Transforming Geometry Learning Through A GeoGebra-Assisted Boom Crane Path Modeling Task for 21st-Century Competencies

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ABSTRACT

This study presents an innovative integration of curriculum design and digital pedagogy through the development and testing of a mathematical modeling task aimed at transforming geometry learning in the digital era. Building on an initial study conducted in May 2025 that mapped students' basic modeling abilities in a senior high school in Bandung, significant weaknesses were identified in the stages of interpreting, validating, and evaluating models. Based on these findings, this research developed a mathematical modeling task grounded in the engineering phenomenon of boom crane motion, representing an authentic trajectory as a context for geometry learning, with GeoGebra utilized as a dynamic exploration tool. The task follows a complete modeling cycle designed to develop the full spectrum of Bloom's Taxonomy. The study employed a mixed-method approach, including expert design validation and field testing. The field trial involved high school students to examine the task's validity, comprehensibility, and effectiveness. The results indicate that the designed task has a high level of validity and is effective in improving students' ability to understand context, formulate models, develop spatial reasoning, and enhance higher-order thinking skills (HOTS). Weaknesses remain in the stages of mathematical solving and model evaluation. These findings demonstrate that integrating engineering contexts, modeling, and digital technology can strengthen the relevance and competence of 21st-century geometry learning.

Keywords: *curriculum innovation, GeoGebra, geometry learning, mathematical modeling*

1. INTRODUCTION

Mathematics education in the 21st century requires higher-order thinking skills (HOTS) and 4C skills integrated with digital literacy. However, instructional practices in Indonesia are still dominated by LOTS-oriented procedural approaches. Findings from PISA 2022 indicate a decline in Indonesian students' performance in mathematics, particularly in the aspects of contextual problem-solving and spatial reasoning (OECD, 2022; 2023). Countries such as Germany, Australia, Singapore, and China have responded to this global trend by explicitly integrating mathematical modeling into their curricula (Lee & Ng, 2015), thus underscoring the urgency of a similar pedagogical transformation in Indonesia.

In the realm of geometry, challenges arise as students tend to perceive the material as a collection of formulas rather than as representations of real-world phenomena. Research by Greefrath and Siller (2018) indicates that the gap between the abstract world and concrete contexts is at the root of students' low spatial and analytical abilities. The mathematical modeling approach offers a solution by engaging students in the process of identifying problems, simplifying, solving, and interpreting models (Blum & Borromeo Ferri, 2009; GAIMME, 2016). This approach affirms mathematics as a meaningful tool for thinking, not merely as algorithms.

Engineering contexts offer opportunities to present more authentic modeling experiences. Research by Frassia and Serpe (2017) shows that engineering objects can enhance students' reflective and spatial abilities in modeling tasks. The mechanical phenomenon of a boom crane, which involves rotation, elevation angles, and load trajectory, serves as an ideal context for GeoGebra-assisted geometry modeling tasks. Prior research on the effectiveness of GeoGebra in learning reinforces the idea of its integration in this study. Therefore, the development of a boom crane-based modeling task is expected to strengthen students' spatial thinking, visual representation, and mathematical creativity through the synergistic integration of mathematical modeling, digital pedagogy, and engineering contexts, as a relevant 21st-century learning practice.

Mathematical Modelling in Mathematics Education

Mathematical modeling is a systematic process of connecting real-world situations with mathematical representations through the stages of understanding, simplifying, formulating, solving, and validating within the original context (Blum & Borromeo Ferri, 2009; GAIMME, 2016). This process requires students to use mathematics not merely as a set of rules, but as a tool for thinking in solving ill-defined problems.

The modeling cycle, utilizing a diagnostic approach model from a cognitive perspective, serves as the foundation for a comprehensive understanding of mathematical modeling. In this modeling study, the modeling cycle/stages to be adopted are those proposed by Galbraith & Holton (2018). The mathematical modeling stages used in this study are as follows.

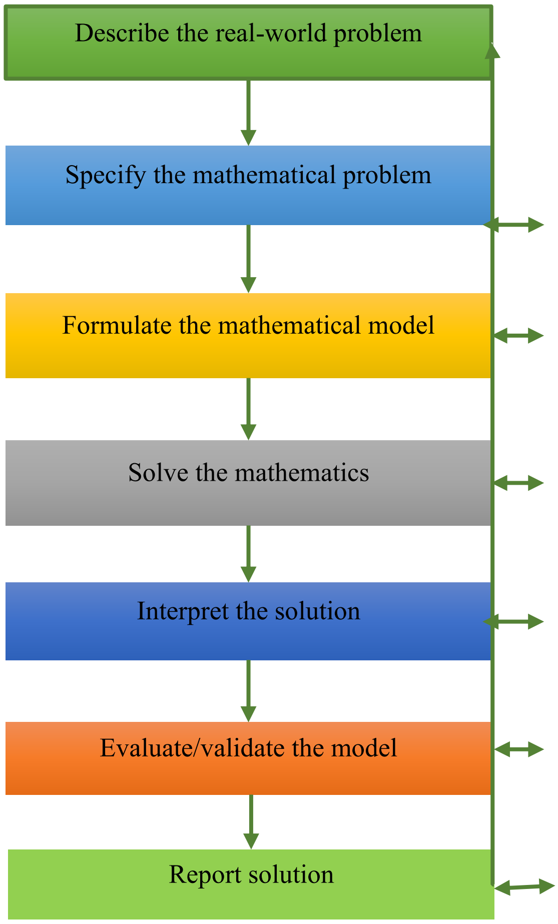

Figure 1. The Galbraith-Holton (2018) Modeling Framework

The research problem is formulated based on a triple deficit in mathematics education in Indonesia, namely: (1) a geometry abstraction deficit, wherein students are confined to symbolic procedures without developing visual–spatial understanding rooted in real-world contexts; (2) a digital exploration deficit, where GeoGebra is more frequently utilized as an illustrative tool rather than as a conceptual exploration medium that supports HOTS; and (3) a 21st-century skills gap, as reflected by the low performance in contextual problem-solving in PISA (OECD, 2022; 2023). Preliminary research findings (May 2025) indicate significant weaknesses in the model interpretation, validation, and evaluation stages, thus necessitating an intervention that enables students to take problem ownership and use GeoGebra as an environment for model construction and reflection in greater depth.

This study develops a modeling task based on the authentic, contextual, and open-ended phenomenon of a Boom Crane's end trajectory. Using GeoGebra as a digital cognitive space for construction, simulation, and reflection, this task targets the activation of analyzing, evaluating, and creating abilities. Pedagogically, this intervention shifts learning towards student-centered learning, strengthening HOTS as well as 21st-century competencies such as collaboration and communication. Its success is evaluated through the quality of the models and changes in students' thinking processes, based on a modeling rubric and digital HOTS indicators.

This study aims to develop and implement a mathematical modeling task based on the Boom Crane phenomenon in GeoGebra-assisted geometry learning. In addition to evaluating its effectiveness in enhancing students' critical thinking, spatial, and collaborative abilities, this study also analyzes the modeling process that occurs during discussions and task completion. Thus, the study not only evaluates the final learning outcomes but also maps students' thinking dynamics, interactions, and mathematical representations as a reflection of 21st-century contextual learning.

2. METHODOLOGY

2.1 Research Design

This study adopts a qualitative-descriptive approach within the framework of Design-Based Research (DBR) to develop and test a prototype mathematical modeling task based on the boom crane engineering phenomenon. It utilized an iterative design cycle that included design, limited implementation, observation, and reflection (McKenney & Reeves, 2019). Data were collected through observation, interviews, and analysis of student work to ensure the design's validity and practicality, as well as to provide insights into how students construct and validate mathematical models within an authentic modeling context. Qualitative data were analyzed using a descriptive thematic analysis focusing on students' modeling processes across the seven stages of the Galbraith-Holton modeling cycle.

2.2. Participants of the Study

The subjects of this study were grade XI science (MIPA) students from Al-Azhar Syifa Budi Parahyangan High School, West Java, during the 2025/2026 academic year. Participants were selected using purposive sampling, considering variations in academic ability and active engagement in project-based learning. A total of 26 students participated, who were divided into 8 small groups to facilitate collaborative discussions during the modeling activities. Permission to conduct the study was obtained from the school, and students' participation was voluntary with all data anonymized for research purposes.

2.3 Research Instruments

The instruments used in this study consist of four components:

1. Task development instrument (task validation sheet)
2. Observation sheet of the modeling processes

3. Assessment rubric for students modeling products
4. Assessment rubric for HOTS and 4C

All instruments were reviewed by mathematics education experts to establish content validity prior to classroom implementation.

2.4 Data Analysis Techniques

Data analysis was conducted using a qualitative-dominant approach, supported by descriptive quantitative analysis according to the type of instruments employed.

1. Task Validation Sheet

   Expert validation data were analyzed quantitatively by calculating the average score for each aspect (content, construction, digital components, and practicality).
2. Observation Sheet of the Modeling Processes

   Data from observations of the seven modelling stages (Galbraith–Holton, 2018) were analyzed qualitatively through reduction, categorization, and thematic analysis within the DBR evaluation and reflection phase.
3. Modelling Product Assessment Rubric

   The data were analyzed using descriptive quantitative methods, while the qualitative interpretation focused on describing the characteristics of students' products, including accuracy, digital representation, and creativity.
4. HOTS and 4C Rubric

   The data were assessed quantitatively by calculating mean scores and analyzed qualitatively to interpret observable behaviors that reflect the development of HOTS and 21st-century skills.

Triangulation across observation data, student products, and rubric scores was applied to strengthen the credibility of the findings.

3. RESULTS AND DISCUSSION

Based on preliminary discussions with teachers at the observation school, mathematical modeling is still rarely implemented. Numerous factors must be considered, such as time constraints, student preparedness, and teacher readiness in preparing for modeling instruction. Nevertheless, the implementation of mathematical modeling has often been advocated for and is frequently discussed at the teacher deliberation forum (MGMP) level. Awareness of the importance of modeling instruction is significant; however, tangible support from relevant stakeholders is required for it to be implemented effectively.

Teaching materials pose a primary challenge, alongside teachers' modeling competencies. The design of modeling tasks cannot be arbitrary, as it must fulfill key criteria, such as relevance to students' real-life contexts and an appropriate level of problem difficulty to build students' modeling competencies. Proceeding from this fact, the researcher decided to develop a modeling task related to geometry material, utilizing GeoGebra in the implementation of the modeling learning process.

3.1. Modeling Task Validity

Validation data were collected from the task validation results during the expert review stage. The validation assessed the content validity, task construction, digital integration, and implementation practicality of the boom crane mathematical modeling task prior to its classroom implementation. The validators consisted of expert lecturers in mathematics education and experienced senior high school teachers. On the validation sheet, the assessment scores provided were on a scale of 1 to 5. After the validation scores were obtained, they were categorized to determine the validity of the instructional material. The following are the validity categories based on the scores obtained, according to the guidelines in Sugiono (2014).

Table 1. Modeling Task Validation Results

No	Aspect	Average	Category
1	Content relevance	85%	Very Valid
2	Task construction	90%	Very Valid
3	Digital integration	80%	Valid
4	Implementation practically	75%	Valid
	Overall	**83%**	**Very Valid**

3.2. Observation Results of the Students' Modeling Process

The following is a recapitulation of the observation results of the students' modeling activities, observed during the modeling process in the classroom. Each stage was developed into two indicators, which served as a guide for analyzing the attainment of each stage.

Table 2. Observation Results of the Student Modeling Process

No	Aspect	Average
1	Describing/Understanding	90,83%
2	Specifing/Simplifyng	78,83%
3	Formulating/Mathematising	73,08%
4	Solving	59,62%
5	Interpreting	61,54%
6	Evaluating/Validating	55,77%
7	Reporting	73,04%
	Overall	**70.33%**

The observation results indicate that the students' modeling ability is in the 'good' category, with an attainment of 70.33%. This is characterized by high performance in understanding the context of the boom crane phenomenon, identifying variables, and formulating the mathematical problem. This finding confirms that students have mastered the fundamentals of modeling, but still require reinforcement in the analysis and evaluation aspects so that the resulting models are more comprehensive and realistic.

During the modeling instruction, students were divided into heterogeneous ability groups, as recommended by school modeling experts. Although mathematics is often perceived as an individual activity due to the culture of individual assessment in schools, mathematical modeling is essentially teamwork. The problems encountered in modeling are generally complex and unstructured, thus requiring a collaborative approach. This aligns with the views of COMAP & SIAM (2019) and Kandemir & Erylmaz (2025), who assert that group work is highly recommended as it enables students to overcome modeling challenges more creatively and in a coordinated manner.

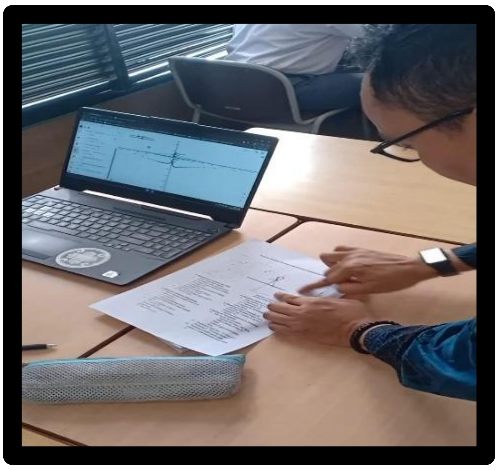

Figure 2. Providing scaffolding during discussion on the use of GeoGebra

Blum and Ferri (2009) emphasize the important role of the teacher in mathematical modeling instruction, which is to maintain a balance between providing support and fostering student autonomy. Effective teaching requires the teacher to provide necessary guidance while allowing students the space to develop their own abilities. This aligns with the Montessori principle, "Help me to do it myself." This balance becomes crucial when students face complex modeling tasks, as they require a combination of appropriate direction and the opportunity to think and solve problems independently.

Observations showed that assistance through GeoGebra illustrations helped students understand the solution steps and visualize the boom crane's movement; however, this support still needs to be limited so that the discovery and knowledge construction processes occur independently. GeoGebra, as a Dynamic Geometry Software (DGS), enables the simultaneous integration of algebraic, geometric, graphical, and numerical representations (Greefrath & Siller, 2018), allowing students to manipulate parameters and observe their impact directly. Previous research indicates that the use of GeoGebra can enhance representational ability, spatial reasoning, and learning interest (Pasco & Roble, 2020; Rabi et al., 2021). In the context of modeling, GeoGebra functions as a digital environment that supports the mathematization and validation processes through visualization and interactive simulation. It thus serves as an effective medium for exploratory, reflective, and constructivist learning that aligns with the principles of student-centered learning.

3.3. Assessment Results of Student Modeling Tasks

The assessment rubric for the modeling task in this study is based on the modeling assessment rubric designed by Garfunkel & Montgomery (2019) in GAIMME, which evaluates all criteria across the 7 stages of mathematical modeling. The following is a recapitulation of the assessment results for the boom crane trajectory modeling task in this study.

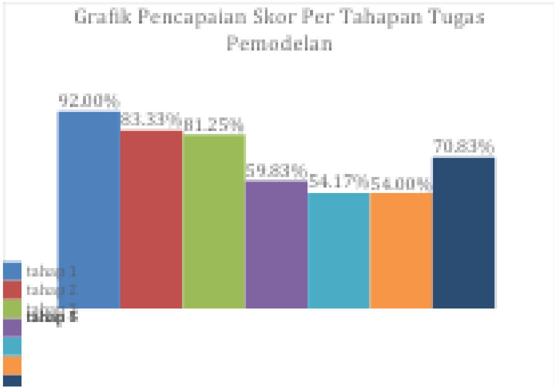

Figure 3. Scores per Modeling Task Stage

The graph of score attainment by modeling stage shows a pattern that is highly consistent with the results of the in-class process observations. The initial stages, such as Describe and Specify, obtained the highest scores, confirming that students possessed a strong understanding and were capable of accurately identifying important variables. This finding aligns with Borromeo Ferri (2018), who stated that students are generally stronger in the initial phases of modeling, which involve understanding the context and simplifying real-world situations. The Formulate stage also showed good mathematical representation ability, consistent with the research by Kaiser & Sriraman (2006), which emphasized that the ability to establish relationships between variables is a crucial foundation in the transition from the context to the mathematical mode.

Conversely, the declining scores in the Solve, Interpret, and Evaluate stages reaffirm the challenges previously identified during in-class observations. In these stages, students often experienced difficulties in performing advanced calculations, interpreting simulation results, and evaluating the model's suitability. This pattern is consistent with the research by Maaß (2010), which found that students' abilities in the intermediate and final modeling stages are often weaker, as they necessitate higher-order mathematical reasoning and critical reflection.

The low attainment in the evaluation stage supports the findings of Ikeda & Stephens (2017) that students tend to accept model results without checking their assumptions and validity. Meanwhile, the relatively high score in the Report stage indicates that students' mathematical communication skills have developed well, as affirmed by Hoyles & Noss (2015) that technology-based environments like GeoGebra can enhance the quality of mathematical representation and communication.

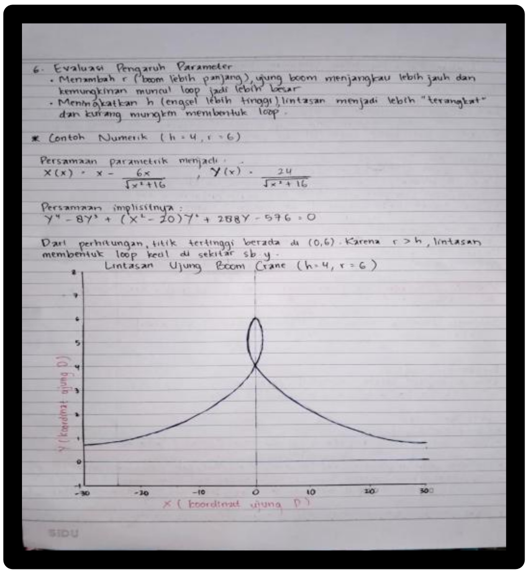

Figure 4. Sample of Student Modeling Task Answers

The correspondence between the modeling task results and the process observation results reveals a consistent pattern: students excelled in the conceptual and representational stages (Describe, Specify, Formulate), but required reinforcement in the analytical and reflective stages (Solve, Interpret, Evaluate). This consistency reinforces Kaiser's (2017) conclusion that modeling success relies heavily on students' ability to integrate mathematical procedures with contextual reasoning—two aspects that often develop unevenly. Thus, the findings of this study not only demonstrate student attainment but also affirm the need for learning interventions that are more directed toward strengthening the analytical, evaluative, and reflective processes in mathematical modeling.

3.4. Development of HOTS Skills and 21st-century Competencies (4C)

This rubric was used to assess students' higher-order thinking skills (HOTS), spatial abilities, and collaboration and communication skills during and after the modeling activities. The following is a recapitulation of the results from this study.

Table 3. Observation Results of Students' HOTS Skills and 4C Competencies

No	Aspect	Average
1	Critical thinking	71,15%
2	Creativity	73,08%
3	Spatial reasoning	67,31%
4	Collaboration	84,62%
5	Communication	82,69%
	Overall	**75,77%**

The HOTS and 4C assessment results indicate that students' Critical Thinking ability is in the 'good' category (71.15%), although the aspects of assumption evaluation and model validation still require reinforcement. This aligns with the findings of Ikeda & Stephens (2017), who highlighted weaknesses in re-testing and variable analysis in modeling. Creativity (73.08%) is also categorized as good, evident from the variety of strategies and model representations constructed by the students, which is in line with Borromeo Ferri (2018) and Hoyles & Noss (2015) regarding the role of technology in facilitating creative exploration. Meanwhile, Spatial Reasoning (67.31%) is in the 'moderate' category, indicating that students still experienced difficulties with complex spatial representations.

In the aspect of collaboration, students demonstrated excellent performance (84.62%), supporting the findings of Kemple et al. (2016) that structured group work enhances understanding and mathematical arguments. Communication was also high (82.69%), evident from the clarity of the presentations and visual representations delivered, consistent with the findings of Hoyles & Noss (2010) regarding the importance of mathematical communication and the role of visual technology. Overall, these findings indicate that the integration of technology-assisted modeling can strengthen students' HOTS and 4C, particularly in creativity, communication, and collaboration, although the aspects of analysis and model validation still require improvement.

3.5. A Scaffolding-Based Modeling Task Design Model: Construction of Stages and Guiding Questions

The design of the boom crane trajectory modeling task was developed using a scaffolding approach to provide graduated support for understanding the context and constructing the model independently. This approach aligns with the findings of Sugiati et al. (2021), who emphasized the effectiveness of scaffolding through guiding questions and concept review when students encounter conceptual barriers. The principles of Explaining, Reviewing, and Restructuring, as well as Developing Conceptual Thinking, were used as the basis for structuring the tiered question stages in the Boom Crane task, guiding students from reading the physical situation and identifying variables to constructing simple geometric relationships. This design also integrates the four-step solution plan from Siller et al. (2023), which affirms the importance of support at each modeling step, as well as during the inter-step transitions, through sequential questions that guide students from understanding the context to evaluating the model's suitability with the physical phenomenon.

The effectiveness of this scaffolding model is supported by the findings of Sofiatun et al. (2018), which showed that scaffolding significantly improves mathematical reasoning abilities, as well as by Nuryadi et al. (2018), who demonstrated that the "scaffolding with a solution plan" strategy yielded good modeling abilities in high school students. The consistency of these results reinforces the relevance of using scaffolding in the Boom Crane task, where graduated support through questions helped students understand the task context with greater confidence. Thus, scaffolding serves as an effective bridge connecting real-world contexts with students' mathematical abilities in the modeling process.

4. CONCLUSION

This study indicates that the mathematical modeling task based on the Boom Crane context, integrated with GeoGebra and scaffolding support, can improve the quality of geometry learning. The developed task was found to be valid and practical and assisted students in navigating the modeling process from understanding the context to evaluating the model. Students were able to establish relationships between variables, construct accurate visual representations, and perform digital simulations, although the aspects of mathematical problem solving and model evaluation still require reinforcement. Scaffolding played an important role in clarifying thinking processes, guiding modeling strategies, and reducing conceptual barriers, aligning with previous research findings.

In addition to enhancing cognitive attainment, this modeling activity also contributes to the development of 21st-century competencies, especially HOTS, collaboration, communication, and creativity. Students were able to collaborate in simplifying the phenomenon, developing models, and presenting their results in a clear and communicative manner. Therefore, context-based modeling instruction is recommended to be systematically integrated into mathematics learning with the support of scaffolding and technology such as GeoGebra. Further research could explore other modeling contexts and variations in scaffolding strategies to expand the contribution of mathematical modeling in education.

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REFERENCES

Blum, W., & Borromeo Ferri, R. (2009). Mathematical modelling: Can it be taught and learnt. *Journal of mathematical modelling and application*, *1*(1), 45-58.

COMAP, & SIAM. (2019). *GAIMME: Guidelines for assessment & instruction in mathematical modeling education. Society for Industrial and Applied Mathematics* (2nd ed.).

Ferri, R. B. (2018). *Learning how to teach mathematical modeling in school and teacher education* (pp. 121-133). New York: Springer International Publishing.
Frassia, M. G., & Serpe, A. (2017). Learning geometry through mathematical modelling: an example with GeoGebra. *TOJET: The Turkish Online Journal Of Educational Technology*, (01-11-2017), 411-418.
Galbraith, P., & Holton, D. (2018). *Mathematical modelling: A guidebook for teachers and teams*. Springer.
Greefrath, G., & Siller, H. S. (2018). GeoGebra as a tool in modelling processes. In *Uses of Technology in Primary and Secondary Mathematics Education: Tools, Topics and Trends* (pp. 363-374). Cham: Springer International Publishing.
Hoyles, C. (2010). *Mathematics education and technology: Rethinking the terrain*. J. B. Lagrange (Ed.). Springer.
Ikeda, T., & Stephens, M. (2017). Students' difficulties in validating mathematical models. *Journal of Mathematical Modelling and Application, 11*(2), 23–39.
Kaiser, G. (2017). The teaching and learning of mathematical modeling. In *Compendium* (Vol. 267, pp. 267-291).
Kaiser, G., & Sriraman, B. (2006). A global survey of international perspectives on modelling in mathematics education. *Zdm*, *38*(3), 302-310.
Kandemir, M. A., & Eryilmaz, N. (2025). Innovative approaches in mathematical modeling: Harnessing technology for teaching second degree equations to Future Mathematics Educators in Türkiye. *Social Sciences & Humanities Open*, *11*, 101281.
Kemple, K., Lee, R., & Harris, M. (2016). Young children's mathematics learning through social interaction. *Early Childhood Education Journal, 44*(3), 1–12.
Lee, N. H., & Ng, K. E. D. (Eds.). (2015). *Mathematical modelling: From theory to practice* (Vol. 8). World Scientific.
Maaß, K. (2010). Classification scheme for modelling tasks. *Journal für Mathematik-Didaktik*, *31*(2), 285-311.
Nuryadi, A., Santoso, B., & Indaryanti, I. (2018). Kemampuan pemodelan matematika siswa dengan strategi scaffolding with a solution plan pada materi trigonometri di kelas X SMAN 2 Palembang. *Jurnal Gantang*, *3*(2), 73-81.
OECD. (2022). *PISA 2022 results (Volumes I & II): Country notes – Indonesia*. OECD Publishing.
OECD. (2023). *PISA 2022 mathematics framework*. OECD Publishing.
Pasco, J. C., & Roble, D. B. (2020). Mathematical modelling integrated with dynamic geogebra applications and students' performance in mathematics. *Science International (Lahore), 32*(2), 165–168.
Rabi, F., Fengqi, M., Aziz, M., Ullah, M. I., & Abduraxmanovna, N. H. (2021). The impact of the use of GeoGebra on students' mathematical representation skills and attitudes. *European Journal of Education Studies, 8*(12).
Siller, H. S., Nitzan-Tamar, O., & Kohen, Z. (2023). Scaffolding practices for modelling instruction in STEM-related contexts: Insights from expert and novice teachers. *Zdm–mathematics Education*, *55*(7), 1351-1364.
Sofiatun, S., Sampoerna, P. D., & El Hakim, L. (2018). The effect of scaffolding techniques on the ability of students' reasoning ability and mathematics anxiety reviewed from gender. *Unnes Journal of Mathematics Education, 7*(1), 63-71.
Sugiati, I., Prayitno, A., & Rahayuningsih, S. Proses Konstruksi Scaffolding Dalam Pemodelan Matematika. *Edu-Mat: Jurnal Pendidikan Matematika*, *12*(1), 80-95.