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MULTI-DIMENSIONAL ANALYSIS OF MODELING PROCESSES AND DIGITAL TOOL INTEGRATION IN INTERDISCIPLINARY LEARNING SYSTEMS

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Abstract- The integration of mathematical modeling and digital technologies represents a key component of STEM-based interdisciplinary learning systems that connect mathematics with real-world scientific contexts. However, prospective teachers often encounter difficulties in effectively implementing modeling-based activities supported by information and communication technologies (ICT), particularly in primary education settings. This study examines the structural relationships between computational modeling processes and techno-pedagogical competencies among prospective elementary school teachers during their teaching practicum. Data were collected from 143 pre-service teachers using a structured questionnaire covering different stages of the modeling cycle and dimensions of techno-pedagogical self-efficacy. Descriptive statistics were used to summarize response patterns, while correlation analysis and Multiple Correspondence Analysis (MCA) were employed to explore relationships and underlying data structures. The results indicate that computational modeling competencies form an interconnected and structured system rather than isolated skills. Difficulties related to mathematization, ICT integration, and model validation are strongly interrelated, highlighting the systemic complexity of implementing STEAM-based teaching approaches in primary education. These findings emphasize the need to strengthen initial teacher education through integrated training frameworks that simultaneously develop mathematical modeling, digital competence, and pedagogical design skills in a coherent and systemic manner.

Keywords: Computational Modeling, STEAM Education, ICT Integration, Modeling Cycle, Prospective Teachers, TPACK, Teacher Education.

1. INTRODUCTION

Teaching mathematics in elementary school represents a significant pedagogical challenge, particularly in connecting abstract concepts such as arithmetic, geometry, and measurement to meaningful real-world contexts. Integrating authentic situations from scientific and applied domains supports students' conceptual understanding, motivation, and development of reasoning skills [1, 2].

Mathematical Knowledge for Teaching (MKT) highlights the importance of teachers' deep understanding of mathematical concepts for effective instruction and student achievement [3, 4, 5, 6]. However, research shows that both pre-service and in-service teachers often demonstrate limited conceptual understanding in key areas, leading to a preference for procedural and rule-based teaching approaches rather than conceptual and modeling-oriented instruction.

To address these limitations, recent approaches emphasize the importance of integrating interconnected knowledge structures that link mathematical content with pedagogical strategies and students' prior knowledge [3]. In this context, computational modeling and STEAM-based approaches provide opportunities to engage learners in meaningful problem-solving processes grounded in real-world phenomena.

Despite their educational potential, mathematical modeling activities remain underrepresented in primary education curricula in several contexts, including Morocco [7]. This limits prospective teachers' exposure to modeling-based instruction during their initial training and contributes to difficulties across all stages of the modeling cycle, including problem identification, mathematization, simulation, interpretation, and validation.

Although existing research has extensively explored mathematical modeling and ICT integration separately, fewer studies have investigated the structural relationships between modeling difficulties and techno-pedagogical competencies among pre-service primary teachers. This study addresses this gap by providing a multidimensional quantitative analysis of modeling-related challenges and ICT integration using descriptive statistics, correlation analysis, and Multiple

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Correspondence Analysis (MCA). By examining the relationships between different stages of the modeling cycle and techno-pedagogical self-efficacy, this study contributes to a better understanding of computational modeling as an integrated system of competencies. It extends previous work [7] by offering a structural and data-driven perspective on the interaction between modeling processes and technology-enhanced teaching practices. To explore prospective primary school teachers' perceptions of computational modeling processes supported by ICT within a STEAM-based framework and to derive implications for teacher education, the following research questions are formulated:

1) What perceptions do prospective primary school teachers hold regarding the challenges associated with computational modeling processes and ICT integration in STEM-related teaching contexts?
2) How are these perceived difficulties structured across the stages of the computational modeling cycle, and what relationships exist among computational modeling competencies and techno-pedagogical self-efficacy?
3) What implications do these structural relationships have for the improvement of initial teacher education programs in terms of STEAM-based and ICT-integrated training?

2. LITERATURE REVIEW

Recent research highlights that the shift toward modeling-based mathematics teaching requires a profound transformation in prospective teachers' beliefs, knowledge, and instructional practices [8, 9]. Although prospective teachers generally express positive attitudes toward the use of real-world contexts, a persistent gap remains between these intentions and their ability to design and implement authentic modeling tasks [10, 11, 12, 13]. Moreover, studies indicate that novice teachers often adopt a simplified conception of mathematical modeling, reducing it to everyday contexts or routine computational exercises, rather than engaging in genuine mathematization of phenomena from scientific or engineering domains [10, 13, 14]. This limited understanding constrains the development of tasks that foster deep conceptual learning and system-based reasoning.

However, research also shows that structured training programs emphasizing collaboration, reflection, and task design can significantly enhance prospective teachers' ability to develop mathematically rich and contextually meaningful modeling activities [13, 15]. Engagement in communities of practice further supports the development of professional competencies related to task design and pedagogical adaptation [9, 13]. From a pedagogical perspective, modeling-based teaching requires a shift from knowledge transmission to learning facilitation [14, 16]. This transition involves managing open-ended learning environments, supporting diverse solution strategies, and guiding students without directly providing solutions. Nevertheless, studies report that many prospective teachers struggle to adopt such practices due to the persistence of traditional instructional models and limited classroom-based modeling experience [14, 16].

The literature suggests that the development of effective modeling practices depends not only on theoretical knowledge but also on sustained engagement in authentic teaching experiences that integrate mathematical, pedagogical, and contextual dimensions of learning.

3. THEORETICAL FRAMEWORK

3.1. Mathematical Modeling in Primary School

Mathematical modeling is an iterative and cyclical process that transforms real-world situations into mathematical representations to solve applied problems [17]. In STEAM-oriented education, it is not a linear procedure but a dynamic process involving continuous transitions between contextual understanding and mathematical formalization. The modeling cycle, as described by [18], provides a structured framework for analyzing these transitions, encompassing real-world interpretation, mathematical formulation, solution processing, interpretation, and validation. In primary education, mathematical modeling plays a key role in supporting learners' ability to connect mathematics with real-world phenomena, while fostering the development of abstraction and critical thinking skills [19, 20].

However, the implementation of modeling-based activities is associated with several cognitive and pedagogical challenges. These include difficulties in constructing appropriate situational models, reliance on overly linear reasoning, obstacles in transitioning between real and mathematical representations, limited engagement in result validation, and affective barriers such as uncertainty when dealing with open-ended tasks [18, 21, 22]. From a STEAM and computational modeling perspective, these challenges reflect the complexity of modeling as an integrated system requiring the simultaneous development of mathematical reasoning, interpretive skills, and validation processes.

3.2. Technological Pedagogical Content Knowledge Model

The Technological Pedagogical Content Knowledge (TPACK) framework provides a conceptual basis for understanding the integration of digital technologies in STEAM-based educational environments, particularly in computational modeling contexts. It extends Shulman's notion of Pedagogical Content Knowledge (PCK) by emphasizing the dynamic interactions between content, pedagogy, and technology in the design of meaningful learning experiences [23, 24, 25]. From this perspective, teaching with technology is not the mere addition of digital tools, but the orchestration of three interdependent knowledge domains: content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK). In STEAM-oriented computational modeling, these domains jointly support scientific inquiry, mathematical formalization, and engineering-based problem solving. Rather than functioning as isolated components, these knowledge domains overlap to form integrated pedagogical configurations:

- PCK: adapting disciplinary content (mathematics and science) to support understanding of modeling processes;
- TCK: understanding how digital tools represent and transform mathematical and scientific models;
- TPK: examining how technology influences teaching strategies and learner interaction during modeling activities;
- TPACK: integrating these dimensions to design and implement effective STEAM-based computational modeling environments.

In computational modeling contexts, TPACK can be viewed as a design-oriented framework that supports teachers in orchestrating system-based learning activities, where digital tools are embedded across mathematization, simulation, interpretation, and validation processes. Consequently, teacher education should move beyond technical training in digital tools toward a learning-by-design approach, in which prospective teachers actively construct STEAM-based modeling environments. This approach fosters a systemic understanding of the relationships between technology, pedagogy, and content, and promotes reflective and design-oriented teaching practices [23].

3.3. Integration of the TPACK Model within a STEAM-Based Computational Modeling Framework

The TPACK model provides a conceptual framework for integrating mathematical modeling within a STEAM-based computational learning environment by articulating the interactions between technological, pedagogical, and disciplinary knowledge. In this perspective, mathematical modeling is conceptualized as a STEAM-oriented process that integrates scientific inquiry, technological tools, engineering reasoning, and mathematical formalization. Within this framework, technology is embedded across all stages of the computational modeling cycle, from system structuring to model validation. Real-world situations are first conceptualized as systems represented through digital tools such as dynamic geometry software or simulation environments (Science and Engineering dimension). These representations are then translated into mathematical and computational forms through Technological Content Knowledge (TCK), enabling simulation and algorithmic processing (Mathematics and Technology dimension).

Finally, digital tools support interpretation and validation by facilitating comparison between model outputs and real-world phenomena (Engineering reasoning dimension). From a pedagogical perspective, the TPACK framework emphasizes the teacher's role as a facilitator of STEAM-based modeling activities [19]. Teachers are expected to identify students' difficulties across modeling stages (PCK), select appropriate digital tools for each phase (TCK), and integrate technology, pedagogy, and content into coherent instructional design (TPACK). In addition, teacher self-efficacy plays a central role in the effective implementation of STEAM-oriented modeling practices. Teacher education programs should therefore strengthen prospective teachers' confidence in using digital technologies as integral components of computational modeling systems that support inquiry, simulation, and validation processes.

4. METHODOLOGY

4.1. Research Objectives

This study analyzes prospective primary school teachers' engagement with a computational STEAM-based modeling system, focusing on their perceived difficulties in transforming real-world phenomena into mathematical and computational representations. It further examines their ability to operate within a structured modeling pipeline involving abstraction, digital simulation, and validation, as well as the role of ICT tools in supporting the development of these engineering-oriented competencies.

4.2. Population and Sample

The target population consists of students enrolled in the Elementary Teacher Education Program at the Higher School of Education and Training, Ibn Tofail University, Kenitra, Morocco. The final sample includes 143 pre-service teachers (*N*=143), voluntarily selected after completing a teaching practicum. This sampling choice is justified by participants' direct exposure to classroom practice, which is essential for examining their engagement with mathematical modeling processes within STEM contexts. The sample includes participants with varying levels of practicum experience, ranging from short-term to extended training periods, ensuring diversity in exposure to real classroom environments. It also presents variation in ICT training background and the use of real-world contexts in mathematics instruction, providing a heterogeneous profile suitable for analyzing computational modeling and STEAM-based teaching competencies.

4.3. Data Collection Instrument

A structured survey was developed to collect data on prospective primary school teachers' engagement with computational mathematical modeling processes within a STEAM-based framework. The instrument consists of three interconnected sections capturing both contextual information and cognitive-process dimensions related to modeling and ICT integration.

The first section gathers background information on participants, including teaching practicum experience, duration of training (classified into intervals of [1-5], [5-10], [5-15], and [15-20] weeks), academic profile, and prior exposure to ICT in educational settings. These variables are used to characterize the sample in relation to readiness for computational modeling practices.

The second section includes Likert-scale items (ranging from "strongly disagree" to "strongly agree") measuring perceived difficulties across stages of a computational modeling cycle embedded in STEM contexts. These stages include:

- mathematization and system abstraction (M1-M3);
- computational modeling and ICT-supported problem solving (W1_ICT-W3_ICT);
- interpretation and validation of model outputs (I1-I3);
- model communication and critical evaluation (V1-V3).

This structure reflects a process-oriented view of mathematical modeling as a structured cognitive and computational system.

The third section assesses techno-pedagogical effectiveness, focusing on self-efficacy beliefs, perceived impact of ICT on modeling competencies (S1-S3), and perceived need for targeted training in STEAM-based computational modeling practices. The complete survey instrument is presented in Table 1.

Table 1. Survey administered to prospective teachers

Do you participate in teaching practice during your training?	Yes		No		
Duration of the training in weeks	1 to 5	5 to 10	10 to 15	15 to 20	
Have you attended any training on the use of ICT in education?	Yes		No		
Have you ever implemented a complete mathematical modeling cycle in a STEM/STEAM context (problem, model, simulation, validation)?	Yes		No		
List of Engineering modeling decomposition tasks	Strongly disagree	Not agree	Neutral	Agree	Strongly agree
M1: Identifying relevant variables from real-world engineering / physics / biology systems for mathematical modeling					
M2: Translating real-world systems into simplified mathematical representations suitable for simulation or computation in primary education					
M3: Selecting appropriate digital tools (GeoGebra, PhET, simulations) for computational modeling of real-world systems					
W1_ICT: Supporting students in interpreting outputs from computational models (simulation results, graphs, digital representations)					
W2_ICT: Guiding students in the digital execution of mathematical models using simulation-based environments					
W3_ICT: Integrating physical manipulation and computational simulation within a hybrid modeling system					
I1: Relating model outputs to real-world system behavior in physics, biology, and engineering contexts					
I2: Using ICT tools to validate and test the reliability of computational models					
I3: Detecting and correcting conceptual errors through simulation-based feedback mechanisms					
V1: Facilitating collaborative validation and refinement of mathematical models among students					
V2: Using digital tools to visualize, compare, and communicate alternative modeling solutions					
V3: Guiding students in critical evaluation of computational model accuracy and limitations					
System performance / engineering competence					
S1: I am confident in my ability to manage a complete computational modeling cycle (problem formulation, modeling, simulation, validation) in STEM contexts using educational technologies.					
S2: ICT improves my ability to structure and execute computational modeling tasks in scientific and engineering contexts.					
S3: Structured training in computational STEAM modeling systems would significantly improve my ability to design and implement engineering-based learning activities.					

4.4. Collection Procedure

The online questionnaire was conducted using Google Forms. The data were exported and analyzed using SPSS software. The variables were coded according to their nature: Likert scales for the difficulty items and categorical variables for the participants' characteristics.

4.5. Data Analysis Methods

This study adopts a convergent mixed-methods approach, primarily based on quantitative data analysis. On the quantitative side, Multiple Correspondence Analysis (MCA) was used to examine relationships among categorical variables derived from the survey. These variables include dimensions of computational modeling processes (M1-M3, W1_ICT-W3_ICT, I1-I3, V1-V3), techno-pedagogical competence perceptions (S1-S3), and contextual variables such as ICT training, practicum duration, and the use of real-world contexts in mathematics teaching. MCA was selected due to the categorical and ordinal nature of the data (Likert-scale responses).

This method is well-suited for exploring complex associations among qualitative variables in a multidimensional space. As noted in [26], MCA extends correspondence analysis and enables the visualization of relationships between variable categories in a reduced geometric space, thereby revealing latent structures within the dataset. In this study, MCA is used to:

- explore interrelationships among the stages of the computational modeling process;
- examine associations between perceived difficulties and ICT integration in STEM teaching;
- identify typological profiles of prospective teachers based on modeling-related difficulties and techno-pedagogical competencies.

5. RESULTS

The results are presented in a structured analytical sequence to ensure methodological rigor. First, the validity of the data collection instrument was assessed to confirm the adequacy of the measurement model. Second, descriptive statistics were computed to summarize participants' responses across all survey items. Third, correlation analysis was conducted to examine relationships between variables related to computational modeling competencies and techno-pedagogical perceptions. Finally, Multiple Correspondence Analysis (MCA) was applied to identify the underlying multidimensional structure of the data and derive typological profiles of prospective teachers.

5.1. Validity of the Instrument

The Cronbach's alpha coefficients obtained (α=0.796 for 12 items and α=0.791 for 15 items) indicate strong internal consistency of the survey. Since the values exceed the 0.70 threshold, they indicate satisfactory reliability of the items in educational science measurements, which consistently measure the same construct. The similarity of values between standardized and non-standardized items also confirms the instrument's stability. Thus, the questionnaire can be considered reliable for data analysis, as Table 2 illustrates.

Table 2. Survey validity

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	*N* of Items
0.796	0.796	12
0.791	0.790	15

5.2. Descriptive Statistics Results

Table 3 reports the descriptive statistics of the survey items, including three techno-pedagogical perception indicators and twelve items related to perceived difficulties in the computational modeling process.

Table 3. Descriptive statistics results

	N	Mean	Std. Error	Std. Deviation
M1	143	2.73	0.101	1.204
M2	143	2 .92	0.112	1.345
M3	143	2.81	0.114	1.368
W1_ICT	143	3.27	0.095	1.138
W2_ICT	143	2.82	0.104	1.248
W3_ICT	143	2.76	0.107	1.274
I1	143	2.65	0.097	1.164
I2	143	2.75	0.104	1.242
I3	143	2.76	0.103	1.235
V1	143	2.60	0.100	1.199
V2	143	2.76	0.098	1.170
V3	143	2.90	0.108	1.291
S1	143	3.13	0.105	1.252
S2	143	3.53	0.103	1.226
S3	143	3.78	0.097	1.158

5.3. Correlation Results

Multiple Correspondence Analysis (MCA) was applied to examine the underlying structure of relationships among categorical variables derived from the survey. This approach enables the exploration of associations between variables related to computational modeling difficulties and techno-pedagogical competencies among prospective elementary school teachers. Table 4 summarizes the main relationships and variable contributions identified by the MCA.

Table 4. Correlations between variables

	M1	M2	M3	W1_ICT	W2_ICT	W3_ICT	I1	I2	I3	V1	V2	V3	S1	S2	S3
M1	1.000														
M2	0.308	1.000													
M3	0.173	0.254	1.000												
W1_ICT	0.244	0.169	0.241	1.000											
W2_ICT	0.259	0.324	0.201	0.156	1.000										
W3_ICT	0.216	0.264	0.240	0.135	0.317	1.000									
I1	0.243	0.178	0.186	0.247	0.081	0.125	1.000								
I2	0.056	0.170	0.239	0.186	0.178	0.196	0.170	1.000							
I3	0.186	0.205	0.300	−0.010	0.347	0.347	0.253	0.256	1.000						
V1	0.365	0.184	0.150	0.234	0.250	0.294	0.344	0.306	0.322	1.000					
V2	0.185	0.200	0.256	0.289	0.188	0.289	0.165	0.324	0.275	0.395	1.000				
V3	0.172	0.190	0.306	0.123	0.315	0.240	0.193	0.284	0.309	0.257	0.323	1.000			
S1	0.279	0.199	0.302	0.281	0.226	0.414	0.224	0.304	0.382	0.371	0.248	0.276	1.000		
S2	0.143	0.195	0.235	0.322	0.145	0.262	0.217	0.451	0.187	0.240	0.390	0.339	0.500	1.000	
S3	0.241	0.109	0.235	0.324	0.271	0.272	0.272	0.337	0.227	0.328	0.330	0.285	0.389	0.536	1.000

5.4. Results of the Multiple Correspondence Analysis (MCA)

5.4.1. The Graphical Representation of Individuals

The individual factor map illustrates the distribution of participants within the two-dimensional space defined by the first MCA axes, providing a visual representation of prospective teachers' profiles based on their perceived difficulties in computational modeling processes.

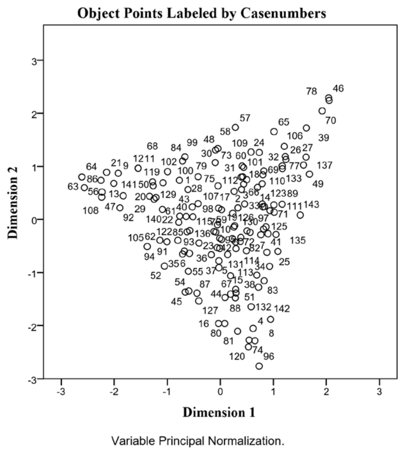

Figure 1. Graphical representation of prospective teachers' perceptions of modeling difficulties in elementary school

The second factor map displays the positioning of prospective teachers within the two-dimensional MCA space based on their perceived techno-pedagogical difficulties.

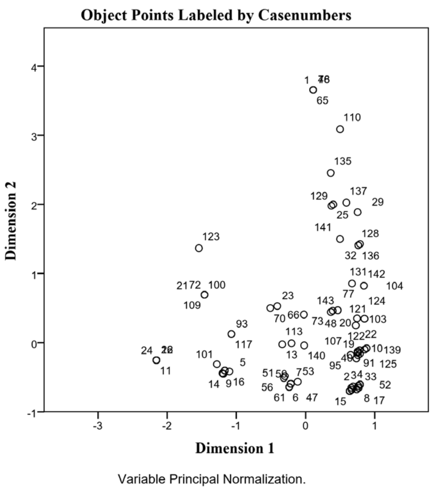

Figure 2. Graphical representation of prospective teachers' perceptions of techno-pedagogical difficulties in elementary school

5.4.2. Discrimination Measures of Variables

Discrimination measures derived from Multiple Correspondence Analysis (MCA) were used to assess the contribution of each survey item to the definition of the factorial axes. These variables relate to computational modeling difficulties and ICT integration among prospective primary school teachers during their practicum.

The first figure presents the discrimination measures for variables associated with perceived modeling difficulties in elementary school contexts.

The second figure presents the discrimination measures for variables related to prospective teachers' techno-pedagogical perceptions, highlighting their contribution to the factorial dimensions derived from the Multiple Correspondence Analysis.

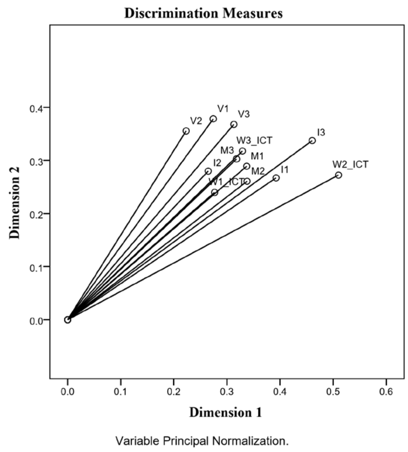

Figure 3. Measures of discrimination among prospective teachers regarding modelling difficulties in elementary school

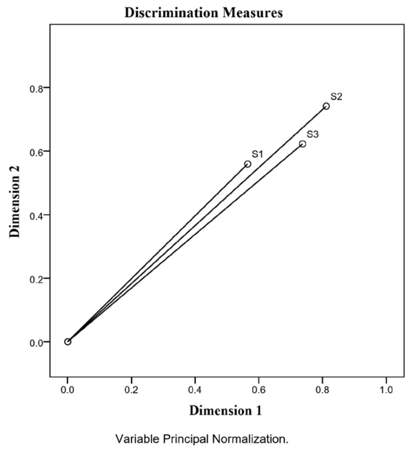

Figure 4. Measures of discrimination among prospective teachers regarding technological and pedagogical difficulties in elementary school

6. DISCUSSION

The results indicate that prospective elementary school teachers report moderate levels of difficulty in implementing computational modeling processes. The distribution of responses suggests relatively balanced perceptions, without strong polarization, reflecting heterogeneous yet generally consistent viewpoints. At the dimensional level, challenges related to the mathematization of real-world situations remain moderate, indicating difficulties in identifying relevant variables and translating contextual information into accessible mathematical representations. Similar patterns are observed in the interpretation and validation phases, suggesting that these stages constitute persistent areas of difficulty within the modeling process.

In contrast, ICT-related dimensions exhibit greater variability. While participants report relatively positive perceptions of their general confidence in using digital tools, they encounter more pronounced challenges in supporting students during simulation and computational processing tasks. This discrepancy points to an uneven development of techno-pedagogical competencies, where familiarity with digital tools does not necessarily translate into effective instructional integration.

Furthermore, the relatively higher levels of techno-pedagogical self-efficacy indicate a generally positive perception of the role of ICT in teaching. However, the variability in responses suggests differences in training exposure and practicum experience, reflecting the presence of diverse competency profiles among prospective teachers. In addition, these findings suggest that modeling-related competencies are not uniformly developed but rather structured as an interconnected system, in which difficulties in mathematization, ICT integration, and validation processes influence one another. This systemic perspective underscores the importance of strengthening initial teacher education through structured STEAM-based approaches that integrate computational modeling, digital technologies, and pedagogical decision-making.

The correlation analysis reveals a generally positive, yet weak to moderate, network of associations among the dimensions of computational modeling competencies. The findings indicate that, although the variables remain conceptually distinct, they are structurally interconnected, reflecting the integrated nature of modeling-related skills in teacher education. At the level of mathematization, positive correlations among items (M1-M3) indicate that difficulties in identifying relevant elements of real-world situations are associated with challenges in translating these situations into mathematical representations.

ICT-related dimensions (W1_ICT-W3_ICT) also show consistent associations with both mathematization and interpretation variables, indicating that difficulties in using digital tools are embedded within broader cognitive and pedagogical processes. Similarly, interpretation and validation dimensions (I1-I3, V1-V3) exhibit moderate inter-correlations, highlighting the close relationship between understanding model outputs, communicating results, and critically evaluating models in classroom contexts. In addition, techno-pedagogical self-efficacy variables (S1-S3) display strong internal coherence and are positively associated with ICT-related indicators, suggesting that confidence in digital tool use is closely linked to perceived pedagogical value and training needs.

Moreover, these findings indicate that computational modeling competencies are structured as an interconnected system rather than a set of isolated skills, with ICT playing a central mediating role across the different stages of the modeling process.

The Multiple Correspondence Analysis (MCA) reveals a structured pattern of associations among prospective elementary school teachers' perceptions of computational modeling difficulties and ICT integration in mathematics education. The projection of individuals in the factorial space shows a largely homogeneous distribution, with most participants clustered near the center. This pattern reflects a shared moderate perception of modeling-related challenges, while the presence of a limited number of distant profiles indicates variability in modeling competencies and techno-pedagogical readiness.

From a system-oriented perspective, this distribution points to a partially structured competency system, in which computational modeling skills are organized along a continuum of proficiency rather than uniformly distributed. The factorial structure highlights two main latent dimensions. The first dimension is primarily associated with mathematization and ICT-supported computational processes, reflecting challenges in system abstraction, variable identification, and digital simulation.

The second dimension relates more strongly to interpretation, communication, and validation processes, emphasizing difficulties in analyzing model outputs, supporting collaborative reasoning, and evaluating results. The discrimination measures further confirm that modeling-related variables are strongly embedded within these dimensions, indicating that mathematization, digital simulation, and validation function as interconnected components of a unified computational modeling system.

In addition, techno-pedagogical self-efficacy variables display strong internal coherence and are positively associated with ICT-related dimensions, suggesting that confidence in using digital tools is closely linked to perceived instructional capability at the system level. This finding is consistent with the TPACK framework, which emphasizes the integration of technological, pedagogical, and content knowledge in teaching practices [25]. The eigenvalue structure confirms the predominance of the first dimension (4.616), indicating that it captures the largest share of variance and represents a dominant latent factor related to computational modeling complexity.

This suggests that difficulties in mathematization, digital simulation, and validation are not independent but emerge from shared structural constraints in the development of competencies. These results align with previous research highlighting the complexity of modeling-based learning in science and mathematics education [27], particularly the challenges involved in translating real-world phenomena into appropriate mathematical representations.

The findings extend beyond a purely educational interpretation by revealing the underlying systemic organization of modeling competencies. They highlight that challenges in mathematization, ICT-based simulation, and model validation form part of an integrated system, supporting the need for STEAM-based teacher education approaches that emphasize computational thinking, system modeling, and digital tool integration.

7. CONCLUSION

This study examined prospective primary school mathematics teachers' perceptions of the challenges associated with implementing computational modeling processes and integrating ICT into science-related mathematics instruction during their practicum. The findings provide an integrated perspective on how modeling competencies and techno-pedagogical skills are perceived within teacher education contexts.

The results indicate moderate levels of difficulty across the stages of the modeling cycle, particularly in mathematization, ICT-supported simulation, and model validation. Correlation and multivariate analyses further reveal that these dimensions are structurally interconnected, suggesting that difficulties in one stage tend to influence performance in others, reflecting a systemic organization of competencies. From a techno-pedagogical perspective, the findings show that although participants report a generally positive sense of self-efficacy regarding the use of digital tools, notable variability persists in their ability to effectively integrate ICT into modeling-based instruction. This variability appears to be associated with differences in training exposure and practicum experience.

Importantly, this study extends beyond a purely educational perspective by conceptualizing computational modeling as an integrated competency system that combines mathematization, simulation, interpretation, and validation processes. This system-oriented view highlights the need to approach modeling as a coherent cognitive and technological framework rather than a set of isolated pedagogical tasks.

These findings underscore the importance of strengthening initial teacher education through integrated STEAM-based approaches that simultaneously develop modeling competencies, ICT integration, and pedagogical decision-making. Such approaches are essential for supporting the effective implementation of technology-enhanced modeling practices in primary science and mathematics education.

Future research should build on these results by incorporating classroom-based experimental designs and implementation studies to further examine the impact of computational modeling on student learning outcomes and instructional effectiveness.

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