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CRITICAL DEFICIENCIES IN BASIC MATHEMATICS: A CROSS-SEMESTER DIAGNOSTIC STUDY AMONG ENGINEERING STUDENTS

CRITICAL DEFICIENCIES IN BASIC MATHEMATICS: A CROSS-SEMESTER DIAGNOSTIC STUDY AMONG ENGINEERING STUDENTS

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Abstract -- Mathematics is the fundamental pillar of engineering. However, the level of mathematics upon entering a university degree program is deficient. The COVID-19 pandemic exacerbated these deficiencies globally, particularly at the pre-university level.

This study evaluated the basic math skills of 113 engineering students in their first to seventh semesters at TecNM campus Ciudad Juárez using a diagnostic instrument with nine questions in four areas of basic math: arithmetic, algebra, geometry and trigonometry, and problem solving. Psychometric analysis revealed acceptable reliability (Cronbach's alpha = 0.74) and excellent factorial adequacy (KMO = 0.97), validating the instrument for assessment.

The results showed critically low performance, with an average score of 1.78 out of 10. Thirty-one point eight percent of students scored zero, while only 4.4% scored above 6 out of 10 points. The distribution across semesters showed no significant differences, indicating that deficiencies persist throughout the university career. Algebra questions presented the greatest difficulty (10.88%), followed by trigonometry (14.15%) and arithmetic (23.89%).

These findings highlight an educational urgency, as they reflect deficiencies in pre-university mathematics education that do not improve throughout the degree program.

Keywords-- Mathematical skills in higher education, diagnostic assessment, academic performance in engineering, psychometric validation.

Abstract --Mathematics is a fundamental pillar of engineering education. However, students often enter university degree programs with significant deficiencies in their mathematical preparation. The COVID-19 pandemic further exacerbated these deficiencies worldwide, particularly at the pre-university level.

This study evaluated the basic mathematics skills of 113 engineering students from first to seventh semester at TecNM campus Ciudad Juárez. A diagnostic instrument composed of nine items across four areas—arithmetic, algebra, geometry and trigonometry, and problem-solving—was used for this purpose. Psychometric analysis demonstrated acceptable reliability (Cronbach's alpha = 0.74) and excellent factorial adequacy (Kaiser–Meyer–Olkin = 0.97), confirming the validity of the instrument for diagnostic assessment.

Results revealed critically low performance, with an average score of 1.78 out of 10. A total of 31.8% of the students scored zero, while only 4.4% scored above 6 out of 10 points. Cross-semester analysis showed no significant differences in performance, indicating that deficiencies persist throughout the university trajectory. Among the content areas, algebra items showed the highest difficulty (10.88%), followed by trigonometry (14.15%) and arithmetic (23.89%).

These findings underscore an urgent educational issue, reflecting structural deficiencies in pre-university mathematics training that remain unaddressed during the engineering degree program.

Key words-- Academic performance in engineering, diagnostic assessment, mathematical competencies in higher education, psychometric validation.

INTRODUCTION

High failure rates in the first semesters of engineering represent a persistent problem in Mexican higher education. Previous studies [1, 2] have identified that these academic failure rates are directly related to deficient foundations in basic mathematics, which constitute the fundamental basis for success in disciplines such as calculus, physics, and statistics, basic science subjects in engineering curricula. The level of school dropout is related to academic performance issues, and this relationship accounts for 70% of cases in the first semesters of university education [3]. Although some studies do not find conclusive results [4, 5] due to the existence of economic, social, and personal factors, academic performance remains one of them.

Deficiencies in basic mathematics in primary education were significantly exacerbated by the disruption to education caused by the COVID-19 pandemic [6], which deepened the gaps in pre-university mathematics education. Students' perceptions of education or the teaching-learning process also had an influence during this period [7], and there were even signs of improved academic performance [8]. However, five years later, the academic outlook is not encouraging [9, 10], as social inequalities and knowledge of digital technologies were factors that prevented students from developing basic mathematical skills in a uniform manner.

Although multiple studies have assessed the level of entry [11, 12, 13], there is a critical gap in longitudinal evaluation to determine whether these deficiencies are overcome during university studies or, on the contrary, persist as a structural limitation throughout professional training. It is true that attempts have been made to redesign diagnostic instruments for mathematics for university admission [14], but these have not been validated in practice, which is one of the main differences with the present study.

The objective of this research is to present a validated diagnostic tool that demonstrates the low level of basic mathematics with which students enter an engineering program and to show that this level does not improve over the course of the semesters. A cross-semester analysis, covering the first through seventh semesters, evaluates the hypothesis that the deficiencies identified upon entry remain without significant improvement over time, which would suggest the inadequacy of current remedial mechanisms within the various academic programs.

The relevance of this research lies in its potential to reorient mathematics leveling strategies in the most compromised areas of mathematics, moving from specific interventions in the first semester to a cross-cutting approach that addresses these deficiencies throughout engineering education.

DEVELOPMENT

Materials and Methods

To carry out this research, a diagnostic test of basic mathematics was developed, covering four areas of knowledge: arithmetic, algebra, geometry and trigonometry, and problem solving, based on the information presented in [14].

The exam questions are shown below:

1. Calculate following the hierarchical order of operations:
$5-2\times3+4^2\div(1+3)=$
2. Simplify:
$\left\{\frac{3}{2}\div\left(\frac{1}{4}+\frac{1}{2}\right)\right\}\times\frac{3}{5}=$
3. Solve for x:
$2(x-3)+5=3(2x+1)-4$
4. Factor completely:
$3x^2-12x-36=$
5. Simplify:
$\frac{x^2-4x+4}{x^2-4}=$
6. A right triangle has legs measuring 3 cm and 4 cm. How long is the hypotenuse?
7. In a right triangle, one of the legs is 2 units and the hypotenuse is 8 units. What is the value of the remaining leg?
8. One number is three times another. If the sum of both is 48, what are the numbers?
9. A rectangle has a perimeter of 50 cm. If the length is 5 cm more than the width, what are its dimensions?

The questions are weighted according to Table 1. A total of 20 points were considered, and a scale of 0 to 10 was used as a basis for grading.

To encourage good performance among students, they were offered extra points or participation points for their first exam in the subject, based on their score on the diagnostic test. To carry out the review, it was considered that all questions should show the procedure or, where appropriate, include the note "I did it mentally." If the procedure was correct or partially correct, but the result was not, part of the value of the question would be taken into account. In addition, the use of notes or calculators was not allowed.

Table 1. *Area and weighting of the questions*.

Item	Mathematics area	Weighting
1	Arithmetic	1
2	Arithmetic	1
3	Algebra	2
4	Algebra	3

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5	Algebra	3
6	Geometry and trigonometry	2
7	Geometry and trigonometry	2
8	Problem solving	3
9	Troubleshooting	3
Total		20

Source: *Own elaboration* (2025).

After developing and applying the instrument, we proceeded to psychometrically validate it, as well as determine the level of difficulty of the items and their discrimination. These indices are presented below.

Psychometric validation of the diagnostic instrument

To ensure the reliability and validity of the diagnostic test, two fundamental psychometric tests were applied. First, Cronbach's alpha coefficient [15], calculated using the formula:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k}\sigma_i^2}{\sigma_{total}^2}\right) \quad \text{Eq. (1)}$$

Where:

α: Cronbach's Alpha coefficient
k: Number of reagents ($k = 9$)
σ_i^2: Variance of item *i*
σ_{total}^2: Variance of the total score

This coefficient measures internal consistency, which estimates the reliability of a measurement instrument composed of multiple items, in this case, the diagnostic instrument. This coefficient has been used to validate diagnostic instruments [5] and quantifies the degree to which the items actually measure students' basic math knowledge. According to [16], this value presents the following possible results:

$\alpha > 0.9$: Excellent
$\alpha = 0.8$: Good
$\alpha = 0.7$: Acceptable
$\alpha = 0.6$: Questionable
$\alpha < 0.6$: Unacceptable

Subsequently, the second psychometric test calculated was the Kaiser-Meyer-Olkin (KMO) index using:

$$KMO = \frac{\sum_{i=1}^{k}\sum_{j=1}^{k} r_{ij}^2}{\sum_{i=1}^{k}\sum_{j=1}^{k} r_{ij}^2 + \sum_{i=1}^{k}\sum_{j=1}^{k} p_{ij}^2} \quad \text{para } i \neq j \quad \text{Eq. (2)}$$

Where:

KMO: Kaiser-Meyer-Olkin index
r_{ij} *:* Simple correlation between item *i* and item *j*
p_{ij} *:* Partial correlation between item *i* and item *j*
k: Number of items ($k = 9$)

This index assesses the degree to which the diagnostic items share a common dimension, i.e., basic math skills. A value close to 1 indicates that the data are highly suitable for identifying underlying constructs, while low values suggest that the items measure unrelated concepts [17]. Multiple studies [18] point to the validity of the index.

Additionally, the difficulty index of correct answers was estimated:

$$D = \frac{X_{aciertos}}{Np} \quad \text{Eq. (3)}$$

Where:
$X_{correct\ answers}$: number of points obtained in the item
N: number of students
P: weighting of the item

This criterion ranges from 0 to 1, with 0 being extremely difficult, because no one obtained a single point, and 1 being extremely easy, because everyone got the item right. This is done in order to verify the difficulty with which students perceive the exam.

Additionally, the discrimination index was determined using the point-biserial correlation, r_{pb},such that:

$$r_{pb} = \frac{\bar{X}_1 - \bar{X}_0}{s_x}\sqrt{pq} \quad \text{Ec.(4)}$$

Where:
r_{pb} : discrimination index
$\bar{X}_1$: Mean total score for those who answered the item correctly
$\bar{X}_0$: Average total score for those who answered the item incorrectly
σ_x : Standard deviation of the total score
p : Proportion of correct answers on the item
q : 1 - p"

The discrimination index quantifies the ability of an item to differentiate between high- and low- tendees. It is calculated by correlating the response to the item with the total test score, where high positive values indicate that the item is effective in identifying different levels of competence [19]. This value ranges from 0 to 1, such that:

0.4-1: Excellent
0.3-0.39: Good
0.2-0.29: Acceptable
0-0.19: Poor
Negative: Defective

A score of 0.4-1 clearly distinguishes between students with good and poor math skills.

For the case study, Excel software tools were used, with a table that included the number of students, semester, score for each item, and total score in the assessment. In the specific case of the discrimination coefficient, the COEF.DE.CORREL function in Excel was used to calculate it.

The following section analyzes the results of the psychometric validation of the instrument and discusses and analyzes the results obtained in the diagnostic test.

DISCUSSION AND ANALYSIS OF RESULTS

The study included a sample of 113 students from various engineering programs: Logistics, Mechatronics, Computer Systems, and Industrial Engineering, from the first to seventh semesters.

Since the study shows the level of mathematics throughout the semesters in engineering, the distribution of students is shown in Figure 1. The percentage of first-semester students is 25%, while the percentage of students in the third to seventh semesters accounts for 75% of the sample.

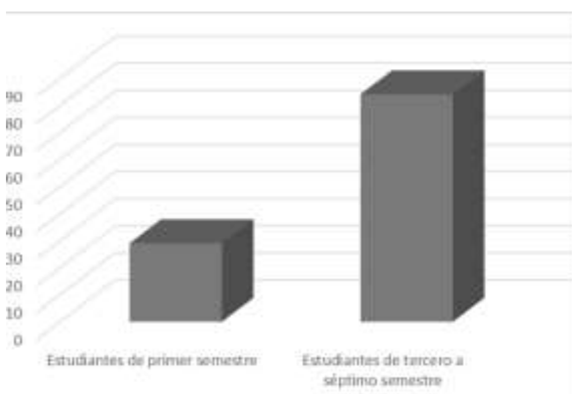

Figure 1. *Distribution of students by semester*. **Source:** *Own elaboration* (2025).

To validate the instrument, Cronbach's alpha was determined. Table 2 shows the values used in accordance with Eq. (1).

Table 2. *Data for determining Cronbach's alpha*.

Concept	Value
Number of items (k)	9
Variance of each item	
Var(P1)	0.223940794
Var(P2)	0.118059363
Var(P3)	0.46988801
Var(P4)	0.793131804
Var(P5)	0.30390007
Var(P6)	0.40691358
Var(P7)	0.322656434
Var(P8)	1.941498943
Var(P9)	1.273748923
Sum of Variances for each item (SVR)	5.85373792
Total variance	17.45798418
Cronbach's alpha (α)	**0.747782614**

Source: *Own elaboration* (2025).

The value obtained for this parameter was $\alpha = 0.74$, which, according to [16], is at an acceptable level to characterize the instrument as valid for effectively measuring students' mathematical knowledge.

Subsequently, the Kaiser-Meyer-Olkin (*KMO*) index was determined according to Eq. (2). The values used for this are shown in Table 3.

Table 3. *Data for determining the KMO*.

Concept	Value
Number of Items	9
Number of students	113
Sum of correlations squared	20.70
Maximum possible	72
Sum of residual squares	0.46
KMO	**0.97**

Source: *Own elaboration* (2025).

The value obtained *was KMO=0.97*, which is quite high according to Kaiser's criteria [17]. This value suggests that the diagnostic instrument has an extremely coherent factorial structure. This high sample adequacy, combined with Cronbach's alpha of 0.74, strongly supports the validity of the measured construct and confirms that the deficiencies identified genuinely reflect the level of students' mathematical knowledge , rather than problems related to the instrument.

Following the psychometric validation of the instrument, the level of difficulty of each item was determined using Eq. (3) as shown in Table 4. Additionally, the level of difficulty by area of mathematics was obtained.

Table 4. *Item difficulty or percentage of correct answers.*

Item	**Difficulty (% of correct answers)**	**Average difficulty by area**
P1	33.18	
P2	14.60	23.89
P3	15.70	
P4	12.09	

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P5	4.86	10.88
P6	19.46	
P7	8.84	14.15
P8	37.61	
P9	19.02	28.31

Source: *Own elaboration* (2025).

The levels of difficulty range from 4.86% (highest difficulty) in the area of algebra, in the topic of factorization, to 37.61% (lowest difficulty) in the topic of problem solving. The area of greatest difficulty is algebra, with an average success rate of only 10.88%, while the area of problem solving presented the least difficulty, with a success rate of 28.31%.

Finally, using Eq. (4) in Excel, the discrimination index, $r_{(pb)}$, was determined for each of the items. The results of these indices are illustrated in Table 5 below.

Table 5. *Discrimination indices, r_{pb}, for each item.*

Item	r_{pb}
P1	0.39
P2	0.50
P3	0.60
P4	0.64
P5	1
P6	0.63
P7	0.60
P8	0.66
P9	0.66

Source: *Own elaboration* (2025).

The discrimination indices range between 0.39 and 1, which according to [19] is within the good to excellent range. This means that in the case of item 5 with r_{pb}=1, there is one student (in the fifth semester) who answered the item correctly and, similarly, the entire exam. This allows us to effectively distinguish the students' level of basic math skills. The combination of the high difficulty of item 5 (4.86%) with its r_{pb}=1 correctly discriminates the validity of the diagnostic instrument to show that there is at least one student with excellent basic math skills.

As shown in this section, we have a validated diagnostic instrument, α = 0.74 and KMO = 0.97, that correctly measures the level of basic math knowledge of engineering students in their first to seventh semesters, because the level of difficulty of the questions is consistent with the discrimination index obtained.

With a validated diagnostic instrument, the results of the grades obtained showed averages on a scale of 0 to 10, see Table 6.

Table 6. *Average grades by semester*.

Students	Grade point average
First semester	1.30
Third semester and beyond	1.94
Total number of students	1.78

Source: *Own elaboration* (2025).

This table shows that the average score for first-semester students is 0.64 points lower than the average for students in subsequent semesters. However, an average score of 1.94 out of 10 is still insufficient for students who are advanced in their engineering studies. The average for the entire sample is 1.78, which highlights critical problems in basic mathematics skills upon entering engineering and in subsequent semesters.

On the other hand, there is the percentage of students who did not answer any questions correctly or left the exam blank. Table 7 shows this distribution. It shows that there were 6 first-semester students and 30 students in later semesters who did not answer a single question correctly, representing 31% of the sample of 113 students.

Table 7. *Distribution of students with a score of zero*.

Students	First semester	Later semesters	Total
Number	6	30	36
Percentage	17	83	31
Percentage per semester	21	36	

Source: *Own elaboration* (2025).

In proportional terms, Figure 2 shows the percentage of zeros recorded among first-semester students and students in subsequent semesters.

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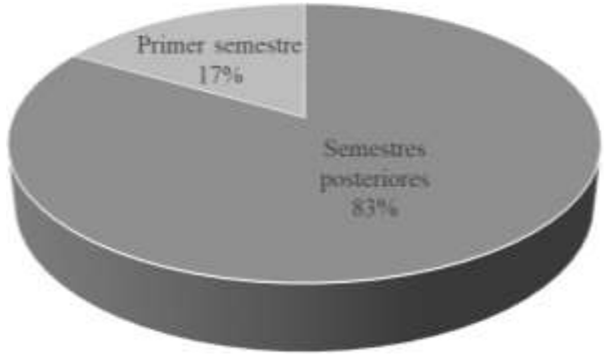

Figure 2. *Percentages of students with zero correct answers*.
Source: *Own elaboration* (2025).

In percentage terms, according to semester, first or subsequent semesters, as shown in Table 7, Figure 3 and Figure 4 show the distribution of these percentages respectively.

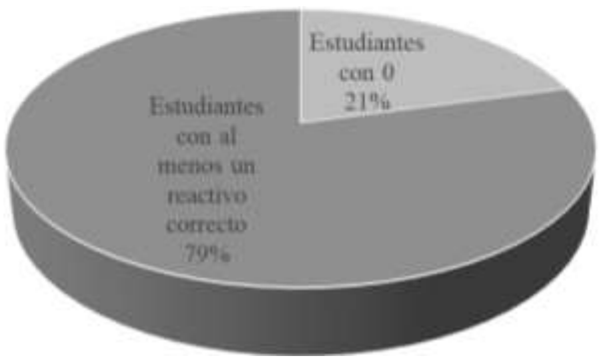

Figure 3. *Percentage of first-semester students with zero correct answers*.
Source: *Own elaboration* (2025).

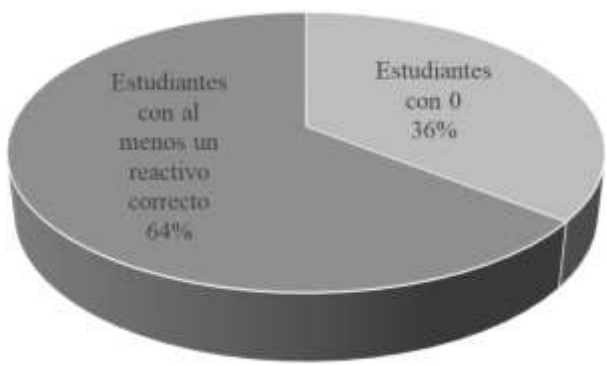

Figure 4. *Percentage of students in subsequent semesters with zero correct answers*.
Source: *Own elaboration* (2025).

It is important to note that, in percentage terms of the sample per semester, advanced semesters recorded a higher proportion of students with zero correct answers (36%) compared to first-semester students (21%). This may mean that basic math skills are completely forgotten over time.

Likewise, it should be noted that the percentage of students whose average score does not constitute 60% of the questions. Table 8 shows the number of students who obtained at least 60% of the correct answers, which is a passing grade in upper secondary education.

Table 8. *Distribution of students with passing grades*.

Students	First semester	Subsequent semesters	Total
Number	0	5	5
Percentage	0	5.9	4.44%
Percentage per semester	0	5.9	

Source: *Own elaboration* (2025).

As can be seen, in the first semester there are no students with a minimum passing grade of 6. In total, the five students who scored above 6 are from later semesters. However, this number represents only 5.9% of students in advanced semesters and only 4.44% of the total 113 students.

According to the average diagnostic test scores, the level of first-semester students (average of 1.30) shows a clear deficiency in basic mathematics at the beginning of their engineering studies. This level, compared to students in later semesters (average of 1.94), does not show a significant improvement over time, because the minimum passing grade at TecNM ( ) is 7.0, and this value is insufficient for understanding more complex topics in the degree program.

In addition, it appears that basic mathematics knowledge is forgotten over time, as a higher proportion of students in later semesters (36%) obtained 0 correct answers compared to 21% of new students. These results show that poor academic performance in basic science subjects stems from a low level of basic mathematics at the beginning and during the first semesters of engineering.

CONCLUSIONS

The results obtained for the validation of the instrument provide solid evidence of its quality. Cronbach's alpha coefficient of 0.74, although within the acceptable range, reflects the heterogeneity in knowledge patterns among students, i.e., not all students have the same specific deficiencies, although they do maintain a low level of knowledge in basic mathematics.

On the other hand, the KMO index of 0.97, considered 'wonderful' according to Kaiser's criteria [17], indicates that the correlation matrix is highly suitable for factor analysis. This suggests that the nine questions in the instrument consistently measure the level of basic mathematics knowledge required for engineering.

This apparent discrepancy with the exceptionally high KMO can be explained by the fragmented nature of mathematical knowledge in the student population. In other words, the instrument is excellent for measuring, but what is measured varies considerably between individuals. The combination of a high KMO and a moderate Alpha corroborates the qualitative findings of the study: while the instrument consistently identifies areas of deficiency (high KMO), students show irregular patterns of correct and incorrect answers (moderate Alpha). This goes hand in hand with the heterogeneity in the level of difficulty in the various areas.

In terms of the level of difficulty and the discrimination coefficient, the former showed that the area of algebra is the most difficult for students (10.88% correct answers) and that the level of discrimination is excellent for demonstrating the students' level of basic math skills.

Regarding the results obtained by the students, the average achieved by first-semester students (1.30) and those in subsequent semesters (1.94) does not show much difference and in both cases shows basic math skills well below the minimum recommended for an engineering degree. In addition to this, the number of students with the minimum passing grade (6.0) is only 4.44% of the total sample, corresponding to students in more advanced semesters. Another interesting result has to do with the percentage of students with no knowledge (zero correct answers), which turned out to be higher in students in advanced semesters compared to first-semester students.

The results confirm the existence of significant deficiencies in basic mathematics among engineering students, which persist throughout the semesters and even worsen in some cases. The excellent factorial adequacy (KMO) together with the acceptable internal consistency (Alpha) suggest that these deficiencies constitute a structural problem that transcends initial preparation and may even worsen as the semesters progress.

This study recommends:

- Implementing remedial programs based on the common cores identified by the high KMO.
- Design differentiated strategies that address the heterogeneity reflected in the moderate Alpha, focusing on areas of greatest difficulty, such as algebra.
- Establishing longitudinal follow-ups throughout the semesters to evaluate the impact of these interventions.

As future work, the diagnosis is intended to be implemented each semester over the next few years to verify a variation in results, that is, to determine a turning point. The purpose of this is to establish whether the level of basic mathematics remains the same, increases, or decreases and, with this, to analyze what factors in basic education could be related.

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