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An Integer Linear Programming Model for Diagnosing Unmastered Mathematical Topics Based on Bloom's Cognitive Domains

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ABSTRACT

This study aims to develop an Integer Linear Programming (ILP)-based mathematical model to identify and map unmastered mathematics topics among senior high school students based on Bloom's cognitive domains, namely Knowledge (C1), Comprehension (C2), and Application (C3). The study employed a quantitative approach using test data obtained from a 48-item instrument covering 16 mathematical subtopics, administered to 147 twelfth-grade students in the Natural Science program. The data were analyzed using LINDO 6.1 software to generate a detailed profile of student mastery across subtopics and cognitive domains. The results indicate that student mastery was relatively higher in the Knowledge (C1) domain, with eight subtopics meeting the mastery criteria. In comparison, six subtopics were achieved in the Comprehension (C2) domain and five subtopics in the Application (C3) domain. Of the total 48 test items, only 19 items (39.6%) were classified as mastered, while 29 items (60.4%) were not mastered. Notably, the Equations and Inequalities (X2) subtopic was not mastered in any of the three cognitive domains, indicating a critical area requiring focused intervention.These findings highlight the need for instructional strategies that emphasize not only factual knowledge but also deeper conceptual understanding and contextual application. The ILP-based model demonstrated its effectiveness as a diagnostic tool by providing a structured and objective identification of students' learning deficiencies. Consequently, the resulting mastery map can serve as a valuable reference for teachers in designing targeted remedial programs. Furthermore, the proposed model has the potential to be replicated in other educational settings as a tool for continuous monitoring and improvement of student learning outcomes.

Keywords: Mathematical Model, Integer Linear Programming, Proficiency Mapping, Cognitive Domains, Bloom's Taxonomy, Senior High School Mathematics

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1. INTRODUCTION

Education serves as the foundation for a nation's development and is a crucial indicator of its civilizational progress (KEMENRISTEKDIKTI, 2020). In this context, the quality of mathematics education at the Senior High School (SMA) level holds strategic importance, not only as a compulsory subject in the national curriculum but also as a vehicle for developing higher-order thinking skills such as logical, analytical, critical, and creative thinking (Anderson, et al., 1994). These skills are essential for confronting 21st-century challenges in science, technology, and the knowledge-based economy.

However, various national and international studies indicate that the mathematics learning outcomes of Indonesian students remain suboptimal. Reports from the Programme for International Student Assessment (PISA) and the Trends in International Mathematics and Science Study (TIMSS) consistently rank Indonesia below the average of participating countries in mathematical and scientific literacy (OECD, 2014; Wulandari, et al., 2015). These results point to a serious deficiency in content mastery, which, if not accurately identified and addressed, could result in low competency levels for future generations.

One strategy to address this issue is through student proficiency mapping. This mapping not only identifies mastered and unmastered topics but also serves as a diagnostic tool to help teachers design more targeted learning strategies (Tambunan, 2016). In educational theory, Bloom's Taxonomy has long been a primary framework for classifying learning objectives based on cognitive domains: Knowledge (C1), Comprehension (C2), and Application (C3) (Bloom, 1956). This classification

enables a deeper analysis of learning achievements, allowing teachers to move beyond final scores and understand the depth of students' conceptual mastery.

In the context of diagnosing students' cognitive abilities, several empirical studies have emphasized the importance of analyzing prerequisite knowledge, learning duration, and task completion behavior in understanding students' mathematical achievement. Research also shows that students' success in solving mathematical problems is strongly influenced by their prior knowledge and cognitive readiness (Magdalena, et al., 2025; Manurung, et al., 2023). Moreover, higher-order thinking skills (HOTS), which correspond to higher levels in Bloom's taxonomy, play a crucial role in determining students' ability to analyze, evaluate, and apply mathematical concepts in various contexts. Learning approaches that emphasize HOTS and cognitive engagement have been shown to significantly improve students' conceptual understanding and problem-solving abilities (Subaini, et al., 2022; Magdalena, et al., 2025).

Despite these developments, a significant challenge in practice lies in transforming test data into accurate and actionable diagnostic information. Teachers often focus solely on final scores without conducting an in-depth analysis of error patterns or students' conceptual weaknesses (Dantzig, et al., 1997). As a result, the identification of unmastered topics is often incomplete and less effective for guiding instructional decisions. Therefore, a data-driven approach capable of processing information quantitatively and systematically is required.

In this regard, mathematical optimization provides a promising solution. One relevant approach is the use of integer programming models, which have proven effective in solving various complex problems in education, such as student project allocation (Anwar, et al., 2003), course scheduling (Daskalaki, et al., 2004), and test item evaluation based on cognitive domains (Junoh, et al., 2011; Sitepu, et al., 2017). Furthermore, previous studies have demonstrated that integer optimization models are flexible and powerful tools for solving complex decision-making problems, including educational planning and resource allocation (Sitepu, et al., 2017; Irvan, et al., 2008). Foundational works on integer stochastic programming and optimization modeling also provide strong theoretical support for the development of ILP-based diagnostic models, enabling structured and objective analysis of complex educational data under multiple variables and constraints (Irvan, et al., 2025; Azis, et al., 2026).

At the same time, developments in educational technology further highlight the importance of data-driven diagnostic approaches. Concepts such as Intelligent Tutoring Systems (ITS) and learning analytics have utilized student proficiency mapping to provide adaptive learning and content personalization (Siemens, 2013). Cognitive Diagnosis Models (CDM) are also widely used to identify specific student weaknesses in particular topics (Minn, 2021; Shen, et al., 2023). However, these approaches are generally probabilistic and may have limitations in incorporating optimization constraints simultaneously, indicating the need for alternative methods that can produce more optimal and interpretable diagnostic results.

Recent research further underscores the urgency of implementing accurate diagnostic mapping. For instance, a 2025 study reported that only 34% of students could demonstrate adequate visual representations, and only 15% were able to perform mathematical interpretations in linear programming topics (Muharani, et al., 2025). This finding indicates that student weaknesses are not uniformly distributed but are concentrated in specific subtopics requiring targeted intervention. Other studies also highlight that instructional strategies such as Problem-Based Learning (PBL) and mind mapping can improve students' higher-order thinking and problem-solving abilities (Firdaus, et al., 2023; Nature, 2025; Guo, et al., 2024), while the integration of generative artificial intelligence has shown potential in enhancing learning outcomes and self-efficacy. Nevertheless, these approaches primarily focus on instructional improvement rather than systematically identifying unmastered topics through optimization-based analysis.

Against this backdrop, this research develops an Integer Linear Programming (ILP)-based mathematical model to diagnose and map unmastered mathematics topics among senior high school students based on cognitive domains (C1, C2, C3). The research data, comprising 48 test items across 16 subtopics, are analyzed using LINDO 6.1 software to generate an optimal and detailed student proficiency map. The findings are expected to provide a strong analytical foundation for teachers and

educational policymakers in designing more effective remedial and enrichment programs based on valid and data-driven decision-making.

2. RESEARCH METHOD

A. Research Design

This study employs a quantitative approach with an integer programming-based mathematical modeling method. This approach was selected for its ability to systematically process student test data and provide an accurate cognitive proficiency map (Tambunan, 2016; Dantzig, et al., 1997). The research is descriptive-analytical in nature, aiming to map the unmastered mathematics topics among senior high school students across three cognitive domains: Knowledge (C1), Comprehension (C2), and Application (C3) (Bloom, 1956).

B. Subjects and Research Location

The subjects of this study were 147 twelfth-grade students from the Natural Science program at a public senior high school in Medan City during the 2024/2025 academic year. The subjects were selected using a purposive sampling technique, with the consideration that these students had already studied all the tested topics. The research was conducted within the school environment over a two-week period, encompassing the testing and data processing stages.

C. Research Instrument

The instrument used was an objective test consisting of 48 items, developed based on 16 senior high school mathematics subtopics and aligned with the national examination framework (KEMENDIKBUD, 2024; BSNP, 2024). Each subtopic was represented by three test items, each corresponding to the C1, C2, and C3 cognitive domains of Bloom's Taxonomy (Anderson, 1994). The test items were validated by three mathematics education experts to ensure content validity, while reliability was tested using Cronbach's Alpha coefficient (Nunnally, et al., 1994).

D. Research Procedure

The research was carried out in three main stages:

a. Preparation Stage
   1. Determining the topics and subtopics to be tested based on the curriculum and an analysis of core competencies.
   2. Developing and validating test items according to the cognitive domains.
   3. Preparing a mapping table format linking subtopics to cognitive domains.

b. Data Collection Stage
   1. Administering a written test to the students with a duration of 120 minutes.
   2. Collecting student answer sheets and performing scoring.
   3. Calculating the number of students who answered each test item correctly.

c. Data Analysis Stage with the Mathematical Model

   This stage aimed to identify and map unmastered mathematics topics systematically using an Integer Linear Programming (ILP)-based mathematical model. The analysis was conducted through the following steps:

   1. Model Formulation

      The mathematical model was formulated by adapting the notation from (Anwar, et al., 2003). The objective function was to maximize the number of test items mastered by students based on subtopic and cognitive domain. The model was formulated as follows:

$$\text{Maximize } Z = \sum_{i=1}^{p} \sum_{j=1}^{q} X_{ij}$$

      Subject to:

$$\sum_{j=1}^{q} X_{ij} \leq 1, \quad \forall i = 1, 2, ..., p$$

$$\sum_{i=1}^{p} X_{ij} \leq b_j, \quad \forall j = 1, 2, ..., q$$

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$$X_{ij} \in \{0,1\}$$

Keterangan:
Z = Objective function (maximum number of mastered test items)
X_{ij} = Binary variable (1 if the item for Subtopic-I and Domain-j is mastered, 0 otherwise)
p = Number of subtopics (16 subtopics)
q = Number of cognitive domains (3 domains: C1, C2, C3)
b_j = Maximum limit of items for domain-j according to the test distribution.

2. Mastery Criteria
   A test item was declared "mastered" if the percentage of students answering it correctly met or exceeded the predetermined Minimum Completion Criteria. If it did not meet this threshold, the item was categorized as "not mastered."
3. Model Optimization
   The ILP model was solved using LINDO 6.1 software to obtain the optimal solution for the Z objective function. This solution indicates the combination of test items and cognitive domains that students have truly mastered.
4. Proficiency Mapping
   The model output, comprising lists of mastered and unmastered items, was mapped onto a cognitive domain proficiency map for each subtopic. The data were visualized in tables and graphs to facilitate the identification of specific student weakness areas by teachers.
5. Data Analysis Technique
   Data were analyzed using LINDO 6.1 software to solve the ILP model. The model output consisted of lists of mastered and unmastered test items. These results were then visualized in a proficiency map showing the distribution of mastery for each cognitive domain across all subtopics.
6. Validity and Reliability of Analysis
   To ensure the validity of the findings:
   a. Construct validity was established through the alignment of the model with the research objectives and Bloom's Taxonomy theory (Anderson, 1994).
   b. The reliability of the analysis was strengthened by re-testing the model on a subset of data (cross-validation).
   c. Data triangulation was performed by comparing the model's results with evaluations from the subject teacher.

3. RESULTS AND DISCUSSION

A. Results

Based on the analysis of test results from 147 twelfth-grade Natural Science students using an Integer Linear Programming (ILP) model in LINDO 6.1 software, a mathematics topic mastery map was obtained, covering 16 subtopics and three cognitive domains (C1 = Knowledge, C2 = Comprehension, C3 = Application).

The optimization results indicate that:

a. 19 test items (39.6%) were declared mastered by students (decision variable value $X_{ij} = 1$)
b. 29 test items (60.4%) were declared not mastered by students (decision variable value $X_{ij} = 0$)

The distribution of mastery per cognitive domain is:

a. a. C1 (Knowledge): 8 subtopics.
b. b. C2 (Comprehension): 6 subtopics.
c. c. C3 (Application): 5 subtopics.

Table 1. Student Mathematics Topic Mastery Map Based on Cognitive Domains

No	Subtopic	Code	C1 (Knowledge)	C2 (Comprehension)	C3 (Application)	Mastery Description
1	Exponents and	X1	1	0	1	Partially

	Logarithms					Mastered (C1 & C3)
2	Equations and Inequalities	X2	0	0	0	Not Mastered
3	Linear Programming	X3	1	1	0	Partially Mastered (C1 & C2)
4	Quadratic Equations & Functions	X4	1	0	0	Partially Mastered (C1)
5	Trigonometry	X5	0	1	0	Partially Mastered (C2)
6	Mathematical Logic	X6	0	1	0	Partially Mastered (C2)
7	Statistics and Probability	X7	0	1	0	Partially Mastered (C2)
8	Polynomials	X8	0	0	1	Partially Mastered (C3)
9	Inverse & Composite Functions	X9	0	0	1	Partially Mastered (C3)
10	Sequences and Series	X10	1	0	0	Partially Mastered (C1)
11	Matrices	X11	1	0	1	Partially Mastered (C1 & C3)
12	Vectors	X12	1	0	0	Partially Mastered (C1)
13	Transformations	X13	0	1	0	Partially Mastered (C2)
14	Three-Dimensional Geometry	X14	1	1	0	Partially Mastered (C1 & C2)
15	Limits	X15	0	0	1	Partially Mastered (C3)
16	Derivatives and Integrals	X16	1	0	0	Partially Mastered (C1)

Student mastery was generally higher in the Knowledge (C1) domain compared to the other two domains. Several subtopics showed mastery in more than one domain, such as Exponents and Logarithms (X1), Matrices (X11), and Three-Dimensional Geometry (X14). Conversely, the Equations and Inequalities (X2) subtopic was not mastered at all across all three cognitive domains, indicating a need for priority intervention. Furthermore, some subtopics were mastered in only one specific domain, for instance, Trigonometry (X5) only in C2, Limits (X15) only in C3, and Transformations (X13) only in C2. This signifies the existence of specific competency gaps at the level of conceptual comprehension and application.

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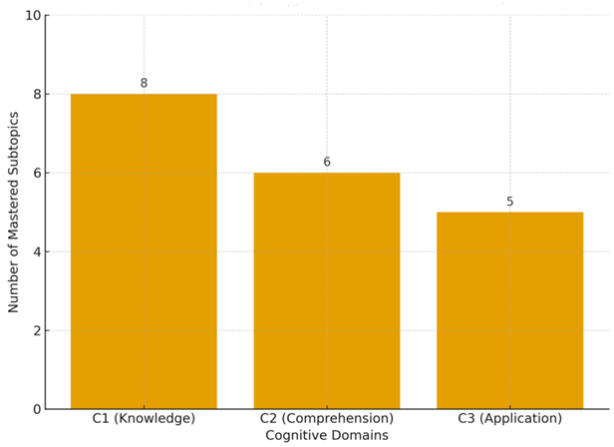


Fig. 1. Distribution of Mastery per Cognitive Domain

Figure 1 shows that the number of subtopics mastered by students decreases from C1 (Knowledge) to C2 (Comprehension) and is lowest in C3 (Application). This indicates that instruction has been more successful at the level of mastering basic facts and procedures compared to the ability to comprehend and apply concepts.

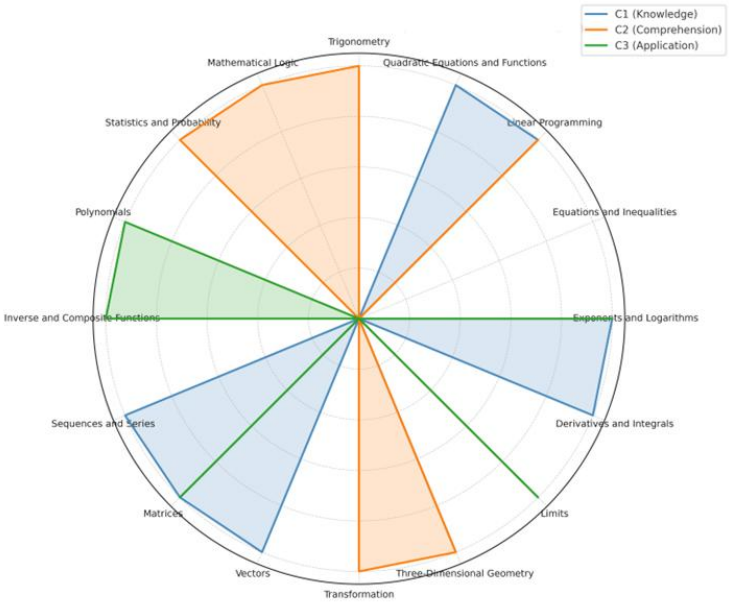


Fig. 2. Mathematics Topic Mastery Map per Subtopic and Cognitive Domain

Figure 2 provides a visualization of student mastery patterns for each subtopic across all three cognitive domains simultaneously. It is evident that several subtopics have a balanced mastery distribution across two domains, while most others excel in only one specific domain. This graph reinforces the identified weaknesses in the Comprehension and Application domains that need to be the focus of improvement.

B. Discussion

The results of this study indicate that senior high school students' mastery of mathematics topics across the three cognitive domains, namely Knowledge (C1), Comprehension (C2), and Application (C3), remains uneven. Among these domains, Knowledge (C1) is relatively better mastered, with eight subtopics meeting the established mastery criteria. This finding is consistent with previous studies suggesting that mathematics instruction in schools tends to emphasize the memorization of

facts, definitions, and procedural knowledge rather than deeper conceptual understanding (Anderson, 1994; Bloom, 1956; Firdaus, 2023).

However, despite the relatively satisfactory performance in C1, the lower achievement observed in the Comprehension (C2) and Application (C3) domains indicates that students still face significant challenges in interpreting mathematical concepts and applying them in unfamiliar contexts (OECD, 2012; Manurung, 2023). This gap reflects a lack of depth in conceptual understanding, which is essential for meaningful learning and problem-solving.

These findings are further supported by prior research indicating that students' mathematical achievement is strongly influenced by prerequisite knowledge and learning duration, both of which are critical for mastering higher cognitive domains. Students with insufficient foundational understanding are more likely to encounter difficulties when dealing with tasks that require comprehension and application skills (Magdalena, et al., 2025; Manurung, et al., 2023).

The disparity in mastery is particularly evident in specific subtopics. For instance, Equations and Inequalities (X2) were not mastered across all three cognitive domains, indicating fundamental conceptual and procedural difficulties. This result aligns with study (Muharani, et al., 2025), which reported low levels of student performance in visual representation and mathematical interpretation in linear programming topics, areas closely related to equations and inequalities. Furthermore, the presence of subtopics mastered only in a single domain, such as Limits (X15), which is mastered solely in C3, suggests that some students are able to solve application-based problems without a solid understanding of the underlying concepts. This phenomenon may lead to superficial learning and potential misconceptions in the long term (Guo, et al., 2024).

From a pedagogical perspective, the low achievement in the Comprehension and Application domains may be attributed to instructional practices that insufficiently emphasize conceptual exploration and contextual application. The PISA report (OECD, 2012) confirms that Indonesian students tend to struggle with problems requiring higher-order reasoning and non-routine problem-solving. Therefore, instructional strategies that promote knowledge construction and active cognitive engagement are essential. Approaches such as Problem-Based Learning (PBL) (Firdaus, 2023) and the use of visual tools like mind mapping (Guo, et al., 2024; KEMENDIKBUD; 2024) have been shown to support the development of higher-order thinking skills (HOTS).

This condition is also consistent with studies highlighting the importance of critical thinking and HOTS in mathematics education. Students exposed to problem-based and HOTS-oriented learning environments tend to demonstrate stronger analytical and evaluative abilities, which are essential for mastering higher levels of Bloom's taxonomy (Subaini, et al., 2022; Magdalena, et al., 2025).

In addition to pedagogical implications, this study demonstrates that the application of an Integer Linear Programming (ILP)-based mathematical model is effective in quantitatively mapping students' learning deficiencies. Compared to conventional evaluation methods, this model provides a more detailed representation of the relationships between subtopics and cognitive domains. These findings are in line with previous research (Tambunan, 2016; Anwar, et al., 2003; Junoh, et al., 2012), which emphasizes the role of quantitative modeling in supporting data-driven decision-making in education, particularly in identifying learning gaps and determining remedial priorities.

From a methodological standpoint, the use of ILP in this study is supported by optimization-based research demonstrating that mathematical programming models are capable of handling complex datasets and generating optimal solutions for decision-making problems. Such models have been widely applied in scheduling, allocation, and planning contexts, and their application in diagnosing students' learning gaps represents a significant extension in the field of educational research (Sitepu, et al., 2017; Irvan, et al., 2008; Irvan, et al., 2025; Azis, et al., 2026).

Practically, the resulting mastery map provides valuable insights for teachers in designing targeted remedial interventions. For example, for subtopics with low achievement in C2, instructional efforts can focus on conceptual discussions, guided explanations, and interpretation exercises. Meanwhile, for weaknesses in C3, students should be provided with more application-oriented tasks, contextual problems, and case-based learning activities to strengthen their problem-solving abilities.

Therefore, the findings of this study not only reveal students' competency gaps but also contribute methodologically by offering a replicable ILP-based diagnostic model. This model can

serve as a sustainable tool for monitoring students' mastery of mathematical topics over time, while also providing a robust foundation for developing more effective and data-driven instructional strategies.

4. CONCLUSION

This study developed and applied an Integer Linear Programming (ILP)-based mathematical model to identify and map unmastered mathematics topics among senior high school students based on Bloom's cognitive domains, namely Knowledge (C1), Comprehension (C2), and Application (C3). The model was implemented using data from a 48-item test covering 16 subtopics, administered to 147 twelfth-grade Natural Science students, and analyzed using LINDO 6.1 software to generate a measurable mastery profile.

The results indicate that students' mastery was highest in the Knowledge (C1) domain, with eight subtopics meeting the mastery criteria. In contrast, only six subtopics were mastered in the Comprehension (C2) domain and five subtopics in the Application (C3) domain. Overall, 19 test items (39.6%) were classified as mastered, while the remaining 29 items (60.4%) were not mastered. Notably, the Equations and Inequalities (X2) subtopic was not mastered in any of the three domains, indicating a critical area requiring targeted intervention.

The findings further suggest that the disparity in mastery across cognitive domains reflects the need to shift instructional practices from an emphasis on memorization and procedural skills toward strengthening conceptual understanding and contextual application. The ILP-based model demonstrated its effectiveness in producing a detailed and structured mapping of students' learning deficiencies, thereby supporting more precise identification of problematic subtopics.

Therefore, this study contributes both practically and methodologically. From a practical perspective, the generated mastery map can assist teachers in prioritizing topics and cognitive domains that require reinforcement. From a methodological perspective, the proposed ILP-based model offers a systematic and replicable approach that can be applied in other educational settings for continuous monitoring and improvement of students' learning outcomes.

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