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Impacts and challenges of mathematical modelling activities on students' learning development: A systematic literature review

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Abstract

Mathematical modelling is essential in mathematics education, presenting real-world problems in mathematical terms. This systematic literature review aims to evaluate the effectiveness of mathematical modelling in education and its implications for teaching and learning. The review used the PRISMA approach and a systematic search of electronic databases to identify relevant articles. The review identified key themes, including the impact of mathematical modelling activities on students' learning development and the challenges of these activities. It identified patterns and trends in students' achievement and skills through modelling activities, the effectiveness of enhancing mathematical learning development, and the challenges in implementing mathematical modelling. Key findings revealed the varying impact of different approaches on diverse modelling tasks. The review emphasized the need for educators to prepare for mathematical modelling practices and suggested that their effectiveness depends on task nature, learners' age, and learning context. Future research should refined best practices, standardize classroom materials, and explore innovative approaches.

Keywords: mathematical modelling, modelling activities, students' learning development, mathematics, impacts, challenges

INTRODUCTION

Mathematical modelling activities are essential in today's classroom since they provide students with various skills and enhance students' learning development in mathematics. In the last few decades, many countries have started incorporating mathematical modelling into their educational curricula. The beneficial implementation of mathematical modelling in school contexts promotes positive impacts on the students' learning development, which is significant in learning mathematics. The incorporation of mathematical modelling into educational curricula allows students to gain experience in the application of mathematics and promotes a deeper understanding of mathematical concepts. These practices are not just about solving equations but involve a comprehensive process where students engage in formulating, analyzing, interpreting, and validating mathematical models (Borromeo-Ferri & Blum, 2019). The educational value of mathematical modelling is widely acknowledged, particularly in developing students' abilities to apply mathematical knowledge in real-world situations (Kaiser & Brand, 2015). This integration also encourages the development of higher-order thinking skills, which are essential for students to explore solutions to learning challenges (Stillman et al., 2017).

The learning process in mathematical modelling requires students to convert real-world problems, including a variety of complex problems, into mathematical representations by using terms and symbols (Blum & Borromeo-Ferri, 2009). This approach has the potential to improve problem-solving skills, encourage students' creativity (Wang et al., 2023; Xu et al., 2022). Besides, it could expand knowledge of mathematics, and increase self-efficacy, which is essential for students who lack confidence in mathematics (Geiger et al., 2018; Haara, 2022). These advantages could encourage students to tackle real-world problems by applying the mathematical

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Contribution to the literature

- This review provides a detailed synthesis of current empirical studies on the impacts of mathematical modelling activities, offering a clear picture of how these activities influence students' learning development.
- This study highlights recurring challenges faced by students and teachers in the implementation of mathematical modelling activities, especially in transitioning between real-world contexts and mathematical representations.
- This review establishes a foundation for future research and offers practical implications for educators and policymakers looking to enhance effective modeling practices in classrooms and professional development programs.

knowledge they have learned. The main advantage of using this approach in teaching mathematics is that it provides students with a deeper understanding of real-world situations and fosters active learning in the mathematics classroom (Niss et al., 2007).

Mathematical modelling in education is grounded in constructivist learning theories, which emphasize the active engagement of students and the construction of knowledge through experience and problem-solving. Key contributors to constructivist theory include Jean Piaget and Lev Vygotsky, who highlighted the importance of active engagement and social interaction in learning. According to constructivist theories, students develop their understanding and knowledge of the world through experience and reflection on their experiences (Bruner, 1997). This approach aligns well with mathematical modelling, which involves translating real-world problems into mathematical formulations to find solutions. These theories provide a foundation for understanding the construction process of knowledge through interactions and experiences.

Students' learning development in mathematics is a crucial focus in education, particularly in understanding how various pedagogical approaches impact their cognitive growth and problem-solving abilities. Significant trends in the literature reveal a growing consensus on the benefits of mathematical modelling in enhancing students' learning development. However, disagreements exist regarding the best methods for integrating mathematical modelling into curricula and the extent to which it should be emphasized. Despite the clear benefits, the implementation of mathematical modelling in educational settings faces challenges. Teachers often struggle with the complexities of teaching modelling, which requires a shift from traditional instructional methods to more interactive and student-centered approaches (Bas-Ader et al., 2023). In contrast, the practices of mathematical modelling in classroom teaching may have implied challenges since their rigorous process and possibility against complex real-world problems (Cevikbas et al., 2023). These challenges need to be addressed to maximize effectiveness and thereby ensure the objective of teaching and learning mathematics is attained. Comparing and contrasting different studies and theories is crucial to understanding the diverse perspectives on mathematical modelling in education (Rojas et al., 2021). Therefore, the impact and challenges of mathematical modelling practices on students' learning development need to be investigated.

This systematic literature review provides a comprehensive overview of the current state of research on this topic, highlighting significant trends, consensus, and disagreements among scholars. By examining recent empirical studies, the review offers insight into the most effective practices and the obstacles that need to be overcome to maximize the benefits of mathematical modelling in education. The findings of this review contribute to the ongoing discussion on integrating mathematical modelling into curricula and provide valuable recommendations for future research and practice (Cevikbas et al., 2023). These studies highlight the importance of nurturing specific cognitive skills to enhance students' abilities to navigate complex mathematical problems. This aligns with Sternberg's earlier work in 1994, which underscores the role of adaptive teaching strategies in catering to diverse cognitive styles, ultimately leading to improved mathematical performance (Sternberg, 1994). All this research points to the need for a better way of teaching and learning mathematics that emphasizes identifying and strengthening each student's cognitive abilities to improve students' learning development.

This study systematically reviews descriptive research to inform scholars about the most effective practices and the obstacles to overcome (Geiger et al., 2018; Wang et al., 2023; Xu et al., 2022). This review focuses on recent empirical studies published within the last ten years to ensure that the findings are relevant to current educational contexts. The analysis encompasses various aspects of mathematical modelling, including students' learning development and the impacts and challenges faced in the implementation of mathematical modelling practices in a school context. By synthesizing all these studies, the paper aims to provide a comprehensive understanding of the current state of modelling practices in schools and offers recommendations for future research.

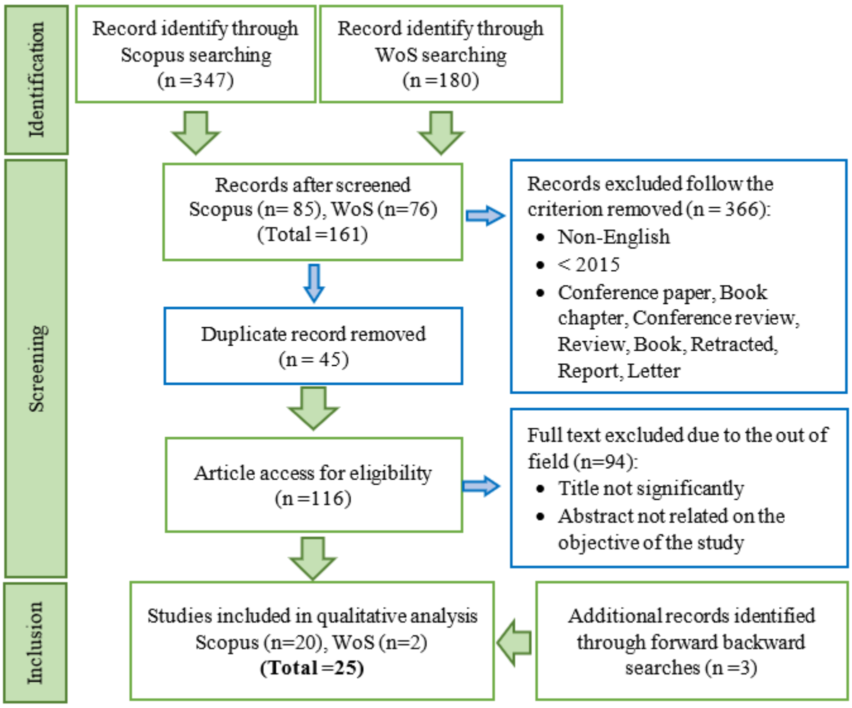

Figure 1. Flow diagram of the PRISMA 2020 proposed by Boers (2018), Mayo-Wilson et al. (2018) and Stovold et al. (2014)

Table 1. The search strings

Database	Search string
Scopus	TITLE-ABS-KEY ("mathematical model*" AND students AND (development OR achievement) AND school)
WoS	Topics ("mathematical model*" AND students AND (development OR achievement) AND school)

Mathematical modelling has gained prominence in mathematics education because it bridges the gap between theoretical mathematics and practical applications. The objective of this study is to examine the impact and challenges of mathematical modelling practices on students' learning development. By analyzing mathematical modelling activities through the lens of classroom teaching and learning, this systematic literature review aims to provide valuable insights for researchers and practitioners, based on the following research questions:

RQ1 What are the impacts of utilizing mathematical modelling on students' learning development?

RQ2 What challenges do students face in mathematical modelling that impact their learning development?

METHODOLOGY

In this section, a descriptive systematic review was carried out to identify an accumulation of empirical research on the issues and implications of mathematical modelling in school education. The new design of Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 proposed by Boers (2018), Mayo-Wilson et al. (2018) and Stovold et al. (2014) were used to organize and improve the review's transparency, accuracy, and quality, as illustrated in **Figure 1** (Page et al., 2021). The review collects, codes, and analyzes numerical data that reflects the frequency analysis of the body of research. The focus is on the general study characteristics and methodologies, including publication years, research samples, and topics. By spotting research trends and providing comprehensible patterns, this paper helps researchers reach broad conclusions about the value of current conceptions, methods, and applications in the area (Page et al., 2021). In the process of selecting suitable papers for this report, the systematic review involves three primary phases which are identification, screening and inclusion.

Identification

The initial phase entails identifying keywords and searching for related terms using thesauri, dictionaries, encyclopedias, and prior research. Search queries were created for the Scopus and Web of Science databases after all relevant terms had been identified, as indicated in **Table 1**. During the initial phase of the systematic review, the current research successfully obtained 527 papers from both databases.

Screening

The second phase, which is screening, involved two stages. The first stage involved the evaluation of 161 articles based on predetermined inclusion and exclusion criteria established by the researchers as shown in **Table 2**.

Table 2. The search strings

Database	Search string
Scopus	TITLE-ABS-KEY ("mathematical model*" AND students AND (development OR achievement) AND school) AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))
WoS	Topics ("mathematical model*" AND students AND (development OR achievement) AND school) AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))

Table 3. The selection criterion in searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2015 - 2024	< 2015
Literature type	Journal (Article)	Conference paper, Book chapter, Conference review, Review, Book, Retracted, Report, Letter
Subject Area	Mathematics	Mathematics

The second stage, which is the removal of duplicate papers, 45 articles were excluded. Literature in the form of research articles was the primary criterion for inclusion, as it serves as the primary source of practical information. Conversely, the study excluded publications such as conference paper, book chapter, conference review, review, book, book, retracted, report, letter as shown in **Table 3**.

Additionally, the review exclusively focused on papers written in English which is one of the limitations of this study and considered a specific time frame from 2015 to 2024. These parameters led to the exclusion of 366 publications in total.

The eligibility assessment required a compilation of 116 articles. To confirm that all the papers met the inclusion criteria and the study objectives, a comprehensive examination of their titles and key contents was carried out at this point. Thus, 94 reports were excluded because their titles were irrelevant, their abstracts were irrelevant to the study's goal, and they were outside the study's scope, which is student development rather than teacher development.

Inclusion

In the third phase, known as the inclusion, 22 articles remained available for verification.

However, three studies have also been included through forward-backward searches (Xiao & Watson, 2019) due to the discussion involving the impact and challenges of mathematical modelling activities to the students' learning development. As shown in **Figure 1**, we finalized a total of 25 articles for review.

Data Extraction and Analyses

In consideration of the study's emphasis on a variety of research designs, the articles were thematically analyzed to demonstrate the most effective methods of integrating the differences through qualitative synthesis. Although numerous qualitative syntheses could be implemented, the current review employed the methodology proposed by Braun and Clarke (2019). They emphasized the flexibility of thematic synthesis in summarizing data from a variety of research designs. Thematic analysis is a method of analysis that aims to detect any similarities or connections that may exist in the available data to identify and indicate the pattern of existing studies (Braun & Clarke 2021). The data collection phase was the first step in the theme's development. We have carefully reviewed a group of 25 papers for statements or information addressing questions from this current research. The two main themes that emerged from the approach are the impacts and the challenges of the implementation of mathematical modelling in school. The authors continued to develop each theme further, incorporating any related concepts, or ideas. Within the framework of this study and throughout the data analysis process, the log was kept recording any analysis, viewpoints, or other challenges essential to the interpretation of the data. Subsequently, the results have been compared to settle any differences in the theme development process. Ultimately, the authors adjusted the created concepts to ensure consistency.

RESULTS AND DISCUSSIONS

This study analyzed 25 research articles, with a focus on the impacts and challenges of mathematical modelling activities on students' learning development. The results show that modelling activities have a significant impact on students' achievement and skills.

Impacts on Students' Learning Development

From the studies, 17 themes emerged from the impacts of mathematical modelling in classroom learning as shown in **Table 4**.

The themes are problem solving skills, critical thinking skills, inquiry skills, reasoning skills, metacognitive skills, algorithmic thinking skills, digital skills, mathematical representation skills, geometry

Table 4. Impacts on students' learning development

Authors	PS	CT	IS	RS	MS	AT	DS	MR	GS	RS	MC	C	CC	SE	SiE	EM	SA
Manunure and Leung (2024)			√								√		√				
Falcó-Solsona et al. (2024)			√										√				
Pelemeniano and Siega (2023)													√	√			
Siller et al. (2023)		√						√									
Wang et al. (2023)	√		√									√					
Chen (2022)	√	√					√						√				
Haara (2022)				√									√			√	
Holenstein et al. (2022)	√			√										√			
Xu et al. (2022)		√									√		√			√	
Lu and Huang (2021)	√				√						√		√				
Albarracín and Gorgorió (2020)	√	√									√	√	√				√
Carreira et al. (2020)						√	√				√		√		√		
Hankeln (2020)					√								√				
Rellensmann et al. (2020)					√				√								
Greefrath (2020)							√									√	
Geiger et al. (2018)					√								√				
Krutikhina et al. (2018)	√										√						
Brown and Stillman (2017)					√						√					√	
Hagena et al. (2017)	√									√							
Tezer and Cumhur (2017)	√							√	√							√	√
Geiger (2017)		√					√						√				
Brown (2015)							√	√							√		
Ledezma et al. (2023)	√	√				√					√	√					
Ledezma et al. (2022)	√	√			√					√			√			√	
Sebastia et al. (2021)	√	√	√										√			√	

PS - Problem solving skills, CT - Critical thinking skills, IS - Inquiry skills, RS - Reasoning skills, MS - Metacognitive skills, AT - Algorithmic thinking skills, DS - Digital skills, MR - mathematical representation skills, GS - geometry skills, RS - Reading skills, MC - mathematical concept, C - Creativity, CC - Communication and collaboration, SE - Self Efficacy, SiE -Simulation & experiment, EM - Engagement & motivation, SA - Social awareness

skills, reading skills, mathematical concepts, creativity, communication and collaboration, self-efficacy, simulation or experimentation, engagement or motivation, and social awareness.

Problem solving skills

Table 4 presents the results of nine studies that highlight the impact of modelling practices on students' problem-solving skills and their learning development. Wang et al. (2023) stated that by practicing the modelling tasks, students gained the encouragement to analyze the real-world problem, thereby fostering students' skills to solve each matter by transforming it into a mathematical representation. This problem-solving skill allows students to develop the necessary skills for engaging with various real-world situations, which could drive them to navigate complex problems effectively. Chen (2022) similarly stated that facing real-world problems and solving the situation has the potential to enhance students' achievement in learning mathematics, whether routine or non-routine.

Furthermore, Holenstein et al. (2022) agree that problem-solving skills used in mathematical modelling activities could bridge the gap between abstraction concepts and practical mathematics. This connection cultivates their ability to apply their understanding effectively and reinforces the improvement of mathematical knowledge. Regular engagement in mathematical modelling activities and problem-solving exposes students to group discussions, potentially enhancing their skills and achievements. Albarracín and Gorgorió (2020) highlight that collaborative group work allows students to enhance their teamwork skills, which are crucial for learning development. Additionally, Lu and Huang (2021) also emphasize that modelling tasks encourage students to have a range of experience, which may help them develop resilience in tackling non-regular obstacles in mathematics and life.

Critical thinking skills

Five studies demonstrate that modelling activities foster critical thinking, an essential skill. Chen (2022) emphasizes the importance of modelling activities in fostering students' ability to apply mathematical concepts to practical contexts, thereby fostering critical thinking as they attempt to solve problems in various ways. Siller et al. (2023) carried out a study utilizing COVID-19 pandemic data, asserting that students require exposure to complex real-world scenarios to enhance their problem-solving skills and foster critical thinking.

Furthermore, Albarracín and Gorgorió (2020) demonstrated that elementary students may develop their problem-solving skills through modelling tasks, which could drive them to cultivate their critical thinking. According to Xu et al. (2022), by fostering the ability to deal with modelling problems, students have the potential to deepen their involvement in learning, which leads to the development of their critical thinking abilities. Geiger et al. (2018) emphasized that modelling activities cultivate critical thinking skills, enabling students to engage with STEM fields that enhance their mathematical comprehension.

Inquiry skills

Inquiry skills emerge impactfully from the implementation of modelling activities. The studies conducted by Manunure and Leung (2024) and Falcó-Solsona et al. (2024) demonstrated that specific stages of inquiry, such as problem formulation and hypothesis generation, are in line with the steps in modelling process, including understanding and constructing the problems. This alignment indicates a strong relationship between inquiry and modelling, which can improve students' understanding and problem-solving skills. However, Wang et al. (2023) state that some obstacles to inquiry phases in learning environments and the possible misunderstanding of teachers regarding the integration of several topic areas may prevent these activities from reaching their full potential. Furthermore, teacher preparation and support are important in integrating inquiry-based approaches with modelling. Teacher expertise and ability to modify teaching strategies to meet students' needs have a significant impact on the effectiveness of inquiry skills gained.

Reasoning skills

A few studies state that reasoning plays a crucial role in enhancing students' understanding and learning development. In the context of mathematical modelling, students could foster these skills by solving real-world problems with their mathematical knowledge. Haara (2022) underscores the importance of reasoning within the framework of pedagogical entrepreneurship and mathematical modelling, emphasizing its contribution to the development of mathematical literacy among upper primary students. The integration of problem-solving and scientific rigor, as suggested by Haara, directly involves reasoning skills, which are essential for interpreting results and applying them to real-world scenarios. This approach not only enriches the modelling process but also supports students' capacity to develop logical, reasoned arguments that are crucial for effective modelling.

Holenstein et al. (2022) extend this perspective by highlighting the role of self-efficacy in modelling. Their findings suggest that students' self-belief and the feedback they receive indirectly influence their reasoning. When students possess strong self-efficacy, their reasoning skills in tackling modelling tasks improve, as they are more likely to engage deeply with the steps of the modelling cycle and apply solution strategies effectively. This suggests that reasoning in modelling is not just a cognitive process but also a motivational one, influenced by how students perceive their abilities and the feedback they receive. Therefore, fostering reasoning through supportive teaching practices and encouraging self-efficacy can significantly impact students' success in modelling, contributing to their overall learning development (Haara, 2022; Holenstein et al., 2022).

Metacognitive skills

Five studies underscored the crucial role of metacognitive skills in modelling activities. This aspect highlights the important role of mathematics in fostering effective learning and problem-solving. According to Lu and Huang (2021), students in China demonstrated a significant gap in metacognitive skills, such as validating their work with critical discussion, which are essential for modelling competency. A school system that prioritizes mathematical foundations over other abilities, including metacognition, causes this shortcoming. Similarly, Hankeln (2020) identified that cultural and educational contexts influence students' metacognitive engagement during modelling tasks. By adapting teaching aids to real-world scenarios, improving metacognitive skills could help students overcome the difficulties in the modelling process.

Additionally, Rellensmann et al. (2020) suggest that enhancing students' performance in geometric modelling tasks requires metacognitive knowledge, particularly strategic drawing knowledge. They propose that providing this information using argumentative teaching techniques will improve students' metacognitive abilities, which will result in more precise problem-solving. Geiger et al. (2018) also emphasize the significance of metacognition, especially predictive metacognition, in the process of modelling. Instead of just reflecting, proactive metacognitive tasks help students better understand and represent real-world situations mathematically. According to Brown and Stillman (2017), students, including those with less mathematical knowledge, could perceive mathematics as a useful tool for understanding real-life situations when they engage with metacognitive participation in modelling tasks. Collectively, these studies suggest that engaging students with modelling activities is vital for developing students' abilities to enhance metacognitive competencies to apply mathematics to complex or real-world problems.

Algorithmic thinking skills

Algorithmic thinking skills are one of the significant impacts that emerged from mathematical modelling activities. It enables students to process the data and establish rules for decision-making systematically, as highlighted by Carreira et al. (2020). In their study, students at the university and ninth grade levels worked together to create a hand biometric identification system. Though their mathematics backgrounds differed, both teams used algorithmic techniques to build models that compared hand measurements and established approval or rejection criteria. This shows that, depending on their educational background, they can convert issues from the real world into mathematical methods, although with variable degrees of complexity. These processes helped students test and refine their algorithms, deepening their understanding of applying mathematical models to real-world scenarios. The iterative nature of algorithmic thinking, involving continuous formulation, testing, and refinement of rules, is crucial in bridging abstract mathematical concepts with practical applications. This critical role of algorithmic thinking in mathematical modelling underscores its significance in enhancing students' learning development.

Digital skills

The integration of technology into mathematical modelling activities has a significant impact on students' digital skills learning and development. These important skills could enhance their ability to solve complex and real-world problems. Chen (2022) discusses how technological tools tend to support mathematical literacy, emphasizing their role in bridging formalization and real-world applications, particularly in mathematical modelling tasks. Similarly, Carreira et al. (2020) highlight the role of digital tools in the development of prototype systems, such as hand biometric recognition, where students utilize mathematical algorithms and simulations to create secure systems. These processes not only engage students in practical applications of mathematics but also foster their ability to manipulate the data, thereby enhancing their problem-solving skills. Greefrath (2020) highlights the influence of technological devices or digital tools on modelling activities and emphasizes that technology not only facilitates the use of mathematical models but also fosters prospective students' professional growth.

Geiger (2017) points out the critical role of modelling in sustaining STEM education, where technology enhances students' ability to apply mathematics in various fields, thus addressing the decline in STEM participation. However, as Brown (2015) points out, students often fail to fully realize the full potential of these technological tools, limiting their capacity to refine mental models through external visualizations. This gap underscores the need for educators to better understand and teach the cognitive roles of these tools, ensuring that students can fully utilize technology to support their mathematical reasoning and modelling processes. The results of these studies suggest that incorporating technology into modelling might result in notable improvements. However, it's crucial to make sure that technology is included in the learning process in a way that balances its cognitive and practical aspects.

Mathematical representation skills

The implementation of modelling activities has a positive impact on mathematical representation skills because it bridges abstract concepts in mathematics with practical applications. According to Siller et al. (2023), the inclusion of fundamental models in mathematics education is essential for helping students comprehend difficult concepts like exponential growth by providing them with a structured representation. Tezer and Cumhur (2017) emphasize that students who are exposed to modelling demonstrate significant improvements in spatial reasoning and problem-solving, highlighting the importance of representation in connecting abstract mathematics with real-world contexts.

Brown (2015) discusses the challenges students face in fully utilizing technology-based visualizations to enhance their mathematical representation. Despite the potential of these tools to transform the learning process, students often fail to recognize their cognitive benefits, underscoring the need for more effective instructional strategies. This suggests that while mathematical representation is fundamental to grasping and applying mathematical models, it requires proper instructional support, particularly in the integration of technology, to maximize its educational impact. All these studies show that effective mathematical representation is essential for deepening students' understanding and enhancing their ability to apply mathematical concepts in varied contexts, particularly when supported by mental models and technology.

Drawing and geometry skills

The impact of mathematical modelling activities on students' learning development is profoundly significant, particularly in the domains of drawing and geometry. Rellensmann et al. (2020) highlighted that strategic knowledge about drawing is crucial for solving geometry modelling problems accurately. Students with a higher level of strategic drawing knowledge exhibited improved performance in geometry, as their drawings were more precise, contributing to a better understanding of geometric concepts.

Similarly, Tezer and Cumhur (2017) found that students exposed to modelling methods demonstrated superior problem-solving abilities and a deeper comprehension of geometric objects compared to those taught using traditional methods. Their research also revealed that the modelling approach positively influenced students' visual perception and spatial reasoning, which are vital components of geometry education. These findings suggest that integrating modelling practices into geometry instruction not only enhances students' drawing accuracy but also fosters their overall cognitive development in mathematics. The findings of these studies demonstrate the importance of using strategic drawing skills in conjunction with modelling to improve students' comprehension and application of geometric ideas, thereby benefiting their overall educational development (Rellensmann et al., 2020; Tezer & Cumhur, 2017).

Reading skills

The discussion around the impact of mathematical modelling practices on students' reading skills highlights the multifaceted relationship between reading comprehension and mathematical understanding. Hagena et al. (2017) explored whether the integration of reading strategies could foster mathematical modelling competencies, particularly in the initial stages of understanding and simplifying or structuring problems. Their study, which involved a 15-week intervention with seventh-grade students, found that reading strategy training had a minimal impact on the development of these competencies. This outcome suggests that while reading comprehension is crucial, it may not be sufficient on its own to significantly enhance mathematical modelling skills.

The research suggests that modelling issues may arise not just from insufficient reading comprehension but also from difficulty in establishing connections between mathematical ideas and textual comprehension. Hence, it is necessary to develop specific reading techniques that are specifically designed for engaging with mathematical concepts to effectively assist students in understanding and tackling complicated modelling problems. This research emphasizes the need for teaching approaches that incorporate mathematical reasoning with reading comprehension, specifically strategies that facilitate students in connecting mathematical concepts to the text, so enhancing their entire modelling skills (Hagena et al., 2017).

Mathematical concepts

The implementation of modelling activities in the classroom shows that mathematical concepts are one of the impacts on students getting stronger throughout the learning process. Albarracín and Gorgorió (2020) highlight the integration of mathematical concepts in project-based learning, where students leverage these concepts to address real-world issues effectively. This approach not only fosters the application of mathematical knowledge but also encourages students to develop a deeper conceptual understanding as they validate and defend their models within their communities. Similarly, Carreira et al. (2020) emphasizes the role of mathematical concepts in the development of biometric systems, where both school and university students engage in modelling tasks that require the application of complex mathematical tools. The study illustrates how different levels of mathematical knowledge influence the modelling process and the conceptual depth achieved by students.

Furthermore, Xu et al. (2022) discuss the different perspectives held by mathematicians, mathematics educators, and teachers regarding the conceptual emphasis in modelling. While mathematicians and educators focus on the epistemological and pedagogical aspects, promoting a deep understanding of mathematical concepts during modelling, teachers often adopt a more applied perspective, emphasizing the practical application of these concepts in real-world scenarios. This divergence highlights the varying degrees of importance placed on conceptual understanding across different educational contexts. Additionally, Lu and Huang (2021) underscore the challenge of integrating mathematical concepts into modelling within China's educational framework, where the curriculum traditionally emphasizes mathematical foundations over broader competencies. This focus on foundational concepts, while essential, may limit students' ability to fully engage in the modelling process, necessitating a balanced approach that incorporates both conceptual and applied aspects of mathematical learning.

Creativity

The impact of modelling practices on students' learning development also highlighted creativity as a significant aspect. According to Albarracín and Gorgorió (2020), in their study, the implementation of modelling activities could foster creative thinking through the variety of activities taken to complete the task, such as analysis, data collection, and visualization. Modelling activities also foster accountability through teamwork, which emerges from creative solutions when solving real-world problems using various methods.

Wang et al. (2023) suggested that modelling activities encourage creative thinking, which can enhance the ability to represent mathematical concepts. The nature of modelling tasks sparked students' curiosity with creative problem-solving. Furthermore, both studies have proven that guided inquiry classroom teaching has the potential to increase students' creativity by giving them the opportunity to find a solution via various methods. The studies also highlight the importance of modelling activities in fostering creativity by involving challenging real-world situations and problems, which could inspire students to increase their motivation to learn mathematics (Albarracín & Gorgorió, 2020; Wang et al., 2023).

Communication and collaboration

Communication and collaboration are crucial in the implementation of modelling practices, within interdisciplinary educational contexts. Research by Manunure and Leung (2024) highlights the importance of teacher collaboration in integrating mathematics and science, showing that such collaboration enhances content integration and pedagogical confidence. Falcó-Solsona et al. (2024) emphasize the necessity of collaborative efforts in designing and implementing learning situations that foster both inquiry and modelling skills, underscoring the role of communication in navigating complex problem-solving processes.

Similarly, Pelemeniano and Siega (2023) demonstrate that collaborative learning environments, supported by contextualized materials, enable students to engage in modelling effectively, promoting self-efficacy and appreciation of real-world applications. Xu et al. (2022) reinforce this notion, noting that group work is essential in the teaching and learning of modelling, aligning with international practices. The findings suggest that communication and collaboration not only facilitate the integration of modelling in the classroom but also enhance students' modelling competencies, teacher efficacy, and the overall educational experience.

Self-efficacy

Self-efficacy is one of the learning impacts of the implementation of modelling activities. Numerous studies have underscored their importance in shaping students' learning growth. Holenstein et al. (2022) highlighted the predictive effect of mathematical self-efficacy on modelling, suggesting that enhancing self-belief can positively impact students' modelling abilities, regardless of their initial skill levels. They advocate for teaching strategies that foster self-efficacy, particularly through positive feedback and individualized support during modelling tasks, as these approaches can help students better understand and engage with the modelling process. This finding aligns with the work of Pelemeniano and Siega (2023), who observed that teachers' instructional strategies, such as using multiple examples and formative assessments, are crucial in developing students' self-efficacy.

Pelemeniano and Siega (2023) emphasized the significance of contextualized instructional materials, which aim not only to teach mathematical concepts but also to boost students' confidence and appreciation for real-life applications. The integration of self-efficacy-focused approaches within modelling is thus essential, as it can lead to improved academic outcomes and greater student engagement. However, it is important to recognize that self-efficacy is not only influenced by instructional methods but also by external factors such as grades, which can either enhance or diminish a student's self-belief (Holenstein et al. 2022). To mitigate the potential negative impacts of low grades, it is recommended that feedback be provided based on individual progress rather than through social comparisons, thereby fostering a positive cycle of self-efficacy and academic achievement.

Simulation and experiment

Implementing modelling in classroom activities has significantly impacted students' learning development towards simulation and experimentation skills, thereby fostering a deeper connection between abstract mathematical concepts and real-world applications. Carreira et al. (2020) underscored the essential role of experimentation in the modelling process of students tasked with designing a hand biometrics identification system. This experimental effort facilitated the integration of mathematical concepts with the practical components of students' models, resulting in a better understanding of the system designed.

Similarly, Brown (2015) emphasized that the effectiveness of technology in supporting mathematical modelling is dependent on students' ability to engage with visualization tools, which serve as external aids to enhance and refine their mental models. However, Brown (2015) observed that a significant number of students have difficulties fully utilizing the capabilities of these tools. This suggests a close relationship between students' ability to effectively use technology resources and the effectiveness of simulation and experimentation in modelling. The practical character of experimentation facilitates the transformation of abstract concepts into concrete activities, affording students the chance to thoroughly examine, authenticate, and enhance their models. This process not only strengthens their mathematical reasoning but also helps them develop a more intuitive understanding of the real-world systems they are modelling, ultimately leading to more meaningful and effective learning outcomes (Carreira et al., 2020; Brown, 2015).

Engagement and motivation

Modelling practices significantly impact student engagement and motivation in the learning process. Brown and Stillman (2017) observed that modelling tasks facilitate engagement by allowing students to relate mathematics to real-world contexts. This connection often shifts students' perceptions of mathematics from abstract concepts to practical tools, thereby increasing their motivation to learn. Xu et al. (2022) observed that teacher-centered instructional approaches typically result in limited student participation. However, the inclusion of modelling techniques promotes group work and independence, resulting in a more active and enjoyable learning environment. According to Greefrath (2020), the use of technology in modelling tasks has the potential to promote student engagement by making complex mathematical concepts more accessible and relevant. Consequently, this may lead to an increase in students' fundamental intention to investigate and comprehend the challenges.

Tezer and Cumhur (2017) demonstrated that students exposed to modelling activities exhibited higher levels of motivation and problem-solving skills compared to those taught using traditional methods. Modelling fosters an active learning environment leading to this increased motivation where students frequently engage with real-world problems, apply mathematical concepts, and see the relevance of their learning. Haara (2022) further emphasized the importance of incorporating pedagogical entrepreneurship into modelling to increase students' engagement. This integration fosters more realistic and meaningful learning, boosting their desire to seek an understanding of mathematics.

Social awareness

The integration of modelling activities into the mathematics classroom has significant implications for fostering social awareness among students. Albarracín and Gorgorió (2020) emphasize that modelling projects specifically designed towards social impact enable students to engage with real-world problems, such as road safety or pollution, within their communities. This approach not only facilitates the development of mathematical abilities but also enhances students' feelings of responsibility and consciousness about social problems. These projects serve to foster student autonomy in learning by addressing community issues, cultivating a more profound understanding of the practical application of mathematical concepts in tackling real-world problems.

Furthermore, this procedure requires students to engage in an evaluation and validation of their mathematical reasoning, increasing their confidence in using mathematics as a tool to effect significant changes in society. Tezer and Cumhur (2017) contribute to this discourse by demonstrating that students who engage in mathematical modelling show greater improvement in problem-solving skills compared to those using traditional instructional methods. The collaborative nature of these projects, as highlighted by Tezer and Cumhur, enhances motivation and leads to a deeper understanding of mathematical concepts, which in turn positively impacts students' social awareness. The findings suggest that as students work together to solve complex problems, they not only develop essential academic skills but also cultivate a greater sense of community and social responsibility. These educational outcomes underscore the importance of integrating modelling into curricula to prepare students to be socially aware and engaged citizens.

Challenges Faced by Students in Mathematical Modelling

The widespread recognition of the potential benefits of mathematical modelling in school environments arises from its ability to enhance students' learning development by effectively connecting theoretical concepts with real-world situations. The integration of mathematical modelling inside educational environments facilitates the development of students' ability to apply abstract mathematical concepts to realistic real-world scenarios, a significant achievement in learning mathematics (Cevikbas et al., 2023).

Despite its benefits, learning mathematical modelling presents numerous challenges. **Table 5** summarizes the challenges faced by students during modelling activities and provides a detailed explanation. The reported challenges fall into six main categories: confidence and self-efficacy issues, deficiencies in foundational knowledge and conceptual understanding, problem formulation and application of mathematical concepts, cognitive load and the complexity of modelling processes, collaborative work and communication, and technological and resource-based issues.

Table 5. Challenges in mathematical modelling activities

Authors	Title	Age (years)	Challenges
Manunure and Leung (2024)	Integrating inquiry and mathematical modelling when teaching a common topic in lower secondary school: an iSTEM approach	13-14	1. Lack of confidence. 2. Limited access.
Falcó-Solsona et al. (2024)	Inquiry and mathematical modelling with real-archaeological objects in secondary education	12-13	1. Struggled in formulate clear understanding. 2. Apply concepts and techniques effectively. 3. Cyclical nature lead to confusion or frustration. 4. The collaborative leads to conflicts or misunderstandings.

Table 5 (Continued). Challenges in mathematical modelling activities

Authors	Title	Age (years)	Challenges
Pelemeniano and Siega (2023)	Integrating mathematical modelling of real-life problems: A contextualized approach to developing instructional material in basic calculus	16-18	1. Deficiency in foundational knowledge. 2. Difficulties in high-level content. 3. Struggled with confidence. 4. Struggled in refining the real-world problems.
Siller et al. (2023)	Mathematical modelling of exponential growth as a rich learning environment for mathematics classrooms	16-18	1. Struggle with mathematical complexity. 2. Identify trends, predictions, and understand the data. 3. Selecting appropriate models and justifying.
Wang et al. (2023)	How does mathematical modelling competency affect the creativity of middle school students? The roles of curiosity and guided inquiry teaching	12-13	1. Understanding and simplifying complex real-world problems. 2. Higher-level mathematical concepts and problem-solving strategies. 3. Lose motivation and interest. 4. Overwhelmed and unable to tackle the tasks.
Chen (2022)	Measurement, evaluation, and model construction of mathematical literacy based on IoT and PISA	14-15	1. May not have prior experience. 2. Communicating and working together.
Haara (2022)	Mathematical modelling in upper primary school: Finding relevance and value for others outside school	10-12	1. Lack of structured guidance and expectation in problem-solving. 2. Fear of failure and mistakes.
Holenstein et al. (2022)	How do self-efficacy and self-concept impact mathematical achievement? The case of mathematical modelling	13-15	1. Struggle with complex tasks. 2. Reading comprehension or understanding the language.
Xu et al. (2022)	Mathematicians', mathematics educators', and mathematics teachers' professional conceptions of the school learning of mathematical modelling in China	16-18	1. Struggled with understanding and simplifying real-world situations. 2. Navigate various steps in modelling. 3. Examination-oriented teaching practices.
Lu and Huang (2021)	Mathematical modelling in China: How it is described and required in mathematical curricula and what is the status of students' performance on modelling tasks	13-14	1. Did not recognise the necessity of validating their mathematical solutions. 2. Lacked the awareness and skills required to critique and validate their work on the tasks.
Albarracín and Gorgorió (2020)	Mathematical modelling projects oriented towards social impact as generators of learning opportunities: A case study	11-12	1. Overwhelming when representing findings. 2. Making decisions. 3. Develop a sense of social responsibility.
Carreira et al. (2020)	Mathematical models and meanings by school and university students in a modelling task	14-15	1. Struggled with mathematical concepts. 2. Validating models.
Hankeln (2020)	Mathematical modelling in Germany and France: A comparison of students' modelling processes	15-18	1. Not familiar with the type of modelling tasks presented. 2. Tendency to prefer precise answers and exact values. 3. Struggled to articulate their thoughts effectively.
Rellensmann et al. (2020)	Measuring and investigating strategic knowledge about drawing to solve geometry modelling problems	14-15	1. Students often relied on provided drawings rather than generating their own. 2. Teaching methods that actively promote the development of strategic knowledge may not be readily available or effectively utilized.
Greefrath (2020)	Mathematical modelling competence. Selected current research developments	14-15	1. Difficulties in recognizing the different phases. 2. Using digital tools and software. 3. Difficult to navigate tasks that require multiple solutions. 4. The process in the modelling may not be fully developed in all students.

Table 5 (Continued). Challenges in mathematical modelling activities

Authors	Title	Age (years)	Challenges
Geiger et al. (2018)	Using mathematics to solve real world problems: the role of enablers	15-17	1. Difficult to monitor and evaluate their own understanding and strategies. 2. Struggle without adequate guidance from teachers. 3. Overwhelming for students.
Krutikhina et al. (2018)	Teaching of mathematical modelling elements in the mathematics course of the secondary school	10-17	1. Insufficient number of applied problems in school textbooks. 2. Struggle with the formal introduction of the term "mathematical model". 3. Difficult to understand how to simplify complex real-world situations. 4. Lack interest or see the relevance of mathematical modelling to their lives. 5. Overwhelm student if they are not adequately prepared in their learning.
Brown and Stillman (2017)	Developing the roots of modelling conceptions: ‘Mathematical modelling is the life of the world’	12-13	1. Concerns about time constraints. 2. Not all students demonstrated critical thinking approach indicating a challenge in adopting mindset.
Hagena et al. (2017)	Using reading strategy training to foster students’ mathematical modelling competencies: Results of a quasi-experimental control trial	11-18	1. Struggled with understanding the language and structure of mathematical word problems. 2. Conceptual obstacles related to semantic problem structures. 3. The interplay between reading and finding mathematical relations was not sufficiently addressed.
Tezer and Cumhur (2017)	Mathematics through the 5E instructional model and mathematical modelling: The geometrical objects	14-15	1. Insufficient prior knowledge. 2. Had misconceptions. 3. Many teachers lacked adequate knowledge about different methods to detect students’ misconceptions.
Geiger (2017)	Designing for mathematical applications and modelling tasks in technology rich environments	15–16	1. Difficulties applying concepts in more complex contexts. 2. Struggled to utilize the technologies.
Brown (2015)	Visualisation tactics for solving real world tasks	16-18	1. Struggled to utilize the technology. 2. Viewed multiple models sequentially rather than simultaneously. 3. Exhibited gaps in their mathematical knowledge.
Ledezma et al. (2023)	Analysing the mathematical activity in a modelling process from the cognitive and onto-semiotic perspectives	12-18	1. Lack of consensus on objectives in doing task. 2. Insufficient mathematical knowledge. 3. Complexity of modelling processes.
Ledezma et al. (2022)	Knowledge and beliefs on mathematical modelling inferred in the argumentation of a prospective teacher when reflecting on the incorporation of this process in his lessons	14-16	1. Lack of sufficient prior knowledge of mathematical concepts. 2. Struggle to comprehend complex problems. 3. Unequal participation or conflicts in group. 4. Encounter misunderstandings or make errors in their mathematical translations and representations.
Sebastia et al. (2021)	Inquiry and modeling for teaching mathematics in interdisciplinary contexts: How are they interrelated?	12-14	1. Struggle with the inherent complexity of mathematical modeling. 2. Overwhelming for those who may not yet possess strong foundational skills. 3. Lack of confidence. 4. Lack of guidance.

Confidence and self-efficacy issues

Several studies have emphasized that a lack of confidence, frequently caused by previous adverse experiences with mathematics, may greatly obstruct students’ engagement in modeling tasks (Manunure & Leung, 2024; Pelemeniano & Siega, 2023). Siller et al. (2023) assert that the intricate nature of the tasks, which demand not only a thorough understanding of fundamental mathematical concepts but also the ability to apply these concepts in practical situations, frequently exacerbates the lack of confidence.

Additionally, students unfamiliar with the iterative and sometimes uncertain modeling process may feel overwhelmed and may doubt their ability to complete the tasks Chen (2022). According to Haara (2022), the fear of failure, especially in environments that promote experimentation and learning from errors, might also discourage students from participating in modeling activities. The challenges of navigating the modeling process when faced with high standards and intricate issues, indicate the need for techniques that increase students' trust in themselves and their ability to face modeling challenges.

Foundational knowledge and conceptual understanding deficiencies

The studies consistently highlighted the challenges that students encounter because of deficiencies in fundamental mathematical understanding, specifically in subjects such as algebra, trigonometry, and geometry (Pelemeniano & Siega, 2023; Tezer & Cumhur, 2017). However, these shortcomings are of the utmost significance since they serve as the foundation for more advanced modelling tasks. Scholars have observed that students encounter difficulties in comprehending abstract ideas that are required for effective modelling (Siller et al., 2023). Furthermore, this challenge often becomes worse when they must apply these concepts in complicated and realistic situations (Wang et al., 2023).

In addition, introducing advanced concepts, such as the phrase "mathematical model," too early in education could cause misunderstandings and affect students' ability to actively participate in the modelling process (Krutikhina et al., 2018). This observation underscores the necessity of employing a more straightforward and organized approach in the classroom teaching of modelling, ensuring students gain a thorough comprehension of fundamental concepts before tackling more intricate tasks. In addition, it is necessary to address misunderstandings at an early stage and provide students with the required basic knowledge to facilitate their success in modelling.

Problem formulation and application of mathematical concepts

Another significant challenge that students face is the initial stages of problem formulation and the subsequent application of mathematical concepts to real-world problems. Quite a few students struggle to clearly understand and define the presented problem, which is an essential first step in the modelling process (Falcó-Solsona et al., 2024). This difficulty in problem formulation can lead to further challenges in applying the appropriate mathematical techniques and concepts to develop a solution (Xu et al., 2022).

The abstract nature of many mathematical concepts, combined with the complexity of real-world problems, often makes it difficult for students to identify the most suitable models and justify their choices (Siller et al., 2023). This challenge gets worse with the need to simplify and translate complex, real-world situations into concise mathematical statements, a task that many students find overwhelming (Albarracín & Gorgorió, 2020; Wang et al., 2023). Therefore, effective strategies to help students navigate these challenges are crucial on problem formulation and the strategic application of mathematical concepts.

Cognitive load and the complexity of modelling processes

The cognitive demands of modelling tasks are another barrier to student success. The process of building a mathematical model necessitates a deep understanding of abstraction, critical thinking, and logical inference, which can significantly strain students' cognitive abilities (Krutikhina et al., 2018). Students often find it challenging to manage the various steps involved in the modeling process, particularly when these steps require a revise at previous stages and refining their approach (Falcó-Solsona et al., 2024).

Moreover, the need to evaluate initial information, introduce missing data, and choose appropriate numerical values adds to the complexity, potentially overwhelming students (Krutikhina et al., 2018). The difficulty of navigating through tasks that require multiple solutions or involve complicated problem-solving also contributes to the cognitive load, making it challenging for students to maintain focus and progress effectively through the modeling process (Greefrath, 2020). To effectively address these cognitive issues, educators must ensure that students receive adequate guidance and support, ensuring that they acquire the required skills and are able to handle the cognitive demands of the activity.

Collaborative work and communication

Collaborative work, a common aspect of modelling tasks, is one of the challenges while doing the activities. Although cooperation has the potential to improve the learning process, it may also cause disagreements and misunderstandings if not properly handled (Falcó-Solsona et al., 2024). Students may struggle effectively communicating their ideas and working together, particularly if they lack previous experience in collaborative problem-solving (Chen, 2022). These challenges are often made worse by the various levels of mathematical intelligence within a group, resulting in difficulty achieving agreement or progress throughout the task of modeling (Albarracín & Gorgorió, 2020).

Additionally, students who have adapted to conventional teaching techniques may encounter further difficulty when faced with collaborative modeling activities due to their less organized and more standalone character (Haara, 2022). Expecting students to engage in open-ended exploration and critical discussion can be stressful, particularly if they lack clear guidelines and support. Ensuring that collaborative work is productive requires careful planning, effective facilitation, and the development of students' communication skills, all of which are critical for successful engagement in modelling activities.

Technological and resource-based

The availability and effective use of technology and other resources also cause significant challenges in modelling. While technology greatly enhances the modelling process, students often struggle to utilize digital tools and software effectively, particularly when these tools require advanced technical skills (Geiger, 2017; Greefrath, 2020). These challenges have the potential to limit students' ability to develop and analyze models, especially when they are unable to fully utilize the functionalities of the tools (Brown, 2015).

Furthermore, the lack of appropriate resources, such as access to necessary technology or physical spaces for collaborative work, could affect modelling activities (Manunure & Leung, 2024). These issues have been particularly understandable in educational environments with limited resources, since the lack of appropriate materials and equipment might restrict students' ability to fully participate in modelling projects. Addressing these challenges requires not only improving access to technology and resources but also providing students with the necessary training to use the tools effectively.

CONCLUSIONS

This study reveals the complex relationships between the potential benefits derived from modelling and the challenges that affect its effective integration in educational environments. In conclusion, modelling represents a significant contribution to bridging the gap between theoretical knowledge and real-world applications. Engaging in these teaching approaches allows students to apply abstract mathematical concepts in realistic problem-solving scenarios, thereby enhancing their understanding and retention of mathematical concepts (Albarracín & Gorgorió, 2020; Siller et al., 2023). However, challenges related to students' perspective and belief in their own abilities can sometimes obstruct the successful inclusion of modelling practices, particularly among those who have had problematic experiences in the field of mathematics. This underscores the need for educational approaches that enhance student confidence and provide incremental learning opportunities that may support a complex process of modelling (Haara, 2022; Manunure & Leung, 2024).

The study also highlights the challenges posed by inadequate fundamental mathematical understanding, which significantly hinders students' ability to actively engage in modelling tasks. Students who lack a solid understanding of fundamental mathematics concepts, such as algebra and geometry, have significant challenges when it comes to both the development and resolution of modelling issues (Pelemeniano & Siega, 2023). Failure to complete complex modelling tasks on time can exacerbate these challenges, leading to misunderstandings and knowledge deficiencies that hinder the acquisition of further relevant information (Xu et al., 2022). Hence, the use of a structured approach for teaching modelling, which continuously enhances students' previously present knowledge and progressively introduces a bit more complex ideas, is essential in fostering efficacious academic performance (Siller et al., 2023). Teaching strategies that prioritize the issue formulation process and the practical application of mathematical ideas have significant importance in assisting students in effectively addressing the difficulties related to real-world problem-solving (Krutikhina et al., 2018).

Finally, this study highlights the significant cognitive needs associated with modelling, as well as the additional challenges caused by collaboration and technology use. According to (Greefrath, 2020), students may have a significant cognitive burden while engaging in modelling tasks, especially when they must deal with handling numerous steps and repeating prior stages of the process. This might result in a possible lack of participant involvement. Engaging in collaborative work, while beneficial for enhancing learning via peer interaction, presents extra intricate structure, particularly when students demonstrate various levels of mathematical skill (Albarracín & Gorgorió, 2020). Although the integration of technology is promising, it also poses challenges, particularly for students with limited technical proficiency in accessing and using digital tools for simulation purposes (Geiger et al., 2018). To tackle these problems, it is essential to provide students with the necessary guidance to handle cognitive burden and ensure equipping them with the appropriate skills and resources needed for efficient collaboration and utilization of technology (Brown & Stillman, 2017; Greefrath, 2020). These observations emphasize the need to implement a complete and supportive educational environment to optimize the advantages of modelling in promoting students' learning development.

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REFERENCES

Albarracín, L., & Gorgorió, N. (2020). Mathematical modeling projects oriented towards social impact as generators of learning opportunities: A case study. *Mathematics*, *8*(11), 1-20. https://doi.org/10.3390/math8112034

Bas-Ader, S., Erbas, A. K., Cetinkaya, B., Alacaci, C., & Cakiroglu, E. (2023). Secondary mathematics teachers' noticing of students' mathematical thinking through modeling-based teacher investigations. *Mathematics Education Research Journal*, *35*(0123456789), 81-106. https://doi.org/10.1007/s13394-021-00389-4

Blum, W., & Borromeo-Ferri, R. (2009). Mathematical modelling: Can it be taught and learnt? *Journal of Mathematical Modelling and Application*, *1*(1), 45-58. https://www.researchgate.net/publication/279478754

Boers, M. (2018). Graphics and statistics for cardiology: Designing effective tables for presentation and publication. In *Heart* (Vol. 104, Issue 3, pp. 192-200). BMJ Publishing Group. https://doi.org/10.1136/heartjnl-2017-311581

Borromeo-Ferri, R., & Blum, W. H.-J. (2019). Barriers and motivations of primary teachers for implementing modelling in mathematics lessons. In *Proceedings of the Eighth Congress of the European Society for Research in Mathematics Education* (pp. 1000-1010). https://www.researchgate.net/publication/333353117

Braun, V., & Clarke, V. (2019). Reflecting on reflexive thematic analysis. *Qualitative Research in Sport, Exercise and Health*, *11*(4), 589-597. https://doi.org/10.1080/2159676X.2019.1628806

Braun, V., & Clarke, V. (2021). Conceptual and design thinking for thematic analysis. *Qualitative Psychology*, *9*(1), 3-26. https://doi.org/10.1037/qup0000196

Brown, J. P. (2015). Visualisation tactics for solving real world tasks. In *International perspectives on the teaching and learning of mathematical modelling*. https://doi.org/10.1007/978-3-319-18272-8_36

Brown, J. P., & Stillman, G. A. (2017). Developing the roots of modelling conceptions: 'mathematical modelling is the life of the world.' *International Journal of Mathematical Education in Science and Technology*, *48*(3), 353-373. https://doi.org/10.1080/0020739X.2016.1245875

Bruner, J. (1997). Humon development celebrating divergence: Piaget and Vygotsky1. In *Human Development* (Vol. 40). https://doi.org/10.1159/000278705

Carreira, S., Baioa, A. M., & de Almeida, L. M. W. (2020). Mathematical models and meanings by school and university students in a modelling task. *Avances de Investigacion En Educacion Matematica*, *17*, 67-83. https://doi.org/10.35763/AIEM.V0I17.308

Cevikbas, M., Greefrath, G., & Siller, H. S. (2023). Advantages and challenges of using digital technologies in mathematical modelling education – A descriptive systematic literature review. In *Frontiers in education* (Vol. 8). Frontiers Media S.A. https://doi.org/10.3389/feduc.2023.1142556

Chen, Y. (2022). Measurement, evaluation, and model construction of mathematical literacy based on IoT and PISA. *Mathematical Problems in Engineering*, *2022*. https://doi.org/10.1155/2022/3278401

Falcó-Solsona, P. J., Ledezma, C., Sala-Sebastià, G., & Font, V. (2024). Inquiry and mathematical modelling with real-archaeological objects in secondary education. *Education Sciences*, *14*(3). https://doi.org/10.3390/educsci14030304

Geiger, V. (2017). Designing for mathematical applications and modelling tasks in technology rich environments. *Mathematics Education in the Digital Era 8: Digital Technologies in Designing Mathematics Education Tasks*, 285-301. https://doi.org/10.1007/978-3-319-43423-0_14

Geiger, V., Stillman, G., Brown, J., Galbriath, P., & Niss, M. (2018). Using mathematics to solve real world problems: The role of enablers. *Mathematics Education Research Journal*, *30*(1), 7-19. https://doi.org/10.1007/s13394-017-0217-3

Greefrath, G. (2020). Mathematical modelling competence. Selected current research developments. *Avances de Investigacion En Educacion Matematica*, *17*, 38-51. https://doi.org/10.35763/AIEM.V0I17.303

Haara, F. O. (2022). Mathematical modelling in upper primary school: Finding relevance and value for others outside school. *European Journal of Science and Mathematics Education*, *10*(4), 555-569. https://doi.org/10.30935/scimath/12403

Hagena, M., Leiss, D., & Schwippert, K. (2017). Using reading strategy training to foster students' mathematical modelling competencies: Results of a quasi-experimental control trial. *Eurasia Journal of Mathematics, Science and Technology Education*, *13*(7), 4057-4085. https://doi.org/10.12973/eurasia.2017.00803a

Hankeln, C. (2020). Mathematical modeling in Germany and France: A comparison of students' modeling processes. *Educational Studies in Mathematics*, *10*(3), 209-229. https://doi.org/10.1007/s10649-019-09931-5

Holenstein, M., Bruckmaier, G., & Grob, A. (2022). How do self-efficacy and self-concept impact mathematical achievement? The case of mathematical modelling. *British Journal of Educational Psychology*, *92*(1), 155-174. https://doi.org/10.1111/bjep.12443

Kaiser, G., & Brand, S. (2015). Modelling competencies: Past development and further perspectives. In *International Perspectives on the Teaching and Learning of Mathematical Modelling*. https://doi.org/10.1007/978-3-319-18272-8_10

Krutikhina, M. V., Vlasova, V. K., Galushkin, A. A., & Pavlushin, A. A. (2018). Teaching of mathematical modeling elements in the mathematics course of the secondary school. *Eurasia Journal of Mathematics, Science and Technology Education*, *14*(4), 1305-1315. https://doi.org/10.29333/ejmste/83561

Ledezma, C., Font, V., & Sala, G. (2023). Analysing the mathematical activity in a modelling process from the cognitive and onto-semiotic perspectives. *Mathematics Education Research Journal*, *35*(4), 715-741. https://doi.org/10.1007/s13394-022-00411-3

Ledezma, C., Sol, T., Sala-Sebastià, G., & Font, V. (2022). Knowledge and beliefs on mathematical modelling inferred in the argumentation of a prospective teacher when reflecting on the incorporation of this process in his lessons. *Mathematics*, *10*(18). https://doi.org/10.3390/math10183339

Lu, X., & Huang, J. (2021). Mathematical modelling in China: How it is described and required in mathematical curricula and what is the status of students' performance on modelling tasks. *Research in Mathematics Education: Beyond Shanghai and PISA*, 209-234. https://doi.org/10.1007/978-3-030-68157-9_12

Manunure, K., & Leung, A. (2024). Integrating inquiry and mathematical modeling when teaching a common topic in lower secondary school: An iSTEM approach. *Frontiers in Education*, *9*. https://doi.org/10.3389/feduc.2024.1376951

Mayo-Wilson, E., Li, T., Fusco, N., & Dickersin, K. (2018). Practical guidance for using multiple data sources in systematic reviews and meta-analyses (with examples from the MUDS study). *Research Synthesis Methods*, *9*(1), 2-12. https://doi.org/10.1002/jrsm.1277

Niss, M., Blum, W., & Galbraith, P. (2007). Modelling and applications in mathematics education. In W. Blum, P. L. Galbraith, H.-W. Henn, & M. Niss (Eds.), *Modelling and applications in mathematics education: The 14th ICMI study* (14th ed., pp. 1-32). Springer Science+Business Media, LLC. https://doi.org/10.1007/978-0-387-29822-1_59

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. In *BMJ* (Vol. 372). BMJ Publishing Group. https://doi.org/10.1136/bmj.n71

Pelemeniano, A. P., & Siega, M. H. (2023). Integrating mathematical modeling of real-life problems: A contextualized approach to developing instructional material in basic calculus. *International Journal of Membrane Science and Technology*, *10*(3), 149-163. https://doi.org/10.15379/ijmst.v10i3.1498

Rellensmann, J., Schukajlow, S., & Leopold, C. (2020). Measuring and investigating strategic knowledge about drawing to solve geometry modelling problems. *ZDM - Mathematics Education*, *52*(1), 97-110. https://doi.org/10.1007/s11858-019-01085-1

Rojas, F., Montenegro, H., & Goizueta, M. (2021). Researching modelling by mathematics teacher educators: Shifting the focus onto teaching practices. *The Learning and Development of Mathematics Teacher Educators: International Perspectives and Challenges*, 367-382. https://doi.org/10.1007/978-3-030-62408-8_19

Sebastia, G. S., Barquero, B., & Font, V. (2021). Inquiry and modeling for teaching mathematics in interdisciplinary contexts: How are they interrelated? *Mathematics*, *9*(15). https://doi.org/10.3390/math9151714

Siller, H.-S., Elschenbroich, H.-J., Greefrath, G., & Vorhölter, K. (2023). Mathematical modelling of exponential growth as a rich learning environment for mathematics classrooms. *ZDM - Mathematics Education*, *55*(1), 17-33. https://doi.org/10.1007/s11858-022-01433-8

Sternberg, R. J. (1994). Styles of thinking and learning. In J. Thornton (Ed.), *Language aptitude invitational symposium program proceedings* (pp. 51-73). Center for the Advancement of Language Learning.

Stillman, G. A., Blum, W., & Kaiser, G. (2017). Crossing boundaries in mathematical modelling and applications educational research and practice. In *International Perspectives on the Teaching and Learning of Mathematical Modelling*. https://doi.org/10.1007/978-3-319-62968-1_1

Stovold, E., Beecher, D., Foxlee, R., & Noel-Storr, A. (2014). Study flow diagrams in Cochrane systematic review updates: An adapted PRISMA flow diagram. *Systematic Reviews*. https://doi.org/10.1186/2046-4053-3-54

Tezer, M., & Cumhur, M. (2017). Mathematics through the 5E instructional model and mathematical modelling: The geometrical objects. *Eurasia Journal of Mathematics, Science and Technology Education*, *13*(8), 4789-4804. https://doi.org/10.12973/eurasia.2017.00965a

Wang, T., Zhang, L., Xie, Z., & Liu, J. (2023). How does mathematical modeling competency affect the creativity of middle school students? The roles of curiosity and guided inquiry teaching. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.1044580

Xiao, Y., & Watson, M. (2019). Guidance on Conducting a Systematic Literature Review. In *Journal of Planning Education and Research* (Vol. 39, Issue 1, pp. 93–112). SAGE Publications Inc. https://doi.org/10.1177/0739456X17723971

Xu, B., Lu, X., Yang, X., & Bao, J. (2022). Mathematicians', mathematics educators', and mathematics teachers' professional conceptions of the school learning of mathematical modelling in China. *ZDM - Mathematics Education*, *54*(3), 679-691. https://doi.org/10.1007/s11858-022-01356-4