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MODELING TEACHER COMPETENCY DEVELOPMENT BY MACHINE LEARNING: A MATHEMATICAL APPROACH APPLIED TO EDUCATIONAL TECHNOLOGY TRAINING

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ABSTRACT

To address the challenges of ambiguous teacher competency assessment and insufficiently precise training programs in educational technology contexts, this study develops a conceptual and theoretical framework for modeling teacher competency development. First, the core dimensions and structural components of teacher competency development are systematically defined, establishing a clear theoretical foundation for competency-oriented educational technology training. Second, the mathematical logic and fundamental modeling principles underlying competency development are elucidated, forming a multidimensional theoretical system for competency representation and evaluation. Finally, optimization pathways for educational technology training are proposed based on modeling-oriented thinking, aiming to enhance the alignment between competency development and training design. In this study, machine learning is conceptualized as a modeling paradigm rather than an algorithmic or data-driven approach, emphasizing abstraction, structural representation, and logical mapping of competency dimensions. The proposed framework provides theoretical support for the scientific assessment and precise design of teacher competency development in educational technology training.

KEYWORDS: Teacher Competency Development; Machine Learning–Inspired Modeling; Educational Technology Training; Conceptual Framework.

1. INTRODUCTION

The deep integration of digital technologies into education has fundamentally reshaped teachers' professional competency structures, making educational technology training a central pathway for enhancing teaching quality and professional development[1-2]. However, existing training practices often rely on experience-based and subjective assessments of teacher competency development, which are characterized by vague indicators and limited capacity for individualized adaptation. Previous studies on teacher competency development have largely focused on qualitative descriptions or outcome-based evaluations, with insufficient attention to the internal structure and developmental logic of competency systems[3-4]. As a result, it remains difficult to systematically capture the multidimensional and dynamic nature of teacher competency development, leading to training designs that lack theoretical coherence and analytical rigor.

Modeling-oriented approaches provide a promising theoretical pathway to address these limitations by abstracting complex educational phenomena into structured and interpretable frameworks[5]. Conceptual modeling has been widely used in educational research to clarify relationships among key variables, support analytical consistency, and inform instructional design[6]. In this study, modeling is adopted as a theoretical and structural approach to conceptualize teacher competency development within educational technology training contexts. Importantly, *machine learning is not treated as an algorithmic or data-driven technique*, but rather as a **modeling-oriented paradigm** that emphasizes abstraction, structured representation, and logical mapping among multidimensional competency elements. Based on this perspective, this study develops a theoretical modeling framework that defines core competency dimensions, elucidates the underlying mathematical logic of competency representation, and proposes optimization pathways for training design[7]. The framework aims to provide a theoretically grounded foundation for the scientific assessment and precise structuring of teacher competency development, while offering a conceptual basis for future empirical and machine learning–based investigations[8-9].

2. MODELING BASIS OF TEACHER'S ABILITY DEVELOPMENT

2.1. *Core Dimensions of Teacher Competency Development*

In alignment with the core objectives of educational technology training and established international standards for teachers' digital competence, a multidimensional framework for teacher competency development is constructed in this study. Prior research has emphasized that teachers' professional competence in technology-enhanced education is not a single skill, but a structured system integrating technical knowledge, pedagogical application, innovation, and reflective practice[10]. Building on this perspective, the proposed framework comprises four primary dimensions and twelve secondary dimensions[11].

First, **Technical Application Competence** focuses on teachers' foundational abilities in applying educational technologies, including the operation of digital teaching tools, educational data processing, and online resource integration. Second, **Teaching Integration Competence** emphasizes the effective integration of technology with pedagogical practice, encompassing technology-supported curriculum design, blended online–offline teaching implementation, and differentiated instructional adaptation. Third, **Innovative Design Competence** highlights teachers' capacity to leverage technology for instructional creativity, including digital resource development, inquiry-based instructional design, and interdisciplinary teaching innovation. Finally, **Reflective Improvement Competence** captures the dynamic and developmental nature of professional growth, involving teaching effectiveness evaluation, reflection on technology use, and continuous learning adaptation[12].

These four dimensions jointly represent a structured competency system rather than isolated skills, reflecting the progressive evolution of teacher competency in digital learning environments. As illustrated in **Fig. 1**, teacher competency development can be understood as a staged and cumulative process, evolving from basic computer-assisted instruction toward more advanced forms of personalized, generative, and human–AI collaborative learning. This developmental trajectory underscores the necessity of modeling competency development as an integrated and dynamic system rather than a collection of independent indicators.

2.2. *Mathematical Logic of Modeling*

The modeling of teacher competency development aims to construct a systematic and interpretable analytical framework through mathematical logic and theoretical abstraction. Traditional qualitative approaches often struggle to represent the multidimensional structure and dynamic evolution of competency development, particularly when multiple competency dimensions interact across different developmental stages. Modeling-oriented approaches, by contrast, enable complex educational phenomena to be abstracted into logically organized structures, thereby facilitating clearer conceptualization and analytical reasoning[13].

From a mathematical logic perspective, the modeling adopted in this study does **not** rely on algorithmic training, predictive computation, or data-driven optimization. Instead, it draws on foundational mathematical tools—such as **set theory, mapping theory, and structural relationships**—to formalize the internal organization of teacher competency development. In this sense, *machine learning is conceptualized as a modeling-oriented paradigm rather than an empirical or algorithmic technique*. The emphasis lies in abstraction, structural representation, and logical mapping among competency elements, which constitute the conceptual foundations underlying many machine learning systems at a theoretical level[14].

Specifically, set theory serves as the foundational tool for defining competency elements. Each primary competency dimension can be represented as a distinct set, while secondary dimensions constitute subsets within the broader competency structure. Through set operations such as union and intersection, the boundaries, overlaps, and interconnections among competency dimensions can be explicitly delineated, thereby avoiding vague definitions and conceptual redundancy. For example, the four primary competency dimensions together form the core competency set, while contextual or institutional influences can be conceptualized as external sets that interact with, but remain distinct from, the core structure. Mapping relationships further enable the representation of developmental transitions across stages, reflecting how teachers' competencies evolve from basic technical application toward integrated, innovative, and reflective professional practice, as depicted in **Fig. 1**.

By employing mathematical logic as a conceptual structuring tool rather than a computational method, this modeling approach provides a theoretically coherent framework for understanding teacher competency development. It establishes a foundation for systematic evaluation and training design, while also offering a conceptual basis for future empirical studies and algorithmic machine learning applications aimed at validating or operationalizing the proposed framework.

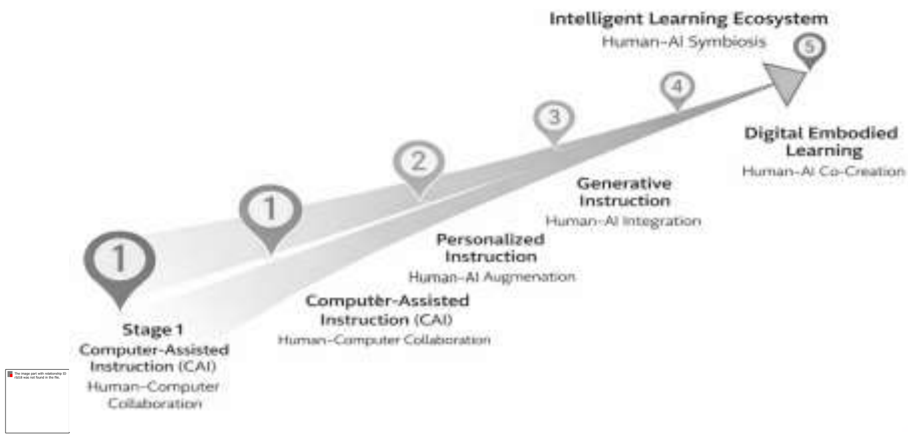

Fig. 1: Staged Evolution of Technology-Enhanced Learning and Teacher Competency Development from Computer-Assisted Instruction to Human–AI Symbiotic Learning.

3. THEORETICAL ADAPTABILITY OF MODELING TEACHER COMPETENCY DEVELOPMENT IN EDUCATIONAL TECHNOLOGY TRAINING

3.1. Alignment Between Training Objectives and Competency Models

The primary objective of educational technology training is to enhance teachers' capacity to effectively integrate digital technologies into teaching practice. The competency modeling framework proposed in this study—comprising technical application, instructional integration, innovative design, and reflective improvement—demonstrates a clear conceptual alignment with this objective. Previous research has emphasized that effective professional development should be explicitly competency-oriented rather than content-driven, ensuring that training objectives are systematically linked to teachers' professional growth trajectories[15].

From a theoretical perspective, the modeling framework clarifies the internal structure of training objectives by mapping specific training components to corresponding competency dimensions. For example, the technical application dimension aligns with foundational modules focusing on digital tool operation and resource utilization, while instructional integration corresponds to training on curriculum design and blended teaching implementation. Innovative design is associated with advanced modules emphasizing pedagogical creativity and interdisciplinary teaching, whereas reflective improvement supports post-training consolidation through evaluation and continuous learning. Together, these dimensions constitute a progressive and structured system of training objectives, avoiding the fragmentation and overgeneralization often observed in traditional training approaches. This alignment provides a coherent theoretical basis for the systematic design of educational technology training programs.

3.2. Compatibility Of Training Processes with The Laws of Competency Development

Teacher competency development is widely understood as a progressive and iterative process, involving foundational skill acquisition, integrated application and innovation, and continuous reflective refinement (Koehler & Mishra, 2009). The modeling framework constructed in this study reflects this developmental logic through explicit mapping relationships between competency dimensions and training stages. Such mapping enables training processes to be theoretically synchronized with the natural evolution of teacher competency development[16].

In practice, this alignment supports a phased training design. The initial phase focuses on foundational construction by strengthening technical application competence through standardized instruction and guided practice. The intermediate phase emphasizes instructional integration, promoting the effective combination of technology and pedagogy through case-based learning and applied exercises. The advanced phase targets innovative design competence, fostering teaching innovation via project-based learning and interdisciplinary collaboration. Finally, the continuous development phase reinforces reflective improvement competence through follow-up guidance, peer exchange, and reflective evaluation. As illustrated in **Fig. 1**, these phases correspond to the broader evolution of technology-enhanced learning—from computer-assisted instruction toward more advanced forms of human–AI integration—highlighting the necessity of aligning training processes with competency development laws. This theoretically grounded staging enhances both the coherence and effectiveness of educational technology training[17].

3.3. Evaluating The Compatibility Between Training Requirements and The Modeling Framework

Traditional evaluations of educational technology training have predominantly relied on outcome-based indicators, often overlooking the developmental processes through which teacher competencies are formed. In contrast, the proposed modeling framework supports a more balanced evaluation approach that integrates both process-oriented and outcome-oriented assessment. This perspective is consistent with prior studies emphasizing the importance of formative and developmental evaluation in professional learning contexts (Reeves & McKenney, 2013).

Within the modeling framework, each competency dimension can be decomposed into observable and theoretically grounded evaluation indicators. For instance, technical application competence may be assessed through indicators such as proficiency in digital tool operation and rationality of resource integration, while instructional integration competence can be evaluated based on curriculum–technology alignment and instructional implementation fluency. By assigning relative weights to different indicators, the framework enables the construction of a structured and transparent evaluation system capable of capturing teachers' competency development across training stages. This multidimensional evaluation logic provides a theoretical foundation for optimizing training effectiveness and supports the continuous refinement of educational technology training programs[18].

4. OPTIMIZATION PATH OF EDUCATIONAL TECHNOLOGY TRAINING BASED ON MODELING THINKING

Building on the proposed competency modeling framework, this section translates modeling-oriented thinking into optimized pathways for educational technology training. Rather than prescribing specific operational procedures, the optimization path emphasizes the alignment between competency structures, training processes, and evaluation mechanisms, ensuring that training design remains theoretically grounded and adaptable across different educational contexts[19].

4.1. Establishing A Targeted Training Content System

A core advantage of competency-based modeling lies in its capacity to guide the systematic organization of training content. By explicitly linking training modules to defined competency dimensions, the proposed framework helps prevent both content oversimplification and functional redundancy, which are common limitations of conventional training programs. Prior research has highlighted that professional development is most effective when training content is explicitly aligned with competency frameworks rather than isolated skill instruction[20].

Within the proposed framework, training content is structured according to four competency dimensions. For **technical application competence**, standardized modules focus on foundational digital tool operation, educational resource integration, and basic data-handling skills, supported by a combination of theoretical instruction and guided practice. **Instructional integration competence** is addressed through practice-oriented training that emphasizes the alignment of technology with curriculum design and the implementation of blended learning models, commonly facilitated through case analysis, collaborative discussion, and instructional design exercises[21]. **Innovative design competence** is cultivated through advanced modules that encourage pedagogical creativity, including teaching resource development, inquiry-based learning design, and interdisciplinary instructional innovation. These modules are typically implemented using project-based learning approaches with mentor guidance to support exploratory and creative engagement. Finally, **reflective improvement competence** is strengthened through continuous learning activities, such as teaching effectiveness evaluation, reflective analysis of technology use, and peer knowledge-sharing mechanisms.

By organizing training content around these competency dimensions, the modeling framework ensures that training materials are not only comprehensive but also purposefully aligned with teachers' developmental needs. This targeted content system supports differentiated learning trajectories and enhances the internal coherence of educational technology training programs.

4.2. Implementation Process of Phased Training Design

Teacher competency development is inherently progressive, involving stages of foundational acquisition, integrated application, innovation enhancement, and reflective consolidation. Consistent with this developmental logic, the modeling framework supports a phased training implementation process that synchronizes training progression with competency growth patterns[22].

In the initial phase, training emphasizes **foundational construction**, focusing on the development of technical application competence. During this stage, teachers acquire basic operational skills in educational technologies through structured instruction and hands-on practice. The intermediate phase centers on **integrated application**, with training activities designed to enhance instructional integration competence by fostering the effective combination of technology and pedagogy through case-based learning and applied instructional tasks. The advanced phase prioritizes **innovation enhancement**, targeting innovative design competence through project-driven learning, interdisciplinary collaboration, and creative problem-solving activities that encourage teachers to explore novel instructional approaches[23]. Finally, the continuous development phase focuses on **reflective iteration**, reinforcing reflective improvement competence through follow-up guidance, peer exchange, and reflective evaluation practices that support sustained professional growth.

This phased implementation process reflects the mapping relationships embedded in the modeling framework and aligns with the staged evolution of technology-enhanced learning environments, as illustrated in Fig. 1. By aligning training phases with competency development laws, the framework enhances the coherence, adaptability, and long-term effectiveness of educational technology training.

4.3. Establishing A Systematic Training Evaluation Mechanism

Effective optimization of educational technology training requires an evaluation mechanism capable of capturing both competency development processes and final outcomes. Traditional training evaluations often emphasize summative outcomes while neglecting formative and developmental dimensions. In contrast, the proposed modeling framework supports a systematic evaluation mechanism that integrates process-oriented and outcome-oriented assessment, consistent with design-based and competency-driven evaluation perspectives[24].

Within this framework, each competency dimension is decomposed into theoretically grounded and observable evaluation indicators. For example, **technical application competence** can be assessed through indicators such as proficiency in digital tool operation and the rational integration of educational resources, while **instructional integration competence** may be evaluated based on curriculum–technology alignment and instructional implementation fluency. **Innovative design competence** can be examined through the originality and feasibility of instructional designs, and **reflective improvement competence** through evidence of reflective practice and adaptive learning behaviors. By assigning relative weights to these indicators, the framework enables the construction of a transparent and structured assessment system that captures teachers' competency development across different training stages[25].

This multidimensional evaluation mechanism enhances the scientific rigor and objectivity of training assessment, supports timely feedback and instructional adjustment, and provides a theoretical foundation for the continuous optimization of educational technology training programs.

5. CONCLUSION AND PROSPECTS

5.1. Conclusion

This study provides a theoretical exploration of teacher competency development in educational technology training through a modeling-oriented perspective. By adopting conceptual modeling and mathematical logic as core analytical tools, the study advances a structured and coherent framework for understanding the multidimensional nature of teacher competency development in digitally mediated teaching contexts.

First, the study establishes a competency dimension system tailored to educational technology training, consisting of four primary dimensions—technical application, instructional integration, innovative design, and reflective improvement—along with twelve corresponding secondary dimensions. This multidimensional structure offers a systematic theoretical foundation for interpreting teacher competency development as an integrated and dynamic system rather than a collection of isolated skills. By clarifying the internal structure of competency development, the framework contributes to a more coherent conceptualization of teachers' professional growth in technology-enhanced learning environments.

Second, the study elucidates the mathematical logic underlying competency modeling, demonstrating how foundational mathematical concepts—such as set theory and mapping relationships—can be employed to formalize the structure and developmental pathways of teacher competencies. Through abstraction and logical organization, the modeling approach enables clearer representation of the relationships among competency elements, developmental stages, and contextual influences. Importantly, machine learning is conceptualized in this study as a modeling-oriented paradigm rather than an algorithmic or data-driven technique, emphasizing structural representation and logical mapping as theoretical foundations for competency modeling.

Third, the study demonstrates the theoretical adaptability of the proposed modeling framework to educational technology training practices. By aligning competency dimensions with training objectives, implementation processes, and evaluation mechanisms, the framework provides a coherent basis for designing targeted training content, phased training pathways, and multidimensional evaluation systems. The proposed optimization pathways illustrate how modeling-oriented thinking can support the scientific design and systematic evaluation of educational technology training programs, thereby enhancing their theoretical rigor and practical coherence.

Overall, this study contributes to the literature by bridging competency theory, modeling logic, and educational technology training design within a unified theoretical framework. It offers conceptual guidance for researchers and practitioners seeking to structure teacher competency development in a more systematic and analytically grounded manner.

5.2. Prospects

As a purely theoretical study, this research inevitably has several limitations that also point toward directions for future inquiry. First, the competency dimensions and weight assignments within the proposed modeling framework are derived from theoretical deduction rather than empirical validation. Future studies may employ empirical methods—such as survey-based measurement, structural modeling, or machine learning–supported data analysis—to test, refine, and validate the proposed competency structure across different educational contexts.

Second, while the optimization pathways offer general guidance for educational technology training design, they do not explicitly account for heterogeneity among teachers, institutions, or educational systems. Differences in regional conditions, educational stages, disciplinary backgrounds, and resource availability may influence the effectiveness of competency development pathways. Future research could adapt and contextualize the modeling framework to specific educational settings, thereby enhancing its practical applicability and contextual sensitivity.

Third, the present study focuses primarily on internal competency structures and training design logic, without explicitly modeling external influencing factors such as institutional support, technological infrastructure, policy environments, or trainer expertise. Incorporating these external variables into future modeling efforts could further enrich the framework and improve its explanatory power. Additionally, future research may explore how empirical machine learning techniques can be integrated with the conceptual framework proposed in this study to support data-informed training evaluation and adaptive professional development systems.

In conclusion, this study lays a conceptual foundation for modeling teacher competency development in educational technology training. By clarifying competency structures, modeling logic, and optimization pathways, it opens avenues for future empirical validation, contextual refinement, and methodological integration, contributing to the ongoing advancement of research on teacher professional development in digital learning environments.

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