Enhancing mathematical understanding through dynamic GeoGebra modeling: A holistic educational approach

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Abstract

This paper presents an innovative approach to enhancing mathematical understanding through interactive modeling using GeoGebra software, based on holistic educational principles. The research describes the development and implementation of a comprehensive complex of dynamic mathematical models created within inter-university projects of the Kharkiv GeoGebra Institute. The complex comprises three distinct categories of models: fundamental mathematical concept visualization, transdisciplinary connections demonstration, and real-world problem-solving applications. A systematic methodology for model development was implemented, incorporating theoretical foundations of holistic education and practical considerations for effective visualization. The paper details the technical implementation using GeoGebra tools, discusses specific examples of models created, and presents the pedagogical framework for their application. Special attention is given to the development of supporting didactic materials that guide learners through active investigation using the dynamic models. The research demonstrates how this approach facilitates deeper mathematical understanding by connecting abstract concepts with practical applications and fostering active learning through visualization and experimentation. Results indicate that the developed complex of models effectively supports the implementation of holistic educational principles in mathematics education, particularly in establishing meaningful connections between mathematical concepts and their real-world applications.

Keywords

dynamic mathematics software, interactive modeling, mathematical visualization, GeoGebra, transdisciplinary connections, holistic mathematics education

CEUR-WS.org/Vol-3820/paper114.pdf

1. Introduction

Contemporary mathematics education faces significant challenges in fostering deep understanding and meaningful engagement among students. Recent studies by Vlasenko et al. [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11], Lovianova et al. [12, 13], Kramarenko et al. [14], Kramarenko and Kochina [15], Ponomareva [16], Merzlykin et al. [17], Tarasenkova et al. [18], Achkan et al. [19] highlight persistent gaps in mathematics education at both secondary and university levels. These challenges manifest in students' difficulties with abstract concepts and their practical applications, ultimately affecting their overall mathematical competence.

The core issues in mathematical education, as identified by Bilousova et al. [20] and diSessa et al. [21], include:

- Students' struggle with abstract mathematical concept comprehension
- Limited ability to apply mathematical knowledge to practical tasks
- Diminishing interest in mathematics due to perceived complexity
- Failure to recognize mathematics' role in other disciplines

CoSinE 2024: 11th Illia O. Teplytskyi Workshop on Computer Simulation in Education, co-located with the XVI International Conference on Mathematics, Science and Technology Education (ICon-MaSTEd 2024), May 15, 2024, Kryvyi Rih, Ukraine
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CEUR Workshop Proceedings ceur-ws.org ISSN 1613-0073

A fundamental challenge lies in students' lack of holistic understanding of mathematics as both a theoretical framework and a practical tool for solving interdisciplinary problems. As Singh [22] emphasizes, this disconnect between abstract mathematical concepts and their real-world applications often results in decreased motivation and engagement.

The holistic educational paradigm offers a promising approach to address these challenges. According to Miller [23, 24], holistic education emphasizes:

1. Learner autonomy and active participation
2. Integration of knowledge across disciplines
3. Connection between academic concepts and real-world experiences
4. Development of comprehensive understanding through practical application

Computer Dynamic Models (CDM) emerge as powerful tools for implementing holistic education principles in mathematics teaching. Research by Semenikhina and Drushliak [25] and Alessi [26] demonstrates that CDMs can effectively:

- Visualize mathematical concepts in real-time
- Enable active exploration of mathematical relationships
- Facilitate understanding of transdisciplinary connections
- Support development of integrated thinking skills

Among available mathematical software, GeoGebra stands out for its comprehensive modeling capabilities. Study by Kramarenko et al. [27] highlight GeoGebra's effectiveness in creating interactive visualizations and supporting mathematical investigation. The software enables seamless integration of geometric and algebraic representations, facilitating dynamic visualization and manipulation of mathematical concepts [28].

The Kharkiv GeoGebra Institute, operating within the International GeoGebra Institute network since 2010, focuses on:

1. Promoting effective implementation of GeoGebra in mathematical education
2. Supporting research in mathematics, physics, and computer science
3. Advancing STEM education through technology integration
4. Fostering international collaboration in mathematical education

This paper presents the results of an inter-university project conducted through the Kharkiv GeoGebra Institute, focusing on developing a comprehensive complex of dynamic models for holistic mathematics learning at the university level.

2. Theoretical framework

The development of our GeoGebra model complex is grounded in both theoretical principles and practical considerations, implemented through a systematic methodology combining theoretical, empirical, and modeling approaches.

2.1. Methodological foundation

The project's initial phase established three fundamental requirements for the model complex:

1. Development of diverse model categories:
    - Basic mathematical concept visualization
    - Transdisciplinary connection demonstration
    - Real-world problem-solving applications
2. Implementation of dynamic, interactive elements to support active learning

3. Cloud-based accessibility through www.geogebra.org

Following Bevz [29] and diSessa et al. [21], we approached transdisciplinary connections through three primary dimensions:

- Content integration across disciplines
- Learning activity structure
- Educational process organization

2.2. Theoretical analysis process

The analytical phase involved comprehensive examination of:

1. Core mathematical concepts and their interdisciplinary applications
2. Curriculum content threads [30, 31]
3. Transdisciplinary connection patterns

This analysis revealed key connection chains between mathematics and other disciplines:

- Mathematics – Computer Science
- Mathematics – Physics
- Physics – Mathematics – Biology
- Mathematics – Economics
- Mathematics – Engineering Design

The theoretical framework was further enhanced through semantic analysis using specialized software tools, including TextAnalyst 2.0, Text Miner 12.1, and Trope 8.4, enabling identification of key learning elements and their interconnections across disciplines.

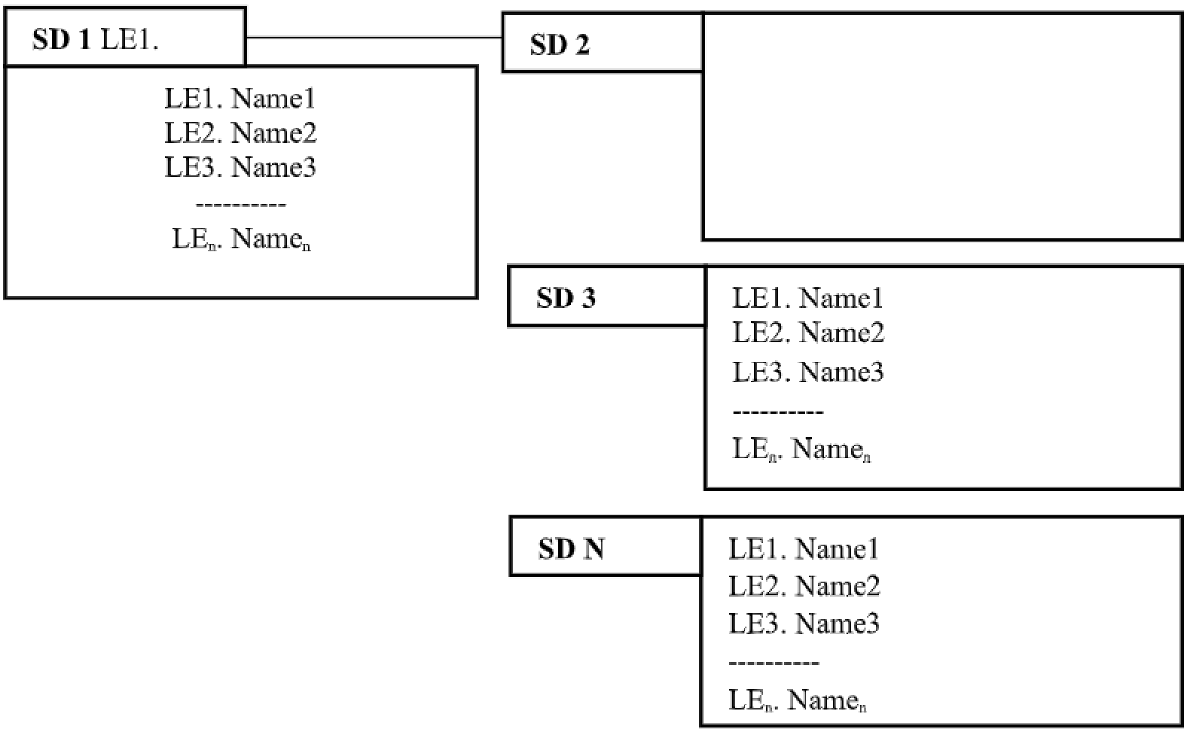

Figure 1: The common scheme of the graph, representing their transdisciplinary links with exact learning elements (LE1...LEn) of subject domains (SD).

This theoretical foundation guided the subsequent development of practical models and their implementation in educational settings. The framework emphasizes the importance of active learning, visualization, and practical application in mathematical education, aligning with holistic education principles outlined by Miller et al. [32] and Mahmoudi et al. [33].

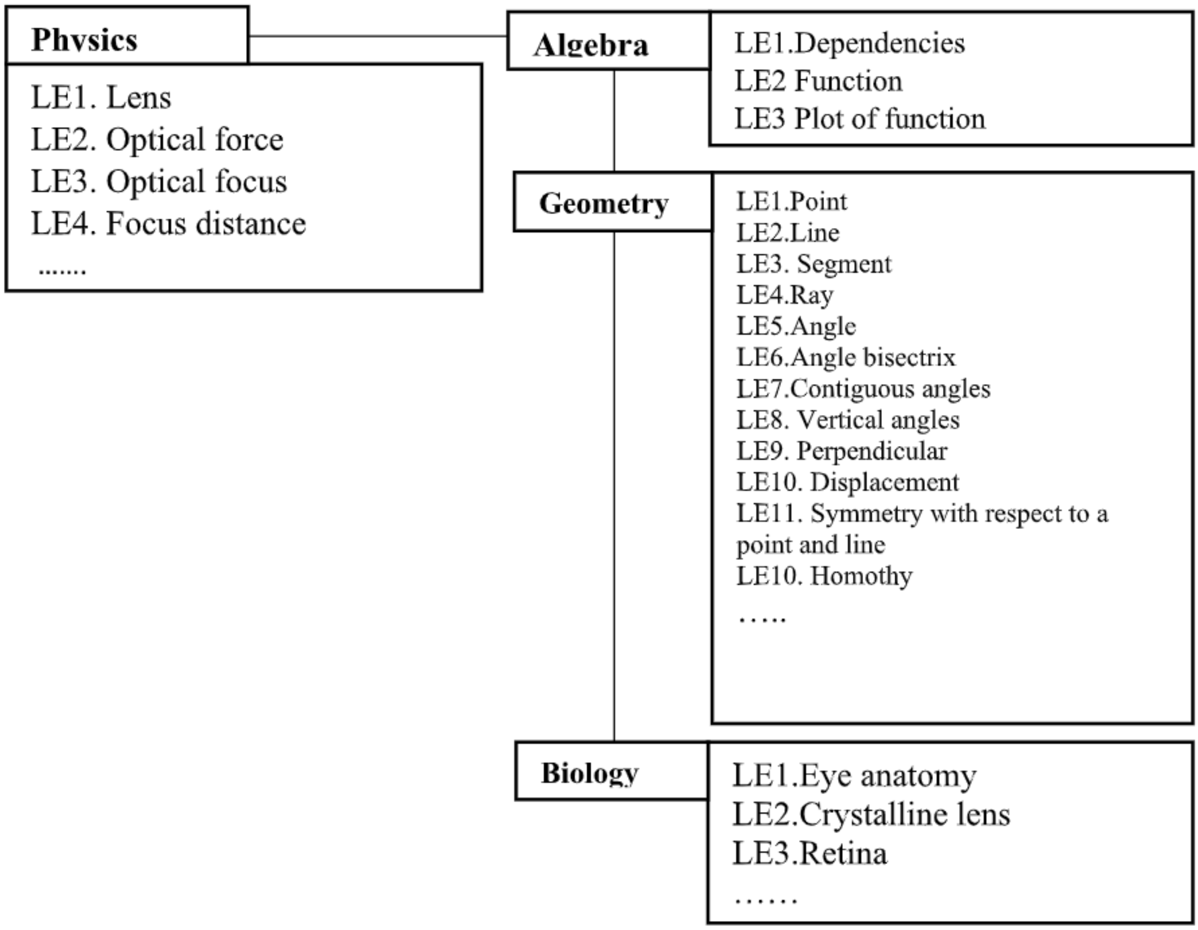

Figure 2: The example of the graph for selected LEs, representing the transdisciplinary links for the chain: Physics – Mathematics – Biology (Used below for the transdisciplinary model "Lens").

3. Results and discussion

3.1. Model development process

The implementation of the theoretical framework resulted in a systematic model development process comprising several key phases:

3.1.1. Phase 1: Mathematical model construction

For each model, the development process included:

1. Analysis of transdisciplinary concept relationships
2. Definition of mathematical dependencies for visualization
3. Specification of model parameters (fixed and variable)
4. Selection of appropriate graphical elements
5. Identification of relevant applications and problems
6. Development of supporting didactic materials

3.1.2. Phase 2: GeoGebra implementation

The technical implementation utilized various GeoGebra tools [25, 28]:

- Standard geometric tools (Points, Lines, Polygons)
- Computer Algebra System (CAS) components

- Dynamic transformation tools
- Action Object and Movement tools

3.1.3. Phase 3: Testing and refinement

The models underwent rigorous testing and improvement cycles to ensure educational effectiveness and technical reliability.

3.2. Model categories and examples

3.2.1. Category 1: Basic mathematical concepts

These models focus on fundamental concept visualization and understanding. Notable examples include:

> **Example: Remarkable curves investigation – epicycloids**
> Chain of transdisciplinary links: Geometry – Algebra – Mechanics
> The model demonstrates epicycloid construction and properties, enabling investigation of:
>
> - Relationship between curve lobes and radius ratios
> - Position calculations using geometric parameters
> - Transformation between epicycloids and hypocycloids

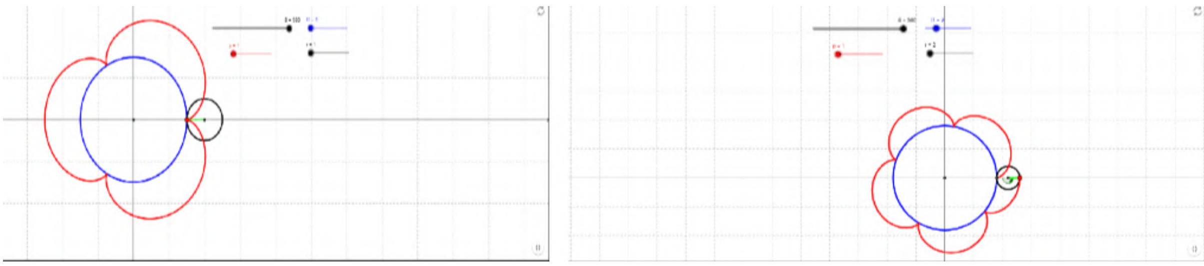

Figure 3: Episodes of the students'cognitive activity with the dynamic model "Remarkable curves investigation – epicycloids".

3.2.2. Category 2: Transdisciplinary connections

These models emphasize interdisciplinary relationships, as demonstrated in the following example:

> **Example: Lens Model**
> Chain of transdisciplinary links: Physics – Mathematics – Biology
> The model illustrates optical principles through mathematical relationships:
>
> - Lens curvature effects on focal points
> - Mathematical relationships in image formation
> - Geometric properties of light paths
>
> Supporting tasks include:
>
> 1. Investigation of mathematical dependencies
> 2. Analysis of geometric properties
> 3. Integration with biological systems (human eye)

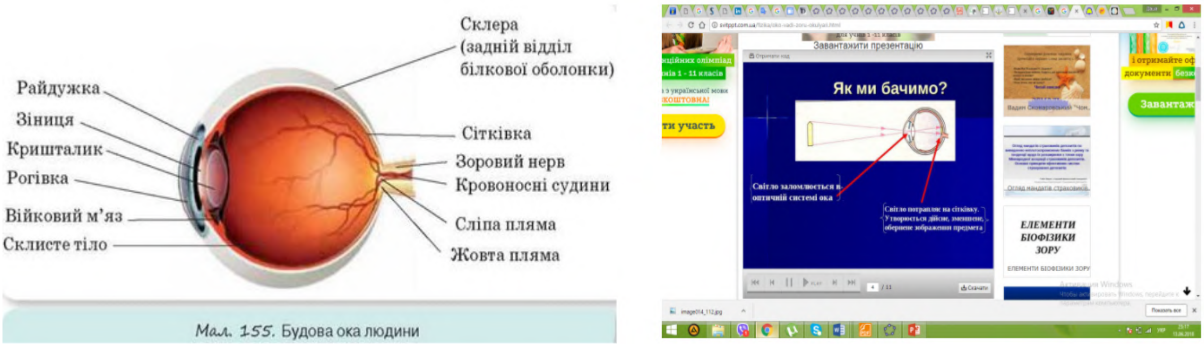

Figure 4: Scheme of the optical system of a human eye.

3.2.3. Category 3: Real-world applications

This category focuses on practical problem-solving, exemplified by:

> **Example: Fermat-Torricelli points investigation**
> The model supports various real-world investigations:
> 1. Construction and property analysis
> 2. Application to urban planning
> 3. Resource optimization problems

3.3. Educational impact and implementation

The implementation of these models demonstrates several key advantages:

1. Enhanced visualization: following principles outlined by Kramarenko et al. [34], the models provide dynamic visualization of abstract concepts.
2. Active learning: as suggested by Tarasenko et al. [35], interactive elements encourage student engagement and exploration.
3. Practical application: the models bridge theoretical understanding and practical implementation, supporting findings by Bilousova et al. [20].
4. Cloud integration: cloud-based accessibility aligns with modern educational needs [36, 37].

3.4. Didactic support framework

The developed didactic support materials include:

1. Transdisciplinary connection tasks
   - Concept relationship identification
   - Cross-disciplinary application exercises
   - Integration-focused problems
2. Practical application tasks
   - Real-world problem solving
   - Industry-specific applications
   - Contextual learning activities
3. Investigation guidelines
   - Step-by-step exploration procedures
   - Parameter manipulation instructions
   - Analysis and conclusion frameworks

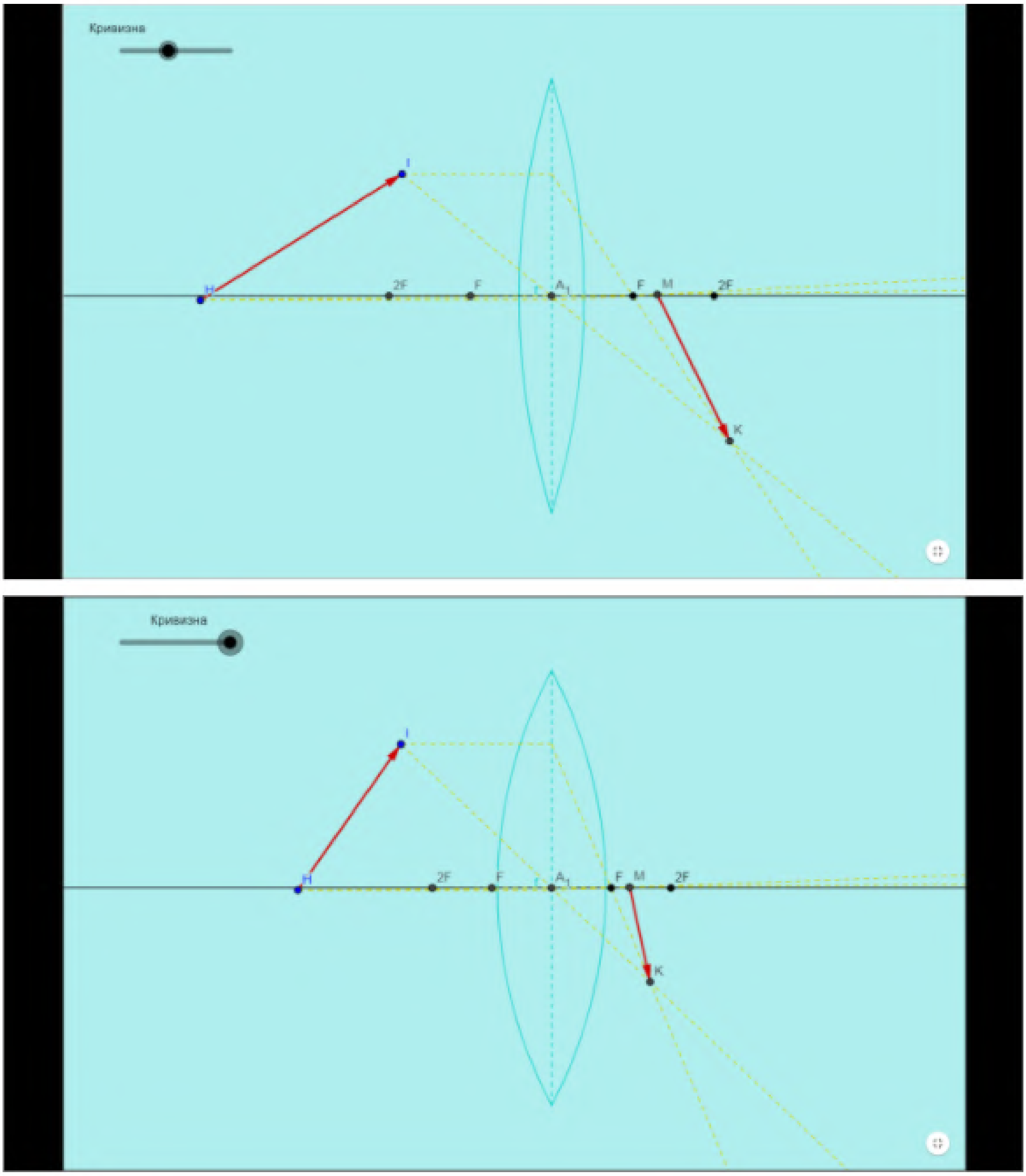

Figure 5: Episodes of transdisciplinary tasks solving, operating the model “Lens”.

3.5. Future research directions

Based on our findings, several promising research directions emerge:

- Long-term impact assessment on student understanding
- Development of additional model categories
- Integration with emerging educational technologies
- Extension to other STEM disciplines

4. Conclusions

This research demonstrates the successful development and implementation of a comprehensive GeoGebra-based modeling complex for enhancing mathematical education through a holistic approach. The key findings and contributions can be summarized in several dimensions:

4.1. Model development framework

The research established a systematic approach to creating educational mathematical models, incorporating:

- Robust theoretical foundations drawing from holistic education principles
- Structured development methodology across three distinct model categories
- Integration of dynamic visualization with practical applications
- Cloud-based deployment for widespread accessibility

4.2. Educational innovation

The developed complex advances mathematical education through:

1. Enhanced visualization: synamic models provide immediate feedback and interactive exploration opportunities, supporting findings by Kramarenko et al. [27] regarding the effectiveness of visual learning in mathematics.
2. Transdisciplinary integration: following principles outlined by Gryzun [38], the models successfully bridge multiple disciplines, demonstrating mathematics' role in various fields.
3. Active learning support: interactive elements encourage student engagement and independent exploration, aligning with Bilousova et al. [20]'s recommendations for effective mathematics education.
4. Practical application: teal-world problem-solving capabilities address the gap between theoretical understanding and practical implementation identified by diSessa et al. [21].

4.3. Technological implementation

The research demonstrates successful utilization of GeoGebra's capabilities through:

- Effective integration of geometric and algebraic representations
- Development of interactive, user-friendly interfaces
- Implementation of cloud-based accessibility
- Creation of scalable and modifiable models

4.4. Pedagogical implications

The research yields significant implications for mathematics education:

1. Enhanced teaching methodology: the model complex provides educators with tools for implementing holistic teaching approaches, supporting findings by Miller [24] regarding effective mathematical instruction.
2. Student engagement: interactive elements and real-world applications increase student motivation and understanding, addressing challenges identified by Singh [22].
3. Flexible learning support: cloud-based accessibility enables both classroom and independent learning, aligning with modern educational needs [39].
4. Comprehensive understanding: the transdisciplinary approach fosters deeper mathematical comprehension, supporting principles outlined by Mahmoudi et al. [33].

4.5. Future directions

The research opens several promising avenues for future investigation:

1. long-term impact studies: systematic evaluation of the model complex's effectiveness in various educational contexts.
2. Model extension: development of additional model categories and applications for emerging educational needs.
3. Technology integration: investigation of integration possibilities with new educational technologies and platforms.
4. Pedagogical framework: further development of supporting didactic materials and teaching methodologies.
5. Cross-cultural implementation: study of the model complex's effectiveness in different educational systems and cultural contexts.

4.6. Final remarks

This research contributes to the advancement of mathematics education by providing a practical framework for implementing holistic educational principles through dynamic modeling. The developed complex of GeoGebra models, supported by comprehensive didactic materials, offers a scalable and effective approach to enhancing mathematical understanding. The success of this implementation suggests that similar approaches could be valuable across various educational contexts and disciplines.

The findings underscore the importance of combining theoretical rigor with practical application in mathematics education, demonstrating how technology can bridge this gap effectively. As educational technology continues to evolve, the principles and methodologies established in this research provide a foundation for future developments in mathematical education.

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