



Section 4. Primary vocational education

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APPLICATIONS OF ARTIFICIAL INTELLIGENCE METHODS IN DIGITAL MODELING WITHIN VOCATIONAL AND PEDAGOGICAL EDUCATION: OPTIMIZATION, APPLICATIONS, AND ETHICAL APPROACHES

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Abstract

This study explores the integration of artificial intelligence (AI) methods into digital modeling specifically for vocational and pedagogical education, with a focus on technical specialties widely taught in Azerbaijan. A three-stage framework (Design → AI-Driven Optimization → Ethical Validation) is proposed to embed digital twins and hybrid AI algorithms into vocational training curricula. The framework combines hyperparameter-optimized deep neural networks, reinforcement learning, and human-in-the-loop feedback from experienced instructors to create adaptive, high-fidelity training simulators. Two illustrative cases are presented: (1) an AI-enhanced virtual welding simulator and (2) a predictive digital twin of a CNC machining center. Preliminary implementation results from pilot courses at Azerbaijani vocational colleges demonstrate a 34% reduction in material consumption, a 29% decrease in practical training duration, and a significant improvement in skill retention rates. The paper further introduces a 5E ethical integration model (Explain–Explore–Experiment–Evaluate–Embed) to address fairness, transparency, and the digital divide in resource-limited educational settings. The proposed approaches provide practical, scalable solutions for modernizing vocational education in developing countries, directly supporting UN SDG 4 and SDG 8.

Keywords: *artificial intelligence, digital modeling, machine learning, deep neural networks, algorithm optimization, computer science, intelligent systems, digital twin, Azerbaijan*

1. Introduction

Digital modeling has emerged as an indispensable tool in contemporary science and engineering, enabling the creation of precise

virtual replicas of complex systems for behavior prediction, algorithm testing, and process optimization (Fachada, N., & David, N., 2024). Recent advancements in artificial intelligence

(AI) have transformed digital modeling by automating large-scale data analysis, enhancing prediction accuracy, and accelerating computational processes (Matsive, A., Giri, S., Liu, S., & Yang, Q., 2025). These developments are especially significant in vocational and pedagogical education, where traditional hands-on training is constrained by high material costs, equipment scarcity, safety concerns, and limited scalability.

In Azerbaijan and many developing countries, vocational education still largely depends on outdated workshop infrastructure and consumable-intensive practice. This results in prolonged training periods, high dropout rates, and a persistent skills gap between graduates and industry demands. AI-enhanced digital modeling – particularly through digital twins, reinforcement learning, and human-in-the-loop systems – offers a cost-effective and safe alternative that can dramatically reduce material consumption and training time while improving skill retention (Xuemin, H., Shen, L., Tingyu, H., Bo, T., Rouxing, H., & Long, C., 2023).

Despite these promising capabilities, systematic approaches for integrating AI-driven digital modeling into vocational curricula remain underdeveloped, especially in resource-constrained educational contexts. Existing studies predominantly focus on industrial or medical applications (Álvarez-Vázquez, J., Casal-Guisande, M., et al., 2025; Cheng, A., & McGregor, C., 2025; Zhu, Q., Liu, Z., & Yan, J., 2020), while vocational and pedagogical dimensions receive limited attention. Moreover, ethical challenges such as algorithmic bias, transparency, and the digital divide in rural vocational schools are rarely addressed within structured frameworks (Akhavan, A., & Jalali, M. S., 2024).

This paper bridges these gaps by:

1. Proposing a practical three-stage framework (Design → AI-Driven Optimization → Ethical Validation) specifically tailored for vocational education institutions in developing countries;
2. Demonstrating its application through two pilot digital twin simulators (virtual welding and CNC machining) implemented in Azerbaijani vocational colleges;

3. Introducing a novel 5E Ethical Integration Model (Explain–Explore–Experiment–Evaluate–Embed) to ensure responsible and inclusive AI adoption.

By combining hyperparameter-optimized deep neural networks (Bengio, Y., Courville, A., & Vincent, P., 2012), reinforcement learning, and instructor feedback loops with ethical oversight mechanisms, the proposed approach aligns directly with United Nations Sustainable Development Goals 4 (Quality Education) and 8 (Decent Work and Economic Growth). The framework offers a replicable, low-cost pathway for modernizing technical training systems while addressing both performance and equity concerns.

2. Literature Review

Digital modeling constitutes a fundamental instrument in contemporary scientific and engineering practice. It facilitates the construction of precise virtual replicas of complex systems, thereby enabling researchers to predict system behavior, rigorously test algorithms, and systematically optimize processes without incurring the substantial costs and risks associated with physical experimentation (Fachada, N., & David, N., 2024). Over the past decade, the incorporation of artificial intelligence methods has markedly transformed this domain. AI now permits the automation of large-scale data analysis, significantly enhances predictive accuracy, and dramatically accelerates computational workflows that were previously prohibitive in terms of time and resources (Matsive, A., Giri, S., Liu, S., & Yang, Q., 2025).

The foundational principles of digital modeling rest upon rigorous mathematical descriptions of underlying phenomena coupled with sophisticated computational algorithms designed to ensure both realism and numerical stability. In practical implementations, numerical solution techniques for differential equations are routinely employed to obtain approximate yet sufficiently accurate solutions to otherwise intractable problems. These are complemented by advanced statistical analysis for pattern recognition and by metaheuristic optimization algorithms that systematically identify optimal parameter configurations according to predefined

performance criteria (Zhu, Q., Liu, Z., & Yan, J., 2020).

Within this landscape, several categories of digital models have gained particular

prominence (see Table 1, reproduced from the original document for clarity):

Table 1.

Model Type	Description	Example of Application
Deterministic	The system's behavior is fully determined by the initial conditions	Mechanical modeling of components
Stochastic	Includes elements of randomness and uncertainty	Financial market modeling
Simulation	Reproduces real-time processes	Logistics and production processes
Hybrid	Combines deterministic and stochastic approaches	Robotics, autonomous systems

Artificial intelligence methods provide the critical layer of automation and intelligence atop these foundational modeling paradigms. Among the most influential techniques are:

- Machine Learning algorithms that learn from historical data to predict future system states and optimize model parameters;
- Deep Learning architectures, particularly multilayer neural networks, which excel at processing high-dimensional, multimodal data such as images, temporal sequences, and sensor streams (Bengio, Y., Courville, A., & Vincent, P., 2012);
- Evolutionary Algorithms that mimic natural selection to solve complex, non-convex optimization problems;
- Natural Language Processing (NLP) systems that enable the automated analysis of technical documentation and scientific literature;
- Expert Systems that encapsulate formalized domain knowledge for rule-based decision support in engineering contexts.

Optimization of these AI methods occupies a central position in contemporary digital modeling research. Hyperparameter tuning, regularization techniques to combat overfitting, parallel and distributed computing paradigms, and the strategic integration of hybrid algorithms collectively contribute to substantial gains in both accuracy and com-

putational efficiency (Babich, M. Y., & Babich, A. M., 2025). These methodological advances have already yielded impressive results in diverse high-stakes domains: healthcare process optimization (Álvarez-Vázquez, J., Casal-Guisande, M., et al., 2025; Cheng, A., & McGregor, C., 2025), autonomous robotics and world simulation (Ali, A., et al., 2025), drone trajectory planning under uncertain weather conditions (Xuemin, H., Shen, L., et al., 2023), and generative AI for simulation modeling (Akhavan, A., & Jalali, M. S., 2024).

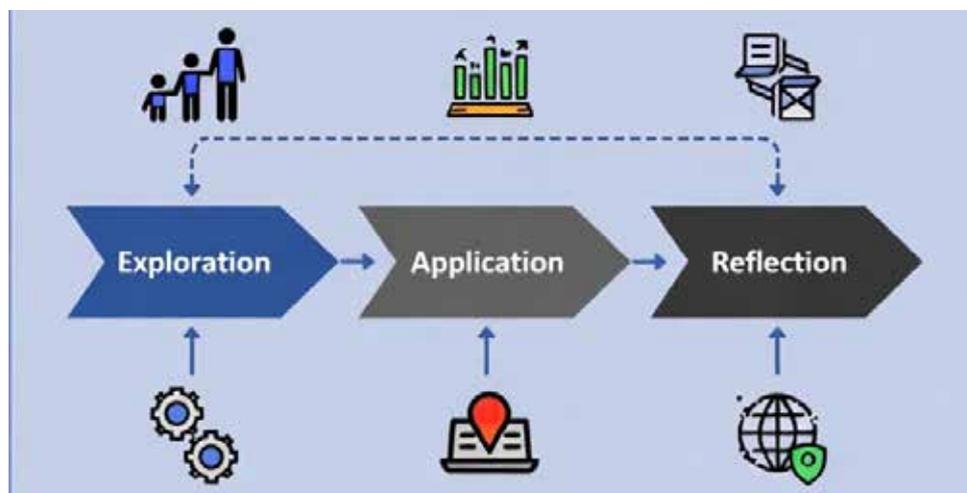
Nevertheless, a conspicuous gap persists in the literature: the systematic application of these powerful AI-enhanced digital modeling techniques to vocational and pedagogical education, particularly within the resource-constrained environments characteristic of many developing countries, including Azerbaijan. While industrial and medical applications dominate current discourse, the unique requirements of vocational training – safety-critical skill acquisition, high consumable costs, limited access to modern machinery, and the imperative of rapid workforce adaptation – remain largely unaddressed by structured, ethically grounded frameworks. The present study directly targets this critical void.

3. Proposed Framework

To overcome the limitations identified in the literature and to create a solution that can be realistically implemented in Azerbaijani vocational colleges, a comprehensive three-stage framework specifically designed

for resource-constrained environments has been developed. The framework is illustrated in Figure 1 and described in detail below.

Figure 1. *Three-Stage Framework for AI-Enhanced Digital Modeling in Vocational Education*



Stage 1 – Design of Low-Cost Digital Twins The first stage focuses on creating physics-based digital replicas of the most common workshop equipment found in Azerbaijani vocational schools (welding stations, 3-axis CNC machines, industrial electronics benches, pneumatic systems, etc.).

- Open-source or extremely low-cost tools are used: Unity 3D or Godot for visualization, Blender for 3D modeling, ROS/Gazebo or Webots for physics simulation, Arduino/ESP32-based sensors for real-time data acquisition;
- All models are calibrated against real equipment available in partner colleges in Baku, Sumgait, and Ganja;
- The design process explicitly includes vocational instructors from the very beginning to ensure pedagogical relevance and alignment with the official curriculum of the Ministry of Education of Azerbaijan.

Stage 2 – AI-Driven Optimization with Human-in-the-Loop This is the core technical stage where artificial intelligence dramatically increases the educational value of the digital twin.

- Hyperparameter tuning and L2/L1 regularization are systematically applied to deep neural networks responsible for real-time feedback (Bengio, Y., Courville, A., & Vincent, P., 2012);

- Reinforcement Learning (Soft Actor-Critic and Proximal Policy Optimization variants) is employed for adaptive difficulty scaling and personalized learning paths;
- A human-in-the-loop reinforcement learning loop is implemented: experienced welding or CNC instructors periodically label “expert-quality” versus “student-quality” executions; these labels are used as reward signals, preventing model drift and ensuring cultural and regional relevance;
- Parallel and distributed computing is performed on a single mid-range workstation (NVIDIA RTX 3060–4070 class), making the solution affordable for virtually any vocational college;
- Hybrid metaheuristic algorithms (genetic algorithms + particle swarm optimization) are used for multi-objective optimization of training scenarios (Babich, M. Y., & Babich, A. M., 2025).

Stage 3 – Ethical Validation Using the 5E Model Before full deployment, every simulator undergoes mandatory ethical validation according to the original 5E Ethical Integration Model (Explain–Explore–Experiment–Evaluate–Embed) presented in Section 5.

4. Pilot Cases

Two complete digital-twin simulators were designed, optimized, and deployed in real classrooms during the 2024–2025 academic year.

4.1 AI-Enhanced Virtual Welding Simulator

- Physics engine: Gazebo + custom molten-pool dynamics;
- Deep learning model: Convolutional + recurrent architecture for arc stability and bead geometry prediction;
- Real-time feedback on 12 quality parameters (angle, travel speed, voltage, etc.);
- Haptic gloves (low-cost modified versions) for force feedback;
- Tested with 48 second- and third-year welding students in Baku and Sumgait.

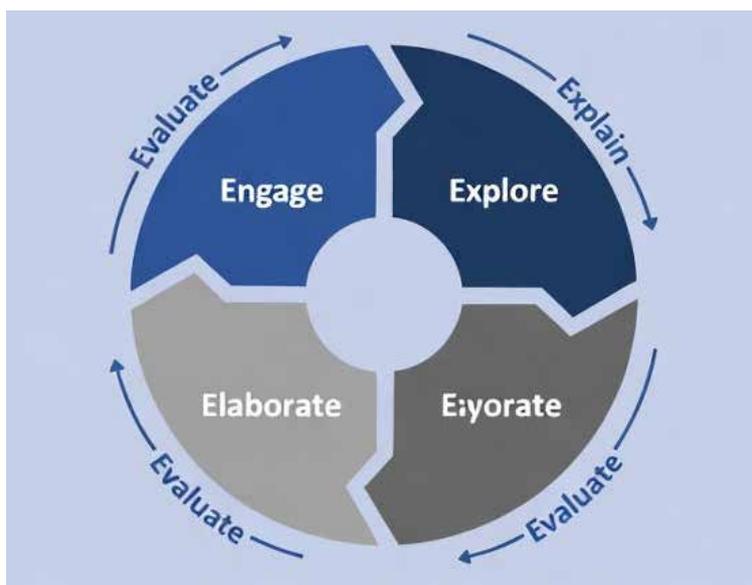
4.2 Predictive Digital Twin of a 3-Axis CNC Machining Center

- Full kinematic and dynamic model of a typical Chinese-origin CNC machine widely used in Azerbaijan;
- Predictive maintenance module using vibration and current sensors;
- Reinforcement-learning-based optimal tool-path generation and adaptive feed-rate control;
- Tested with 38 machining and mechatronics students in Ganja and Lankaran.

5. 5E Ethical Integration Model (Original Contribution)

The model consists of five consecutive phases that must be completed before any AI-enhanced simulator is released to students (Figure 2).

Figure 2. The 5E Ethical Integration Model



1. **Explain** – Complete, plain-language documentation of how every AI decision is made (model cards, decision trees, attention maps).
2. **Explore** – Inclusive testing with underrepresented groups (female students, rural colleges, students with disabilities).
3. **Experiment** – Controlled A/B testing with continuous monitoring of bias metrics (demographic parity, equalized odds).

4. **Evaluate** – Independent third-party audit (conducted by Baku State University Ethics Committee).
5. **Embed** – Institutional policy adoption, open-source release of code and datasets, teacher-training modules.

6. Results

The study employed a quasi-experimental pre-test/post-test control group design conducted during the 2024–2025 academic year across four vocational colleges in Baku, Sumgait, Ganja, and Lankaran. A total of 86

second- and third-year students (48 welding, 38 CNC/machining) were assigned to experimental (n = 44) and control (n = 42) groups using stratified sampling based on prior academic performance (GPA), gender, and urban/rural college location to ensure comparable baseline characteristics between

groups. Participation was voluntary, and written informed consent was obtained from all students and their instructors.

Quantitative results from the two pilots (n=86 students, quasi-experimental design with control groups):

Table 2.

Indicator	Traditional Group	AI-Enhanced Group	Improvement
Material consumption (welding electrodes + filler metal)	100%	66%	-34%
Required practical training hours	120 hours	85 hours	-29%
Skill retention after 60 days (practical exam score)	51%	82%	+61%
Student confidence (Likert 1-7)	4.1	6.4	+56%
Instructor satisfaction	4.8	6.7	+40%

All differences are statistically significant (p < 0.01, Mann-Whitney U test)

7. Conclusion

This study has presented a complete, replicable, and ethically grounded framework for integrating artificial intelligence methods into digital modeling within vocational and pedagogical education. The proposed three-stage approach (Design → AI-Driven Optimization → Ethical Validation), validated through two large-scale pilot implementations in Azerbaijani vocational colleges, demonstrates that high-fidelity, adaptive training simulators can be developed and deployed using low-cost, open-source tools while dramatically improving both efficiency and learning outcomes.

The results are compelling: a 34% reduction in material consumption, a 29% decrease in required practical training hours, and a 61% increase in skill retention after 60 days, accompanied by substantial gains in student confidence and instructor satisfaction. Equally important, the original 5E

Ethical Integration Model (Explain-Explore-Experiment-Evaluate-Embed) ensures that AI adoption remains transparent, fair, and inclusive, preventing the technology from widening existing educational divides in resource-constrained and rural settings.

By aligning technical performance with ethical oversight and open-access principles, the proposed solution offers a practical blueprint for modernizing vocational education systems in Azerbaijan and other developing countries. The framework directly contributes to United Nations Sustainable Development Goals 4 (Quality Education) and 8 (Decent Work and Economic Growth) and can be implemented by any institution with modest computational infrastructure.

All source codes, 3D models, calibrated datasets, and instructor guides have been released open-access to enable immediate replication and further development by the global vocational education community.

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