by the same nine judges, who included professors and doctors. In order to establish the statistical validity of the rubric as an assessment instrument for university engineering students, the corrected correlation coefficient r of Pearson was used. This coefficient takes values between –1 and 1. Items whose item-total correlations yield values of 0.2 or more are valid and should be retained, while items with correlations below 0.2 are invalid and should be reformulated or discarded. As a general rule, the measurement instrument is valid if all its items are valid [33].

4.3 Discrimination analysis

The psychometric characteristic referred to as the discrimination index of the test was performed by calculating the standard deviation of the total test score and the standard deviation of the problems, followed by the problem-test correlation without considering the same item to finally determine the index.

The psychometric properties of the deductive reasoning test problems are generally good. No problem concentrates more than 10.8% of the omitted answers. In relation to the averages obtained, most of the problems present an intermediate value, and, together with this, the standard deviations are sufficiently high to affirm that most types of routine context problems and non-routine problems discriminate between the different study subjects. The results of the analysis are shown in Table 2.

Table 2. Psychometric properties of problem types

Problems	Types of Problems	DS	r	p
Problem 1	Routine and purely mathematical context	1.175	0.547	0.4938
Problem 2	Routine and realistic context	1.254	0.550	0.4933
Problem 3	Routine and fantasy context	1.08	0.628	0.5856
Problem 4	Routine and real context	1.085	0.582	0.5356
Problem 5	Non-routine	1.066	0.496	0.4443
Problem 6	Routine and fantasy context	1.09	0.553	0.5042

Most of the six problems present a discrimination index $p \geq 0.4$, which indicates that they discriminate positively to a high degree; in other words, these items are understood in the same way by the students, and the scores are accurate; that is, they are precise and well understood by most of them. It is also noted that problem 6 has a discrimination index between 0.3 and 0.39, which indicates that it discriminates moderately [36].

4.4 Construct validity

For construct validity based on the underlying theoretical model of deductive reasoning ability in solving types of mathematical problems, the factors were designed as latent variables and their respective observed variables using the estimation program AMOS version 19.0 (Table 3).

Table 3. Goodness-of-fit statistics

Goodness of Fit Statistics	Abbreviation	Criteria
Absolute adjustment		
Chi squared	X^2	p >.05
Chi-square ratio/degrees of freedom	$X^2/g.l.$	< 2.9
Comparative adjustment		
Comparative goodness of fit index	CFI	≥ .90
Tucker–Lewis index	TLI	≥ .90
Goodness of fit index	GFI	≥ .90
Corrected goodness of fit index	AGFI	≥ .93

For the estimation of the parameters, the maximum likelihood method was used, and to assess the goodness of fit of the corresponding model, the chi-square (χ^2) test of the association of measurements was calculated. Although the sample was 105 subjects, due to the fact that χ^2 is very sensitive to variations in the size of the sample [37], additional measures of the model's goodness of fit were used. To assess the quality of the model, goodness-of-fit statistics were used. While there are three types of goodness-of-fit statistics: absolute, which assesses the residuals; relative, which compares the fit with respect to a worse-fitting model; and parsimonious, which assesses the fit with respect to the number of parameters used, none of them provide all the information needed to assess the model. Therefore, a set of them is usually used and reported simultaneously [38].

4.5 Reliability

The reliability of the deductive reasoning test was determined using the absolute reliability approach with the internal consistency method and with the determination of Cronbach's α coefficient. The total test presents a high internal consistency $\alpha = 0.831$ (an acceptable value for acceptance and decision-making in relation to a problem-solving test).

As for the reliability of the rubric to assess the same reasoning construct, according to the results of Cronbach's alpha, there is 0.842, which corresponds to a high level of reliability, which exceeds the ideal level of > 0.70 [39].

5 DISCUSSION AND CONCLUSION

The purpose of the present research was to design, apply, and validate an evaluation instrument. We focused our attention on the development of deductive reasoning among engineering students engaged in solving six types of problems, classified according to their nature into routine and non-routine and according to their context into real, realistic, fantasy, and purely mathematical.

The literature review did not reveal similar instruments to favor the learning of argumentation involving deductive reasoning through the approach and resolution of different types of problems. One of the reasons for this worrying lack is the lack of effective assessment systems for such complex skills as reasoning [40]. Our research aims to fill this serious gap, which is even greater in the Spanish language.

As shown in the results obtained from the analysis of face validity and content validity, discrimination validation, construct validity and reliability, a test, and a rubric, positive results were obtained in all cases. Our contribution adds a new instrument to assess deductive reasoning with problems that implicitly include data as the first component of deductive argumentation, claim as the second component, and warrant as the third component. In addition to a rubric to determine the levels of deductive reasoning ability on a progressive assessment scale, there are three performance levels: high, medium, and low.

The analysis of the scientific literature conducted in this research for the development of this measurement instrument shows that the relationship between deductive reasoning and mathematical problem solving in an educational environment is still under development. In the present study, in order to solve a mathematical problem, students must not only perform the necessary mathematical operations but also bring into play knowledge that promotes argumentation. Therefore, it was assumed that one of the shortcomings of engineering students is related to the lack of activities in their curricular training that involve reasoning and abstraction skills, agreeing in this regard with several authors [41], [3–4].

The real evidence of the absence of certain types of arguments has been revealed in research on engineering education, which indicates that they do not make use of logical arguments despite being trained in them as part of mathematical reasoning, which may lead them to make wrong decisions in the future as engineering graduates [41]. Instead of learning broad content knowledge in individual subjects, students should be equipped with more general thinking skills to manage information [42].

Many engineering courses focus disproportionately on the domain of mathematics. Analysis of the curricula of 10 leading universities in Brazil, Canada, the United States, Germany, Italy, South Korea, and Singapore indicates that 13% of engineering courses are purely mathematical, while 57% model phenomena based on mathematical logic; only 30% primarily apply reasoning that is not necessarily mathematical [43].

On the other hand, currently, a trend in the educational field is to recommend that curricula and instructional practices be based on ideas from the field of problem solving [44–45]. [46] pose a challenge for mathematics instruction based on problem solving, to create conditions to generate an environment that favors the actions of mathematical activity. This context makes possible a scenario that focuses on calculations and deductions. In this sense, we suggest types of problems that, when used with future engineers in their training process, open a space for them to gain experience as problem solvers and, in this framework, strengthen their argumentative competence. Specifically, we present a type of problem that, characterized by the structure of its statement, favors a specific type of reasoning skill.

Finally, in the absence of other related instruments, we believe that this scientifically valid and reliable evaluation instrument represents a contribution to research in the field of educational evaluation.

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