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Research on Computational Modeling and Simulation-Based Instructional Strategies in Higher Vocational Mathematics Education: An Empirical Analysis Using Matrix Operations

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Abstract: To address the disconnection between theory and practice and the inefficiency of knowledge transfer in higher vocational mathematics education, this study proposes an instructional model centered on computational thinking, structured around the framework of "Modeling Concept-Professional Integration-Complexity Simplification-Application Innovation" (MCPAI). Using "matrix operations" as an empirical case, we explore a deep integration pathway between mathematics education and professional practice. Leveraging online-offline blended teaching methods, a three-phase instructional framework ("pre-class preparation, in-class task-driven learning, post-class extension") is designed. This framework incorporates discipline-specific scenarios such as digital image processing and agricultural economic modeling, guiding students to utilize MATLAB tools for modeling, simulation, and optimization, thereby enabling effective translation of mathematical tools into real-world problem-solving. Teaching practices demonstrate that this model significantly enhances students' computational thinking (average improvement: 32.7%), teamwork (improvement: 28.4%), and innovation capabilities (improvement: 25.9%). The effectiveness is validated through pre- and post-test score comparisons (experimental group: N = 45 vs. control group: N = 43, $p < 0.01$). Furthermore, the organic integration of value-oriented elements strengthens the value-guiding function of mathematics education. This research provides a paradigm with both theoretical innovation and practical feasibility for the reform of higher vocational mathematics education.

Keywords: higher vocational education; computational thinking; modeling and simulation; disciplinary integration; Computational Thinking

CCS: applied computing; education; computer-assisted instruction

1. Introduction

Against the backdrop of rapid industry iteration and technological upgrading driven by digitalization and intelligent technologies, there is a significant increasing demand for high-skilled talents with compound intelligent literacy [1,2]. These talents need to deeply integrate information technology, innovation capability,

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and professional knowledge to adapt to the dynamically changing industrial ecosystem [3, 4]. As the core foundation of natural science and the methodological support for intelligent technology innovation, mathematics plays a strategic role in cultivating the core literacy of intelligent talents in the higher vocational education system. However, current higher vocational mathematics education faces severe challenges: Firstly, the teaching content has insufficient relevance to professional scenarios, making it difficult for students to establish logical connections between mathematical tools and engineering practice; secondly, the traditional teaching model focuses on theoretical indoctrination and neglects the systematic cultivation of computational thinking and modeling abilities, restricting the development of students' abilities to solve complex problems. In response to the above issues, the academic community has explored innovative teaching models from multiple dimensions to strengthen mathematical abilities. Through the implementation of various innovative teaching models including "Problem-Based Learning", "Flipped Classroom", "Gamified Teaching", and "Inquiry-Based Learning" [5], the participation and adaptability of students are enhanced. However, it is also found that, for example, Problem-Based Learning (PBL) can improve practical abilities, but it requires a large amount of time to design real projects, and has high demands on teachers' interdisciplinary literacy, easily leading to insufficient depth of mathematical theory [6]; Flipped Classroom optimizes classroom interaction through pre-class knowledge input, but relies on students' autonomous learning ability, which may cause "knowledge disconnection" in groups with weak mathematical foundations, and it is difficult to systematically cultivate modeling thinking [7]; Gamified Teaching enhances learning interest through incentive mechanisms, but over-reliance on game forms may lead to deviation from teaching goals, such as students being addicted to point rewards and ignoring the rigor of mathematical logic [8]; Inquiry-Based Learning focuses on the process of knowledge discovery, but in higher vocational education, students' insufficient abstract thinking ability may lead to low inquiry efficiency, and the lack of standardized evaluation tools makes it difficult to quantify the effect of ability improvement [9]; including some beneficial explorations in recent years, such as the four-dimensional linkage model proposed by [10]. Although it strengthens professional collaboration, it still has shortcomings in the hierarchical cultivation of computational modeling abilities and dynamic adaptation. The "Modeling Concept-Professional Integration-Complexity Simplification-Application Innovation" (MCPAI) teaching model proposed in this study compensates for the shortcomings of existing methods in terms of systematicness, practical relevance, and hierarchical cultivation of abilities through a four-dimensional progressive path. Specifically, with computational thinking as the core, MCPAI runs mathematical modeling through the entire chain of "theory-tool-application", and through the experimental design combining virtual and real situations, it achieves a step-by-step improvement from knowledge construction to innovation ability.

This study takes "matrix operations" as the entry point and promotes the transformation of mathematical knowledge into practical application by simulating professional scenarios and modeling practices. The research objectives include: (1) Constructing a teaching framework with a complete chain through "theory-tool-application"; (2) Validating the effectiveness of integrating computational modeling and majors on students' ability improvement; (3) Exploring the value penetration path of ideological and political elements in mathematics education. In this process, the teaching goal shifts from single knowledge transmission to capability construction, emphasizing computational thinking training, interdisciplinary collaboration ability cultivation, and innovation awareness inspiration. Empirical research shows that this model can significantly improve students' knowledge transfer efficiency and complex problem-solving ability. Meanwhile, through the organic integration of ideological and political elements (such as system philosophy and mathematical aesthetics), the value-leading function of mathematics education is deepened. This exploration provides a paradigm reference with both theoretical innovation and practical feasibility for the reform of higher vocational mathematics education.

2. Instructional Philosophy and Design

Based on Constructivist Learning Theory and Outcome-Based Education (OBE) principles, this study adheres to a "student development-centered, competency-oriented" instructional philosophy, constructing a multidimensional interactive teaching model centered on computational thinking cultivation and anchored in professional scenario simulations. This model leverages a blended online-offline instructional framework to synergistically enhance students' mathematical application capabilities and professional competencies through the integration of knowledge transmission, skill development, and value guidance. The instructional design focuses on four-dimensional objectives—Modeling Concept, Professional Integration, Complexity Simplification, and Application Innovation (MCPAI) —emphasizing the transfer of mathematical tools and innovative practices driven by real-world problems. Its core framework comprises three phases:

2.1. Pre-Class Preparation Phase (Knowledge Construction and Scenario Presetting)

This phase involves restructuring textbook content and conducting in-depth analysis of student learning profiles to clarify hierarchical instructional objectives and practical orientations. Implementation strategies include:

(1) Resource Integration and Distribution

Utilizing MOOC platforms and digital repositories to distribute foundational theories of matrix operations, MATLAB tutorials, and professional case materials (e.g., digital image storage principles). Students are required to complete knowledge previews and preliminary experimental tasks (e.g., image grayscale conversion).

(2) Learning Diagnosis and Optimization

Analyzing platform data (e.g., preview completion degree, test accuracy, and lab report feedback) to identify cognitive gaps and dynamically adjust teaching priorities. For instance, students struggling with matrix multiplication rules receive supplementary visualizations of linear transformations to reinforce intuitive understanding.

2.2. In-Class Teaching Phase (Task-Driven Collaborative Modeling)

The classroom adopts a blended design of "case introduction, task-driven learning, and collaborative inquiry", prioritizing professional scenario simulations to bridge mathematical tools and real-world applications. For example, using digital image storage matrices: (1) Scenario Embedding, Explain the mapping relationship between matrices and pixels to establish connections between mathematical abstraction and engineering practices. (2) Hierarchical Task Design, Basic Task: Perform image superposition via matrix addition to visualize geometric implications of operations. Advanced Task: Design image denoising algorithms using matrix multiplication (e.g., mean filtering) to validate mathematical models. High-Level Task: Construct transportation cost matrices in agricultural economic models, training students to translate multivariate problems into matrix operations. (3) Collaboration and Reflection: Students work in groups to implement tasks via MATLAB programming, presenting modeling logic and algorithm optimization strategies. Instructors provide personalized guidance through real-time data monitoring (e.g., code efficiency, error patterns) to strengthen computational thinking and problem decomposition skills.

2.3. Post-Class Extension Phase (Competency Advancement and Value Internalization)

This phase employs layered training and ideological-political integration to consolidate knowledge and advance higher-order competencies.

2.3.1. Layered Training Design

(1) Consolidation Layer

Deliver micro-lectures (e. g., geometric interpretations of matrix transposition) and foundational programming exercises targeting weaknesses.

(2) Extension Layer

Design interdisciplinary projects, such as 3D image rotation transformations and the mathematical modeling contest problem "Contour Gauge Calibration," requiring students to devise matrix transformation algorithms for engineering challenges.

2.3.2. Value Integration

Infuse case studies with systems philosophy (e.g., dialectical relationships between whole and parts) and mathematical aesthetics (e.g., symmetry in image processing), deepening students' awareness of disciplinary value and professional ethics through reflective reports and group discussions.

2.3.3. Dynamic Feedback Mechanism

Collect assignment data and learning reflections via educational platforms, analyze competency development trajectories using formative assessment rubrics, and inform iterative pedagogical improvements (as shown in Figure 1).

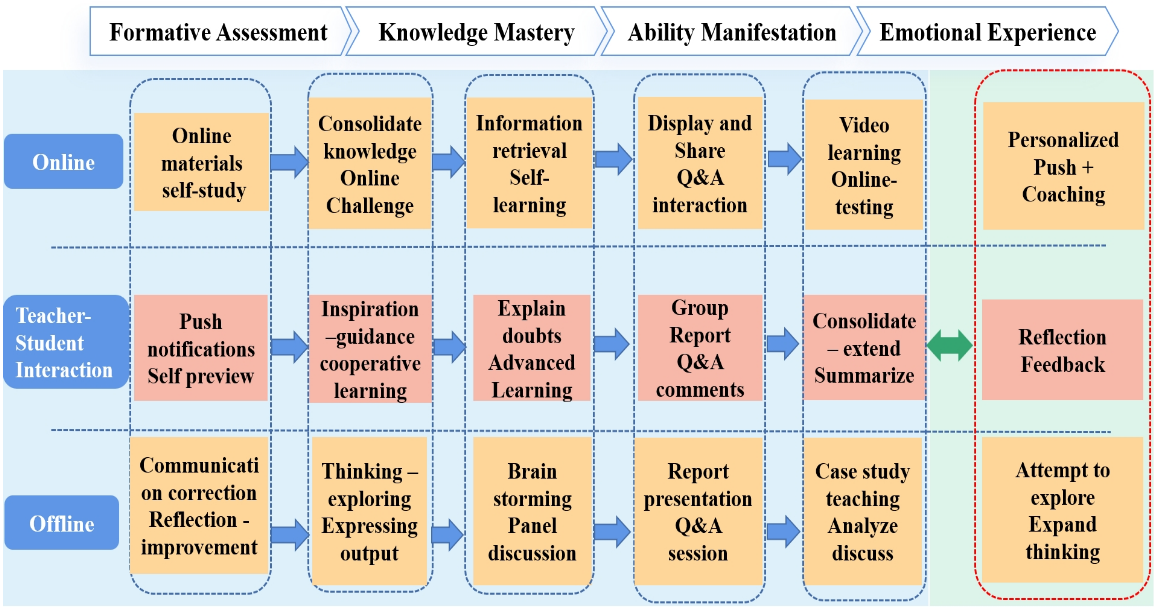


Figure 1. Classroom teaching design.

3. Empirical Analysis of Instructional Design Using Matrix Operations as a Case Study

3.1. Instructional Context and Objectives

Amid the backdrop of digital transformation and interdisciplinary convergence, higher vocational mathematics education urgently requires deep collaboration between foundational and applied disciplines to cultivate interdisciplinary talents equipped with computational thinking and engineering practice capabilities. This study focuses on the "Matrix Operations" module from the linear algebra content in the public foundational course Computer Mathematics and Mathematical Culture for higher vocational education, with the following objectives:

(1) Knowledge Objectives

Systematically master the operational rules of matrix addition, multiplication, and transposition, and understand their logical interconnections within mathematical theory.

(2) Skill Objectives

Implement algorithm design for matrix operations using MATLAB tools, and complete mathematical modeling and simulation verification in professional scenarios such as digital image processing and agricultural economic models.

(3) Competency Objectives

Strengthen computational thinking and interdisciplinary collaboration skills, while enhancing professional identity and awareness of translating mathematical tools into practice.

(4) Value-Oriented Objectives

Infuse systems philosophy (e. g., dialectical relationships between whole and parts) and mathematical aesthetics (e. g., symmetry of matrices in engineering applications) to deepen the value-guiding role of mathematics education.

3.2. Instructional Preparation

3.2.1. Student Profile Analysis

(1) Student Background

The study involved first-year students (second semester) majoring in Computer Application Technology. Industry surveys indicate that this program demands proficiency in digital image processing (e. g., OpenCV applications) and MATLAB/Python programming to address technical needs in fields like computer vision and virtual reality.

(2) Academic Foundation

Based on Gaokao (National College Entrance Examination) mathematics scores, 73.3% of students scored between 60 and 79, indicating moderate mathematical proficiency but high cognitive engagement (classroom interaction frequency: 3.2 times per session).

(3) Technical Skills

Prior coursework covered matrix concepts and arithmetic operations. While 84.4% of students could independently program matrix addition, only 32.4% understood the relevance of matrix multiplication to engineering applications (e. g., image transformation). Additionally, 79.1% possessed basic MATLAB skills (e. g., image reading, grayscale conversion).

(4) Cognitive Characteristics

Students exhibited strong practical orientation and collaborative willingness (89% participation rate in group tasks) but struggled with abstract theoretical comprehension (e. g., only 28.9% could independently derive the geometric meaning of matrix transposition).

3.2.2. Competency-Based Curriculum Design

Aligned with the talent development plan for Computer Application Technology and industry requirements, the instructional design follows a three-dimensional “Knowledge-Skill-Competency” framework (as shown in Figure 2):

(1) Knowledge Layer

Restructure textbook content to highlight the pivotal role of matrix operations in image processing (e. g., affine transformations) and economic modeling (e.g., transportation cost optimization).

(2) Skill Layer

Train students in algorithm implementation and model optimization through MATLAB programming tasks (e.g., noise filtering algorithm design).

(3) Competency Layer

Cultivate systematic problem-solving abilities in engineering contexts using interdisciplinary cases (e.g., the 2020 Mathematical Contest in Modeling problem “Contour Gauge Calibration”), while reinforcing professional responsibility and innovation awareness through reflective case reports.

NO.	Capability Upgrading		High quality intelligent talents		
01	Addition of matrices	Overlay of Images Denoising of Images	Roughly understand/ The principle is unclear	Case Study	Absorbed
02	Multiplication of matrices	Image Enhancement		Operation demonstration	Rigorous
03	Multiplication of matrices	Image Transformation	Students are interested/ Need guidance	Online and offline discussions	Innovate
04	Transpose of matrix	Composite Transformation of Images		Guide Practice	Cooperation
	Theoretical knowledge points	Vocational Skill Points	Academic situation	Teaching Strategy	Ideological and Political Education

Figure 2. Instructional design framework for the "Matrix Operations" course based on the MCPAI model.

3.3. Instructional Strategies

3.3.1. Instructional Philosophy and Principles

Adhering to the "student development-centered, competency-oriented" pedagogical principles, this study employs the MCPAI (Modeling Concept-Professional Integration-Complexity Simplification-Application Innovation) instructional model as its core framework. Driven by authentic project-based problems, the model systematically integrates mathematical tool migration, interdisciplinary collaboration, and innovation capability cultivation through a four-dimensional progressive pathway. It aims to achieve synergistic development of knowledge construction, skill enhancement, and professional literacy.

3.3.2. Interest Stimulation and Problem Introduction

(1) Interest Engagement via Professional Contexts

Cognitive dissonance scenarios are constructed using matrix storage principles in digital image processing (e. g., pixel-mapping mechanisms) and practical applications (e. g., noise filtering, image enhancement). For instance, contrasting raw and denoised images visually reinforces the connection between mathematical abstraction and engineering practices, motivating students to actively explore the geometric and physical implications of matrix operations.

(2) Progressive Problem-Driven Learning Design

A scaffolded problem chain (e.g., image superposition → image denoising → agricultural economic model optimization) spans the entire instructional process. Heuristic questions (e. g., "How can matrix multiplication achieve image dimensionality reduction?") shift student focus from rote memorization to deep logical analysis. Problem design aligns with Vygotsky's Zone of Proximal Development (ZPD) theory, ensuring cognitive-level-appropriate difficulty gradients. This guides students through a complete cognitive cycle: problem identification → model construction → algorithm implementation → outcome validation.

3.3.3. Diversified Pedagogical Methods and Practical Implementation

(1) Case-Driven Heuristic Instruction

High-level interdisciplinary cases (e. g., the Mathematical Contest in Modeling problem "Contour Gauge Calibration") from digital image processing and agricultural economics are selected. A three-stage methodology—case deconstruction, principle tracing, tool migration—bridges abstract mathematical concepts (e.g., geometric interpretations of matrix transposition) with engineering practices. Instructors employ MATLAB visualization tools (e.g., dynamic matrix operation demonstrations) to lower cognitive barriers.

(2) Virtual-Real Integrated Experimental Exploration

A dual-track "simulation-verification → real-world application" experimental design creates a blended practice platform. For example, after simulating image superposition and rotation transformations in MATLAB, students migrate algorithms to real-world scenarios (e. g., agricultural transportation cost optimization) to validate model universality and robustness. Experimental tasks incorporate "trial-error-reflection-iteration" cycles, strengthening problem decomposition skills and engineering thinking.

3.3.4. Addressing Key Challenges and Competency Development

(1) Teacher-Student Collaborative Inquiry

For cognitively challenging topics (e.g., matrix multiplication rules, geometric meaning of transposition), a "teacher-guided, student-led" collaborative inquiry approach is adopted. Dynamic demonstrations of matrix multiplication in image transformations guide students to generalize operational patterns, while self-designed experiments (e.g., 3D coordinate rotation) deepen algorithmic understanding.

(2) Heterogeneous Group Collaboration

Learning communities are formed through heterogeneous grouping, with role specialization (e.g., algorithm design, code debugging, result analysis) fostering complementary expertise and knowledge sharing. The Jigsaw Method is applied: subgroups solve sub-problems (e.g., transportation cost matrix construction), later integrating solutions into a holistic framework to cultivate systemic thinking and teamwork.

(3) Multidimensional Feedback and Presentation

A tripartite feedback system—formative assessment, peer review, expert evaluation—is established. Students present outcomes via academic posters, code reports, and oral defenses, emphasizing modeling rigor and innovation. Instructors use SOLO taxonomy-based rubrics to quantify knowledge mastery, algorithm efficiency, and collaborative contributions, enabling real-time pedagogical adjustments.

3.3.5. Instructional Process Design

(1) Pre-Class Phase (Knowledge Input and Diagnosis)

MOOC platforms distribute matrix operation micro-lectures and professional case materials. Teaching priorities are dynamically adjusted based on diagnostic data (e.g., pre-class quiz accuracy).

(2) In-Class Phase (Deep Interaction and Competency Building)

A closed-loop "problem introduction → task-driven learning → collaborative inquiry → reflective synthesis" process enhances computational thinking and engineering practice capabilities.

(3) Post-Class Phase (Competency Expansion and Value Internalization)

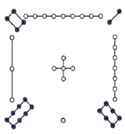
Layered extension tasks (e. g., 3D image rotation algorithm optimization) are paired with value-oriented reflection reports (e. g., systems philosophy in matrix symmetry). Learning platforms track data and deliver personalized resources, achieving a spiral progression of "knowledge consolidation → competency advancement → value internalization."

3.4. Implementation Example: Matrix Operations

3.4.1. Pre-Class Resource Distribution

Students receive curated materials on matrix operations, MATLAB tutorials, and case studies (e. g., digital image storage principles) via MOOC platforms (as shown in Table 1).

Table 1. Pre-class learning checklist.

Object	**Matrix Operations**
Learning content	1. Log in to the MOOC platform, learn about matrix operations, and complete the related questions on Rain Classroom. Course Title: Practical Linear Algebra for Everyone (MATLAB Edition), Chinese University MOOC (icourse163.org). Question: (1) What are the key aspects of matrix operations? (2) $A=\begin{pmatrix}2 & 1\\ 3 & -1\end{pmatrix}$, $B=\begin{pmatrix}0 & 1\\ 3 & 0\end{pmatrix}$, $C=\begin{pmatrix}0\\ 1\end{pmatrix}$ Which of the following matrix operations cannot be performed? A, A + B, ⋯ B, A + C, ⋯ C, A * C, ⋯ D, A − B 2. Select an image and perform the following operations using MATLAB. Upload the experimental results and code: (1) Read A = imread (filename, fmt); Note: filename is the file name (enclosed in quotes), and fmt is the file format (e.g., jpg). This parameter is optional; (2) Display imshow(A); (3) A_gray = rgb2gray(A); %Convert the image to grayscale, View the data structure of A_gray. 3. Read the content on page 156 of the textbook: "The Divine Turtle Presents a Miraculous Map", and experience the unique charm of Chinese culture. Summarize your reading reflections. 
Self-Evaluation	(1) Pre-class Learning Completion Rate: _________% (2) Issues Encountered During Self-study: ________ (3) Suggestions or Feedback for Improvement: ____

3.4.2. Course Introduction (Presenting Professional Scenarios)

This submission version of your paper should not have headers or footers, these will be added when your manuscript is processed after acceptance. It should remain in a one-column format—please do not alter any of the styles or margins. (1) Use examples to illustrate how digital images are stored as matrices in computers (as shown in Figure 3). (2) Explore the specific effects of matrix operations on image processing and their practical applications.

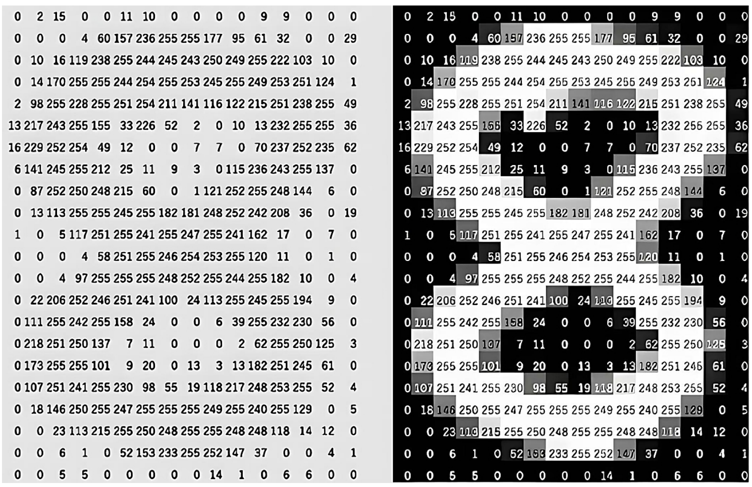


Figure 3. Digital image and grayscale image examples in the "matrix calculation" case study.

3.4.3. Task-Driven Approach

Based on educational principles, teaching tasks are designed to progress step-by-step, from simple to complex, focusing on professional application scenarios. Teachers provide guidance, encouraging students to first explore independently, watch instructional videos, and then collaborate to complete tasks (as shown in Figure 4).

Figure 4. Image overlay effect diagram.

Task 1: Input matrices A and B, and calculate A + B

$$A=\begin{pmatrix}6&5\\4&1\\2&3\\8&5\end{pmatrix}\quad B=\begin{pmatrix}5&3\\4&0\\1&7\\8&6\end{pmatrix}$$

Task 2: Image Double Exposure Adjustment

Given images $f(x,y)$ and $h(x,y)$, use MATLAB to adjust the double exposure according to the formula $g(x,y)=\frac{1}{2}f(x,y)+\frac{1}{2}h(x,y)$. Experience the beauty of mathematics and apply it to real-life scenarios and artistic creations.

3.4.4. Inspirational Application

For a video captured by a stationary camera with noticeable noise, summing each frame and dividing by the number of frames to calculate the average can produce a clean, noise-free image.

Task 3: Agricultural Economic Model

A township has three villages. The crop yields, transportation costs, and purchase prices for this year are shown in the table below (as shown in Table 2):

Table 2. Data table for constructing transportation and purchase cost matrices in the agricultural economic model.

Village	Wheat	Corn	Soybeans	Cotton
Village 1	600	800	400	30
Village 2	550	700	500	20
Village 3	550	700	500	20
Item	Wheat	Corn	Soybeans	Cotton
Transport Cost	12	10	0	90
Purchase Price	1200	1000	1500	8000

(1) Calculate the total transportation costs and purchase costs for four types of crops in each village. (2) Represent the problem (1) using matrices and perform calculations using MATLAB.

Task 4: Profilometer Calibration

Refer to Problem D of the 2020 National Mathematical Modeling Contest for College Students in China: Under different measurement conditions, the position and angle of the profilometer vary. The task is to horizontally calibrate the tilted profilometer (students need to research and learn), as shown in Figure 5.

(1) The problem provides matrix coordinates for horizontal and tilted workpieces. What steps are needed to perform the calibration?

(2) What is the core step?

3.4.5. Application Expansion

Use MATLAB to rotate a 3D airplane model at different angles and observe the rotation effects (as shown in Figure 6).

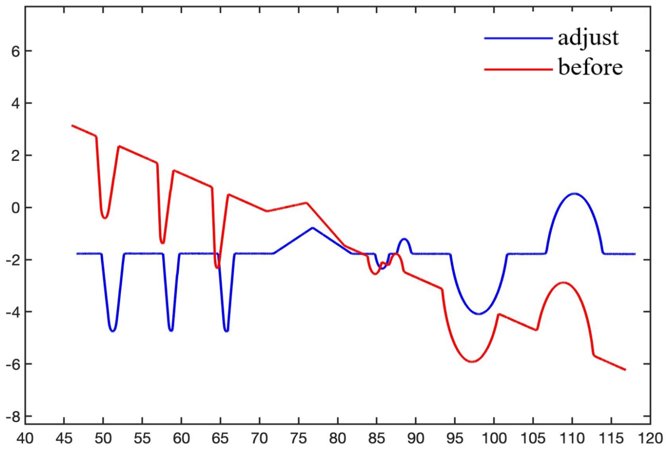


Figure 5. Comparison of profilometer before and after calibration.

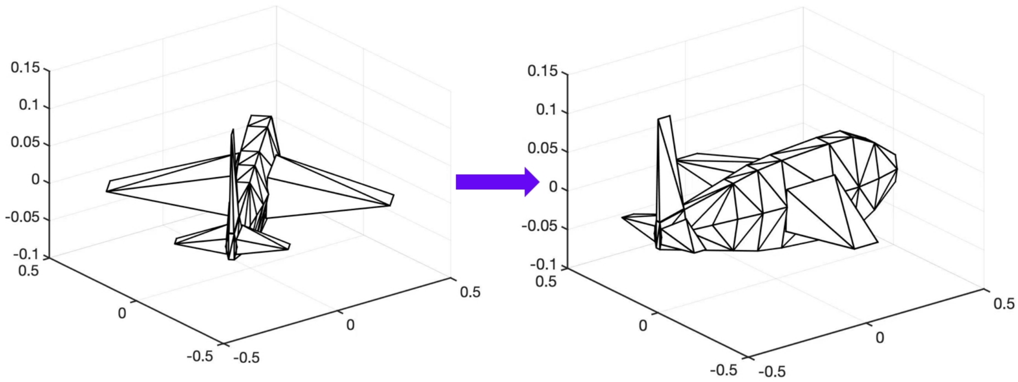


Figure 6. Schematic diagram of 3D image rotation.

3.4.6. In-Depth Explanation and Advanced Learning

(1) Matrix Addition and Subtraction;

(2) Matrix Transposition;

(3) Matrix Multiplication Rules;

(4) Image Rotation Principles: Students can extend these principles to three-dimensional scenarios (as shown in Figure 7).

$$R(\theta)=\begin{pmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}x_1 & x_2 \cdots & x_n \\ y_1 & y_2 \cdots & y_n\end{pmatrix}$$

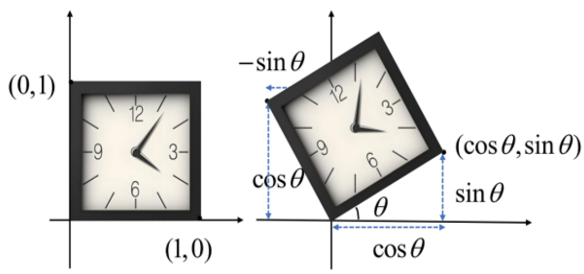


Figure 7. Schematic diagram of image rotation.

3.4.7. Organizing Reports and Sharing Presentations

Based on the teacher's detailed explanations and guidance, students complete learning tasks and produce written outputs through self-study and group collaboration. They present their results, share solutions to problems encountered, and discuss their learning experiences. The teacher provides targeted feedback and suggestions.

3.4.8. Evaluation, Reflection, and Summarization

Personalized learning resources (such as matrix operation techniques and MATLAB image manipulation videos) are pushed through the platform for students to consolidate and summarize offline. Students discuss and resolve doubts from the class, while also providing feedback on their learning process through the online platform (as shown in Table 3).

Table 3. Learning evaluation system for matrix operations course chapters based on the MCPAI model.

Primary Objectives and Weights	Secondary Objective		Evaluation Basis and Tools
Knowledge Construction and Application Ability (30%)	1. Mastery of Mathematical Tools	(1) Accurately describe matrix operation rules and their geometric significance. (2) Independently complete basic MATLAB programming tasks.	Pre-class quizzes, completion of in-class programming tasks, analysis of homework assignments.
	2. Interdisciplinary Transfer Ability.	(1) Apply matrix operation logic to professional scenarios. (2) Explain the universality of mathematical models in engineering practice.	Case analysis reports, interdisciplinary project presentations.
Computational Thinking and Engineering Practice Ability (40%)	1. Algorithm Design and Optimization.	(1) Design matrix transformation algorithms for complex problems. (2) Verify model robustness through simulation experiments.	Code efficiency, records of algorithm iterations.
	2. Collaboration and Problem Decomposition Ability.	(1) Clearly define roles in group collaboration. (2) Systematically integrate solutions to sub-problems.	Peer evaluation records, contribution metrics for collaborative tasks.
Value Recognition and Professional Literacy (30%)	1. Internalization of Ideological and Political Elements	(1) Explain the aesthetic value of matrix symmetry in engineering. (2) Reflect on ethical responsibilities in algorithm design.	Analysis of reflection reports, participation in classroom discussions.
	2. Professional Identity and Innovation Awareness	(1) Actively explore cutting-edge applications of mathematical tools in professional fields. (2) Propose innovative ideas to improve existing models.	Innovative task proposals, academic poster presentation scores.
Dynamic Feedback and Improvement Suggestions	(1) Summary of Learning Questions and Difficulties: Record questions and difficulties during the learning process through platform logs. (2) Specific Suggestions for Course Design: Such as adjusting case complexity and optimizing teaching resources.		Platform learning logs, post-class anonymous questionnaires.

3.4.9. Competency Assessment Methods

A hybrid evaluation toolkit is employed, comprising:

(1) Based on the Computational Thinking Scale (CTS) [11]

The improvement in capabilities was analyzed through post-test and pre-test comparisons, focusing on 12 indicators such as “abstraction”, “algorithm design”, and “problem decomposition” (each scored out of 5), with a total score of 60. The experimental group’s average score increased from 36.4 points to 48.3 points (an increase of 32.7%), while the control group’s score only rose from 36.4 points to 39.1 points ($p < 0.05$).

(2) Team Collaboration Scorecard (based on the PBL collaboration standard) [12]

Scores were given from three dimensions: “task division”, “communication efficiency”, and “result integration” (each dimension scored out of 5, with a total score of 15). The experimental group’s average score improved from 6.2 points to 8.0 points (an increase of 28.4%), whereas the control group’s score only increased from 6.1 points to 6.7 points ($p < 0.05$).

(3) Innovation Capability Indicators

By quantifying the "number of algorithm optimizations" and "interdisciplinary solution innovation," the experimental group proposed an average of 2.3 innovative solutions in the agricultural economic model task (compared to 0.7 in the control group), with 25% of the solutions rated as "highly innovative" by teachers or industry experts (compared to 4% in the control group).

(4) Performance Comparison

The experimental group achieved an average score of 85.6 in the matrix operation application test (compared to 72.1 in the control group), with an ANOVA showing F = 18.74 ($p < 0.01$).

In summary, an independent samples t-test between the experimental group (N = 45) and the control group (N = 43) demonstrated that the experimental group significantly outperformed the control group in computational thinking (t = 4.32, $p < 0.001$) and innovation capability (t = 3.87, $p < 0.01$).

4. Interdisciplinary Transfer and Generalization Validation of the MCPAI Model

This study transcends the limitations of single-course case studies by constructing the MCPAI capability development chain—Mathematical concept modeling, Construction of professional structures, Programming-driven algorithm implementation, Application in engineering scenarios, and Innovation across disciplinary boundaries—systematically addressing three persistent challenges in traditional mathematics education: conceptual abstraction, cognitive fragmentation, and practical disembedding. Using "matrix operations" as a paradigmatic validation vehicle, the model successfully facilitates the following capability transformations: (1) Cognitive dimension, establishes isomorphic mappings between mathematical symbolic systems and engineering semantic spaces. (2) Methodological dimension, forms a computable thinking cultivation pathway of "mathematical model → algorithmic architecture → code implementation." (3) Value dimension, activates the innovative application potential of mathematical tools through cross-disciplinary project-based learning (PBL).

Theoretical and empirical analyses demonstrate the MCPAI model's significant paradigm transferability in STEM education:

(a) Disciplinary Universality: Extendable to core mathematical modules such as eigenvalue analysis in linear algebra, differential equation modeling in calculus, and stochastic process simulation in probability theory.

(b) Capability Adaptability: Dynamically aligns with the mathematical literacy needs of engineering, business, and data science disciplines by adjusting cognitive load intensity (CLI) at each stage.

(c) Technical Scalability: Supports embedded integration with multi-language toolchains (e.g., MATLAB/Simulink, Python/NumPy, Julia) to meet industrial-grade numerical computation standards. Representative migration cases are as follows:

4.1. Calculus Field: Progressive Tax-Driven Piecewise Function Modeling Innovation

4.1.1. Case Implementation

Tasks:

(1) Calculate the tax payable for an individual with a taxable income of 120,000 CNY.

(2) Establish a functional model between taxable income and tax payable based on Table 4.

(3) Develop a MATLAB program to compute the tax for 120,000 CNY and output results.

(4) Analyze the rationale for setting quick deductions and their practical advantages.

4.1.2. MCPAI Capability Chain Construction via Fiscal Policy

Using China's progressive tax system as a socio-economic carrier (Modeling), a five-tier capability chain is constructed: Mathematical Model Construction: Quantify tax bracket rules and derive the mathematical logic of quick deductions (Construction); Algorithmic Engineering: Develop a MATLAB-based tax calculation system for multi-income automation (Programming); Policy Sensitivity Analysis: Analyze the social welfare effects of tax thresholds and rate jumps using decade-long fiscal reform data (Application);Tax Model Innovation: Guide students to design dynamic segmented tax systems adaptable to the gig economy (Innovation).

Table 4. Individual income tax brackets for annual bonuses integrated into comprehensive income.

Tier	Taxable Income (CNY)	Tax Rate	Quick Deduction (CNY)
1	≤36,000	3%	0
2	36,000–144,000 (inclusive)	10%	2520
3	144,000–300,000 (inclusive)	20%	16,920
4	300,000–420,000 (inclusive)	25%	31,920
5	420,000–660,000 (inclusive)	30%	52,920
6	660,000–960,000 (inclusive)	35%	85,920
7	>960,000	45%	181,920

4.2. Probability and Statistics Field: Supply Chain-Driven Regression Analysis Practice

4.2.1. Case Implementation

A company is attempting to sell a new beverage in 22 approximately equal sized cities, with the sales price and weekly sales in these cities shown in Table 5.

Table 5. Sales data of a new beverage across 22 cities.

City	Price (CNY)	Weekly Sales (k Units)	City	Price (CNY)	Weekly Sales (k Units)
1	3.54	3.98	12	2.94	6.00
2	4.80	2.20	13	6.54	1.19
3	5.70	1.85	14	5.70	1.96
4	2.70	6.10	15	4.74	2.76
5	4.74	2.10	16	3.90	4.33
6	5.94	1.70	17	2.70	6.96
7	5.40	2.00	18	3.60	4.16
8	3.90	4.20	18	5.34	1.99
9	4.74	2.44	20	4.74	2.86
10	4.14	3.30	21	5.94	1.92
11	4.74	2.30	22	5.10	2.36

Tasks (thousand units= k units):

(1) Plot a price-sales scatter diagram using MATLAB/Python.

(2) Identify an “ideal price curve” (mathematical model) to predict weekly sales at any given price. Evaluate model efficacy.

(3) Determine the optimal nationwide price to maximize profit, given a unit cost of 1.38 CNY.

4.2.2. MCPAI-Based Regression Analysis Cultivation Pathway

Using price-sales relationships as a business carrier (Modeling), a four-dimensional capability framework is established:

(1) Data Modeling: Construct a regression equation via least squares and interpret the economic implications of the coefficient of determination R^2 (Construction).

(2) Algorithm Implementation: Develop a Python-based automated analysis tool integrating visualization and model validation (Programming).

(3) Decision Optimization: Derive profit-maximizing pricing strategies under cost constraints (Application).

(4) Business Innovation: Design a Bayesian optimization-driven dynamic pricing framework (Innovation).

5. Conclusions and Future Directions

The MCPAI teaching model effectively addresses the disconnection between theory and practice in higher vocational mathematics education, achieving dual goals of cultivating computational thinking and enhancing professional competencies. By integrating computational logic into traditional curricula, it not only stimulates students' exploratory motivation but also significantly improves their comprehensive practical abilities. However, the implementation of the MCPAI model faces challenges:

(1) Faculty Training: Teachers require interdisciplinary expertise and modeling guidance. Developing dual-qualified "mathematics + profession" teacher training programs is recommended.

(2) Student Adaptation: Some students initially struggle with task-driven learning. A phased task design (e.g., "basic → advanced → innovative") can mitigate cognitive load.

(3) Technical Infrastructure: Virtual-physical integrated experiments demand collaborative efforts between academia and industry to build simulation labs.

Future research should refine dynamic feedback mechanisms and leverage AI technologies (e.g., learning behavior analytics) to enable personalized pedagogical interventions. Expanding interdisciplinary case libraries and establishing real-time competency monitoring systems will further enhance the model's scalability and impact.

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