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(Review Article)

The necessity of modeling at school and the teacher's role

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Abstract

The following study highlights the significance of understanding complex systems and integrating mathematical modeling into the educational process. In a world characterized by complex and interconnected systems, developing students' abilities to approach and solve real-world problems through mathematical reasoning is considered essential. Modeling, as a process of transforming a real-life situation into a mathematical model, enhances conceptual understanding, decision-making, and data interpretation. Within the educational context, it is recommended that modeling activities be incorporated from the early stages of schooling, with the teacher playing a pivotal role in facilitating the process. Research conducted in various countries demonstrates the effectiveness of modeling in developing mathematical competencies, fostering hypothetical thinking, and activating students' creativity. Therefore, modeling is not merely a teaching technique but a fundamental tool for cultivating mathematical literacy and for fostering an in-depth understanding of the contemporary world. Finally, it is presented the author's creative model setting an example of modeling reality issues.

Keywords: Modeling; Mathematical Models; Education; Teachers' Role

1. Introduction

We live in a world surrounded by systems. Governments, economic organizations, academic institutions, ecosystems, the World Wide Web, and the human body are just a few examples of complex systems. In the 21st century, it is becoming increasingly important for all individuals—both children and adults—to be capable of understanding and appreciating the world as a complex system, in order to make informed and effective decisions in their lives, both as individuals and as members of a broader community (Jakobsson & Wilensky, 2006, as cited in English, 2006).

Defining such systems is inherently challenging. However, broadly speaking, complex systems can be described as consisting of interconnected elements whose collective behavior emerges in often contradictory and surprising ways from the properties of the individual components and their interrelations (Jakobsson et al., 2006, as cited in English, 2006). Furthermore, according to Jakobsson et al. (2006), it is essential to recognize that engaging with the realities of these systems also entails engaging with models of these systems.

In the field of education, researchers have observed that students often exhibit limited or even no understanding of complex systems. Consequently, there is strong advocacy for a greater emphasis on such systems within the core curricula of primary and secondary education (Hmelo-Silver & Azevedo, 2006; Jakobsson & Wilensky, 2006; Lesh, 2006, as cited in English, 2006). More specifically, it is necessary to integrate targeted activities related to complex systems into school curricula from an early age (Jakobsson & Wilensky, 2006; English & Waters, 2005, as cited in English, 2006).

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One effective approach to achieving this goal is through mathematical modeling, a process in which children engage in mathematical thinking about relationships, patterns, and regularities as they work on authentic, real-world problems.

This paper will primarily focus on mathematical models, the modeling process, empirical research on modeling in primary and secondary school settings, and the role of the educator throughout the modeling process. Finally, we will present an original modeling problem designed for implementation in the upper grades of primary school as well as in lower secondary education.

2. Models and mathematical models

Numerous definitions have been proposed regarding the concept of a model. We present a few representative examples:

Models are images of real-world objects—images that highlight characteristics of the object which are considered to be irrelevant (Neunzert, 2013).

Models are systems of elements, functions, and rules that can be used to describe, explain, or predict the behavior of certain familiar systems (Doerr, 2003; English, 2006).

The modeling process typically begins with an elicitation phase, during which students are confronted with the need to construct such a model. What is particularly noteworthy about these models is that their underlying structure holds inherent mathematical interest (Doerr, 1997; Lesh & Doerr, 2000; Lesh & Doerr, in press, as cited in Doerr, 2003).

In a similar vein, mathematical models can be defined as models that employ mathematical approaches to interpret and make decisions about real-world phenomena (Hernandez, Levy, Felton-Koestler &Zbiek, 2016–2017) or a process of forming a representational system which can be used to interpret and solve a real-world problem (Lesh & Doerr, 2003 as cited in Jung & Wickstrom, 2023). According to Koleza (2009), a mathematical model is *"a representation of objects, relationships, and rules, or of a given problem"* (Koleza, 2009 p. 362).

Thus, a model may take the form of a graph, an Excel spreadsheet, an image, a data table, or a system of mathematical relationships. Models aim to represent the most essential properties of a problem, and they are typically presented in a format that facilitates interpretation (Koleza, 2009).

It is important to note, however, that a model cannot provide an exact depiction of a real-world situation; as such situations are often characterized by unpredictable and complex parameters. During the modeling process, certain secondary parameters must be excluded, a task that requires specialized knowledge. Nevertheless, the use of models can lead to the discovery of new mathematical insights, the development of experimental procedures, and the creation of innovative techniques and concepts (Koleza, 2009).

3. The Modeling competence and the need for its integration into education

As previously mentioned the emerging trends of our era underscore the necessity of modeling competence, as it is vital for individuals' daily lives and for addressing the increasingly complex problems posed by contemporary conditions. According to De Corte (as cited in Koleza, 2009), effectively dealing with these challenges requires individuals to possess the following skills:

- the flexible application and integration of knowledge and skills acquired in school to novel and unfamiliar situations;
- systematic strategies for searching, selecting, and managing relevant and necessary information from large volumes of data;
- metacognitive skills, namely the continuous updating of one's knowledge and competencies beyond formal schooling, in response to rapid developments in the professional, technological, and social domains.

In order to achieve such an educational goal, it is essential to create dynamic learning environments. In the field of mathematics, the foundation for constructing such environments lies in the processes of mathematical modeling and problem solving (Koleza, 2009).

Blum and Niss (1991, as cited in Koleza, 2009) identified four major arguments in favor of integrating modeling into the mathematics curriculum:

The formative and instrumental argument emphasizes on the learner and on the process of his personal growth and cognitive development.

The practical argument highlights both the individual and society, positing that modeling should aim to equip learners with the ability to investigate and understand real-world situations, both within and beyond mathematics.

The critical argument focuses on the societal implications of various models and promotes the acquisition of skills such as critical understanding, analysis, and reflection through the modeling process.

The cultural argument emphasizes on the value of mathematics as a scientific discipline and seeks to highlight its cultural and intellectual significance (Koleza, 2009).

4. Mathematical modeling – Stages of the Modeling process

Mathematical modeling refers to the representation of a real-world situation through a mathematical model. According to GAIMME (Guidelines for Assessment and Instruction in Mathematical Modeling Education), mathematical modeling is defined as *"the process of using mathematics to represent, analyze, make predictions, or otherwise provide insight into real-world phenomena. Modeling is iterative and involves frequent revision. It also involves messy, open-ended problems that require students to make authentic decisions about how to mathematize the situation, what assumptions to make, and how to evaluate the effectiveness of the approach they used"* (GAIMME, 2016, pp. 8 & 13, as cited in Hernandez et al., 2016–17).

Another definition provided by the National Academy of Engineering (NAE) and the International Technology and Engineering Educators Association (ITEEA) describes modeling as *"a product or representation"* (ITEEA, 2007; Katehi et al., 2009, as cited in Mentzer, Huffman, & Thayer, 2014). The NAE further notes that modeling includes *"any graphical, physical, or mathematical representation of key characteristics of a system or process that supports engineering design"* (ITEEA, 2007; Katehi et al., 2009, p. 87, as cited in Mentzer, Huffman, & Thayer, 2014).

Mathematical modeling project production is a multifaceted process that entails identifying and addressing real-life problems through the development of mathematical solution models (Kaiser & Grünewald, 2015; Özbek & Köse, 2022 as cited in Özbek et al., 2023). As a complex educational and cognitive task, it involves a sequence of competencies and stages (Blum &Niss, 1991; Borromeo Ferri, 2006; Erbaş et al., 2014; Maaß, Zehetmeier et al., 2022; Sak et al., 2015 as cited in Özbek & Köse, 2022).

In order for modeling to be effectively implemented, certain stages must be followed. Researchers have proposed several frameworks outlining the steps students should take to model a given problem. Blum and Niss (2007, as cited in Djepaxhija, Vos, & Fuglestad, 2016) conceptualized the modeling process as a sequence of distinct phases (see Fig. 1):

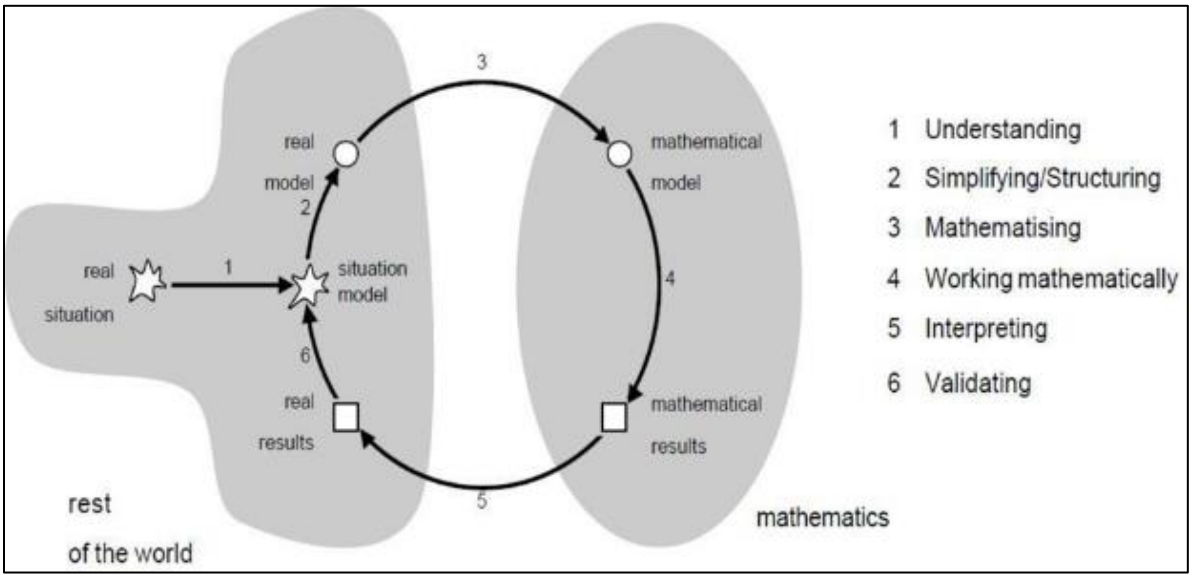

Figure 1 Modeling process of a problem

- Step 1: Understanding the "real-world situation" and constructing a model of the situation.
- Step 2: Idealizing the model into a "realistic model" through relevant structuring, assumptions, and simplifications.
- Step 3: Translating the "realistic model" into a "mathematical model" (typically represented as an algebraic formula).
- Step 4: Utilizing the mathematical model to derive mathematical results.
- Step 5: Interpreting the mathematical results in terms of "realistic results."
- Step 6: Validating the results in light of the original problem context.

Borromeo Ferri (2006), however, argues that the modeling process is more complex and non-linear, with certain phases overlapping. Moreover, the formulation and construction of the problem significantly influence the overall modeling process. She emphasizes that the most critical stage in modeling is *mathematization*—the act of translating a "realistic model" into a "mathematical model." This stage is particularly intricate and, according to research, presents considerable difficulties and obstacles for students (Schaap et al., 2011; Stillman & Brown, 2012; Stillman, Brown & Galbraith, 2010, as cited in Djepaxhija et al., 2016).

Another crucial point within the process of mathematization is the formulation of assumptions. Inadequate or poorly constructed assumptions often lead to an insufficient model of the problem situation, ultimately hindering the quality and applicability of the resulting model (Djepaxhija et al., 2016).

According to GAIMME (2016), the modeling process also consists of six distinct phases, as illustrated in Figure 2:

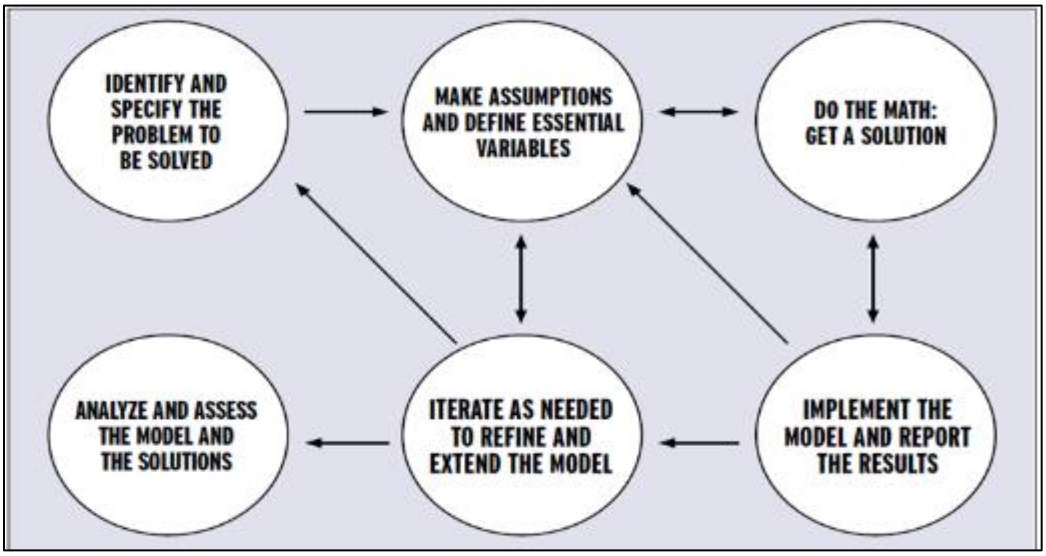

Figure 1 Modeling process' phases

In the initial phase, the problem is identified and understood. Subsequently, hypotheses are formulated, and the variables to be used are defined in order to construct the idealized model. This model is then translated into a mathematical model. The outcomes of the mathematical model are analyzed and evaluated. If necessary, the process is repeated to refine or expand the model. In the final stage, the model is applied to the real world, the results of its implementation are reported, and the solution is integrated accordingly (GAIMME, 2016, as cited in Hernandez, 2016–17).

There are similar or alternative modelling frameworks proposed by other researchers, such as the cycle of modeling by Lester and Kelle (2003, as cited in Koleza, 2009 and Koleza&Iatridou 2006). However, due to space constraints, it is not feasible to include them all in this paper.

Teaching mathematical modeling is a demanding task, particularly for educators who are new to the process. The following framework outlines, in general terms, the teacher's role during students' engagement in modeling activities.

Initially, the teacher is responsible for selecting and designing the modeling task. They must also anticipate potential questions students may raise regarding how to approach the problem mathematically, as well as consider the extent to which students are familiar with the content and mathematical concepts that are likely to be involved in the given task.

Before introducing the modeling activity, it is advisable for the teacher to reflect on several key questions, such as: What types of questions might students ask about the context? What additional information might they require, and how will they obtain it? What assumptions are they likely to make in constructing their model? What kinds of problem-solving strategies are they expected to pursue? These considerations are essential for effectively facilitating the modeling process and supporting student learning.

5. The role of the educator during the Modeling process

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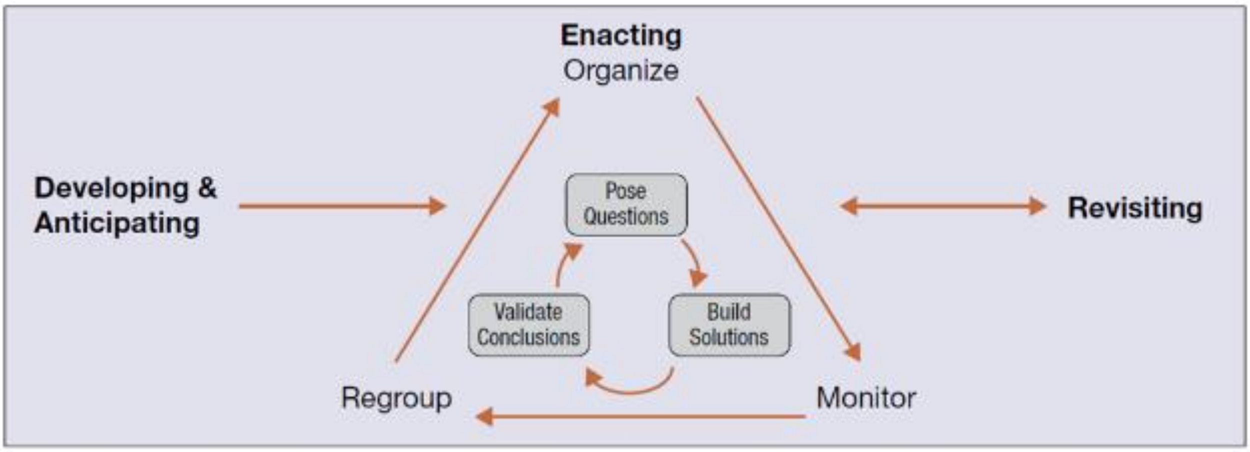

Fig. 4 The diagram illustrates the framework for teachers' roles in modeling (Carlson et al. 2016, p. 122).

Figure 3 Teacher's role during Modeling

According to a substantial body of literature, the role of the teacher during mathematical modeling involves the following key responsibilities:

- Organizing and presenting the modeling task in a clear and structured manner, while allocating sufficient time for students to ask clarifying questions to ensure full comprehension of the problem at hand.
- Facilitating brainstorming sessions to encourage students to share their initial ideas and proposed approaches to the task.
- Documenting students' strategies and assumptions as they engage with the task.
- Periodically regrouping the class to clarify misconceptions, address questions, and offer constructive suggestions.
- Encouraging students to critically analyze their solutions and evaluate the effectiveness and appropriateness of their models.
- Summarizing the central mathematical concepts and methods employed during the problem-solving process.

Reviewing and reflecting on any changes or extensions to the problem, while considering whether students' solutions remain valid and applicable to the revised scenarios (Hernandez et al., 2016–17).

6. Research on the implementation of Modeling

A substantial body of research has been conducted in school settings, particularly within secondary education. Below, we present two indicative studies, outlining their context, sample, and key findings.

6.1. Study A

Twenty students from four different U.S. states were asked to individually engage in a modeling task related to engineering design. The aim of the study was to investigate the types of modeling in which students became involved during the design challenge. Both quantitative methods (recording the time management of the assigned tasks) and qualitative methods (interviews) were employed for data collection. The results, supported by three student case studies presented in the research, revealed that only a few students engaged in mathematical modeling—an essential component in the field of engineering—while the majority focused primarily on graphical modeling. This indicates a notable imbalance in the types of modeling being practiced. According to the researchers, greater emphasis should be placed on training students in mathematical modeling, particularly when their field of study, such as engineering, requires it. This goal can be achieved through the integration of modeling-focused courses within the school curriculum (Mentzer et al., 2014).

6.2. Study B

The second study focused on four randomly selected ninth-grade students in Albania. The motivation for the research stemmed from the poor performance of Albanian students in PISA assessments. The aim was to examine the assumptions students made during the process of "mathematization"—the stage in modeling in which the real-world model is translated into a mathematical one. Data were collected in three phases: observation and video recording of students working in pairs on modeling exercises; students' commentary on selected excerpts from their activities; and individual interviews with one of the researchers for further clarification on specific references made during the problem-solving process.

The results showed that students were capable of making three types of assumptions: parametric assumptions, assumptions concerning the choice of the mathematical model, and extra-mathematical assumptions. However, some assumptions were found to hinder the modeling process. When students formulated correct and meaningful assumptions during mathematization, they were more likely to achieve successful modeling outcomes (Djepaxhija et al., 2016).

6.3. Study C

A modeling study conducted in Queensland, Australia, involved three Year 4 classrooms (students aged 9) and their teachers. Initially, the teachers participated in workshops focused on mathematical modeling problems and strategies for integrating them into classroom practice. Subsequently, in collaboration with the researchers, four modeling problems were implemented in the classrooms, with each task lasting approximately 60–70 minutes.

The study presents in detail the "Swimmer Selection for Friendly Games" problem. In this task, students were provided with a table featuring a series of well-known Australian athletes, along with data regarding their participation (or non-participation) in specific swimming styles and their recorded times. The students were asked to select two swimmers to represent their group in friendly competitions. They worked in small groups of three to four students, without being given specific instructions on how to approach the task. At the end of the activity, each group presented their problem-solving models to their classmates.

A wide range of questions and problem-solving approaches was observed. Unlike traditional problem-solving scenarios, students developed models that offered valuable insights into the variety of mathematical processes they employed. These included data elimination, data classification and organization, assignment of results, calculation and comparison of averages, and the aggregation of differences between successive data sets.

In summary, the study concludes that introducing children to complex systems through mathematical modeling empowers them to engage meaningfully with real-world problems that are of interest to them (English, 2006).

7. Our Modeling Problem – First Version

In a primary school classroom with 18 students, it is decided to cut a Vasilopita (a traditional Greek New Year's cake) in the shape of a rectangular parallelogram with dimensions 30 cm by 40 cm. including the teacher and a symbolic piece for Jesus Christ, the total number of pieces must be 20. The task is to determine the dimensions xx and yy of each piece so that the pieces are as large as possible. Additionally, the cake contains a coin (the traditional "flouri") with a radius of 1 cm.

Area of each piece:

$$A_{piece} = x \cdot y$$

Our constraints for each piece: 1. $x \geq 0$, $y \geq 0$ 2. $x \leq 40$, $y \leq 30$ 3. $20 \cdot x \cdot y \leq 1200\ cm^2$ και $x \cdot y \leq 60$
Our constraints related to the coin (flouri):
Area of the coin: $A_{coin} = \pi \cdot r^2 = 3.14 \cdot 1 = 3.14 cm^2$

1. $x \cdot y \geq 3.14\ cm^2$

2. $x \geq 2$ και $y \geq 2$

Second Version of the Same Problem (More Complex)

In a primary school classroom, students decide to hold a small celebration for the traditional cutting of the *Vasilopita* (New Year's cake). The 18 students of the class, along with their teacher, will participate in the event.

The cake, which is either square or rectangular in shape, will be divided into equal square pieces. It is assumed that the coin (*flouri*) will fall at the center of one piece.

- How many pieces should the cake be divided into, considering that an extra piece will be cut for Christ?
- What are the minimum dimensions each piece must have in order to fully contain the coin?
- What are the minimum overall dimensions of the cake if the coin has a radius of 1 cm?
- Is it possible for the cake that will be ordered to be square-shaped?
- If the cake is rectangular, with dimensions 30 cm by 40 cm and it is to be cut into equal square pieces, what are the possible dimensions of the individual pieces?
- What can we say about the dimensions of the pieces if the same cake does not contain a coin?

We have the following formulas:

$A_{piece} = x \cdot x$ (area of a square)

$A_{cake} = a \cdot b$ (area of a rectangle)

Our constraints for each piece:

$x \geq 2 \cdot r$ (where r is the radius of the coin; if there is no coin, then $r=0$ $r = 0$)

$c \cdot x \cdot x \leq a \cdot b$ (where a, b are the dimensions of Vasilopita, and c the amount of the pieces)

The relationship we are going to examine is:

What we want is: $c \cdot E_{piece} \leq E_{vasilopita}$

Let us consider the inequality: $c \cdot x^2 \leq a \cdot b$, which implies that, the roots of the function $p(x) = a \cdot b - c \cdot x^2$, where $\mathbf{x} \geq 2 \cdot r$, define the maximum allowable size of an individual piece. The segment of the function's graph that lies above the x-axis (i.e., where $p(x) > 0$) corresponds to acceptable values of **x**—that is, feasible piece sizes. However, these do not entirely exhaust the cake, since the difference Total area ofthe cake − Total area of all pieces = $a \cdot b - c \cdot x^2$remains positive, implying that part of the cake is left over. In our model, two distinct functions are considered:

The green curve, p(x):

This represents the graph of the function $p(x) = a \cdot b - c \cdot x^2$, under the constraint $\mathbf{x} \geq 2 \cdot r$—a condition ensuring that each piece is large enough to contain the hidden coin (flouri). If the piece becomes too small (i.e., $\mathbf{x} < 2 \cdot r$), the function has no real roots within the domain, indicating that such pieces cannot accommodate the coin. The portion of the curve lying below the x-axis (where $p(x) < 0$) signifies scenarios in which the total area of the cake is insufficient to produce **c** pieces of size $\mathbf{x^2}$—that is, $\mathbf{c \cdot x^2} > a \cdot b$.

The red segment

This refers to the subset of the green function's graph where the cake can adequately cover all pieces, and the size of each piece satisfies the constraint $\mathbf{x} \geq 2 \cdot r$. It represents the feasible solutions—combinations of piece size and count—where both the spatial requirement of the coin and the total area limitation of the cake are respected.

Adjustable parameters ("sliders") in the model:

c: allows variation in the number of pieces.
a, b: define the dimensions (length and width) of the cake.
r: denotes the radius of the coin; setting
r = 0 encodes the absence of a coin.

8. Conclusion

The present study underscores the critical role of mathematical modeling in contemporary education, emphasizing its potential to equip students with the skills necessary to understand and analyze complex systems. The literature review reveals that modeling fosters essential competencies such as critical thinking, problem-solving, hypothesis formulation, and data interpretation, all of which are vital in a world characterized by dynamic and interconnected phenomena. Empirical research conducted in various educational settings—from primary to secondary schools—demonstrates that modeling not only enhances students' mathematical understanding but also encourages creativity, collaboration, and reflective thinking. Studies further indicate that successful modeling depends heavily on well-designed tasks and the teacher's facilitative role throughout the process, especially in guiding mathematization and assumption-making. Integrating modeling activities into the school curriculum benefits both students and the broader educational environment. For students, it offers a meaningful connection between abstract mathematical concepts and real-life contexts, making learning more relevant and engaging. At the same time, schools become arenas for cultivating mathematical literacy and systemic thinking, preparing learners to make informed decisions as future citizens. The modeling approach thus, emerges not only as a pedagogical tool, but also as a transformative practice with significant cognitive, practical, and cultural implications in education.

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