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PEDAGOGICAL POSSIBILITIES OF DIGITAL PROTOTYPING IN DEVELOPING STUDENTS' PRACTICAL COMPETENCIES

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Abstract. The rapid development of digital technologies is transforming the organization and content of vocational education and creating new opportunities for developing students' practical competencies. Digital prototyping, including three-dimensional modeling, computer-aided design, virtual simulation, digital twins, and interactive visualization, provides opportunities to connect theoretical knowledge with practical activities in a safe and flexible learning environment. This article examines the pedagogical possibilities of digital prototyping in developing students' practical competencies. The study applies theoretical analysis, comparative analysis, modeling, systematization, and pedagogical interpretation of contemporary approaches to digital vocational education. The results indicate that digital prototyping can support practical skill development through repeated practice, early error detection, visualization of technological processes, individualized learning trajectories, formative assessment, and continuous monitoring of students' performance. The article proposes an integrated pedagogical model consisting of diagnostics, digital modeling, virtual simulation, practical implementation, digital monitoring, assessment, and corrective instruction. The study concludes that digital prototyping should not be considered merely a technological tool but as an integrated pedagogical mechanism that can strengthen the connection between theoretical learning and authentic professional practice.
Keywords: digital prototyping, practical competencies, vocational education, digital learning, 3D modeling, virtual simulation, digital twins, practical training, competency-based education, digital assessment.

Introduction. The digital transformation of education is significantly changing the approaches used to organize teaching and learning. The development of automation, artificial intelligence, computer-aided design, virtual reality, digital twins, and other emerging technologies has created new possibilities for preparing students for increasingly complex professional environments. In vocational education, these changes are particularly important because students are expected not only to acquire theoretical knowledge but also to demonstrate the ability to apply that knowledge in authentic practical situations. Practical competence is one of the central outcomes of vocational and professional education. It includes the ability to perform professional operations accurately, select appropriate technological procedures, operate equipment, solve practical problems, comply with safety requirements, and make

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independent decisions. Traditional practical training, however, may face several limitations. These include limited access to expensive equipment, insufficient time for repeated practice, safety risks, differences in students' learning rates, and difficulties in monitoring each student's individual performance. Digital prototyping offers a possible solution to several of these challenges. In an educational context, digital prototyping can be understood as the creation and use of digital representations of objects, systems, technological processes, or professional tasks before or alongside their implementation in the physical environment. Depending on the field, such prototypes may be developed using CAD systems, 3D modeling software, simulation environments, virtual laboratories, digital twins, and interactive visualization tools. The pedagogical value of digital prototyping is associated with its ability to make abstract processes visible, allow students to test alternative solutions, and provide opportunities for repeated practice without the immediate costs or risks associated with physical experimentation. UNESCO-UNEVOC has emphasized that digital transformation in technical and vocational education affects curricula, qualifications, teaching and learning approaches, and the relationship between education and labor-market requirements. Therefore, the introduction of digital technologies should be considered not only as technological modernization but also as a transformation of pedagogical processes. The relevance of this study is determined by the need to identify pedagogically meaningful ways of using digital prototyping for the development of students' practical competencies. The central research problem is therefore to determine how digital prototypes can be integrated into the learning process so that they contribute not only to visualization but also to practical skill formation, assessment, feedback, and individualized learning. The purpose of the study is to theoretically substantiate the pedagogical possibilities of digital prototyping in developing students' practical competencies and to propose an integrated pedagogical model for its implementation.

Literature Review. Recent research demonstrates growing interest in virtual, immersive, and digital technologies in vocational education. Digital transformation is increasingly regarded as a multidimensional process involving technology, curriculum, teacher competencies, learning methods, and institutional management. UNESCO-UNEVOC identifies digital transformation as an important factor influencing the development of TVET systems. Digital technologies can contribute to improving teaching and learning, strengthening the relevance of qualifications, and increasing the flexibility of vocational education. Research on virtual and mixed reality also provides important evidence for the pedagogical use of digital environments. Bödding, Schriek, and Maier conducted a systematic review and meta-analysis of mixed reality in vocational education and training. Their study analyzed 53 primary studies and examined behavioral, cognitive, and affective learning outcomes. The findings indicate that immersive technologies can contribute positively to different dimensions of learning when appropriately integrated into educational processes. Long, Zhang, and Zeng examined the application of virtual reality in vocational practical training and reported that VR-based environments can support theoretical understanding, practical skill development, learning interest, and

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learner satisfaction. At the same time, the authors identified challenges associated with equipment costs, educational resources, and implementation conditions. Digital twin technologies represent another relevant direction. A digital twin can connect a digital representation with information from a physical object or system and can support monitoring, analysis, and optimization. Educational applications of digital twins create opportunities for students to study professional systems through realistic digital representations and to understand the relationship between theoretical parameters and practical processes. However, existing studies often focus on particular technologies such as virtual reality, augmented reality, or digital twins. Less attention has been devoted to conceptualizing digital prototyping as an integrated pedagogical mechanism that combines modeling, simulation, practical implementation, assessment, monitoring, and corrective learning. Therefore, the present study focuses on the pedagogical integration of these functions rather than on a single technological tool.

Research Methodology. The study employs a theoretical and methodological research design. The following methods were used:

- theoretical analysis – to examine contemporary approaches to digital transformation and practical competency development;
- comparative analysis – to compare traditional practical training with digitally supported approaches;
- systematization – to identify the major pedagogical functions of digital prototyping;
- pedagogical modeling – to develop an integrated model for using digital prototyping in practical training;
- interpretation and synthesis – to formulate pedagogical conditions and principles for effective implementation.

The analysis was structured around several dimensions of practical competency: accuracy of professional operations, speed of task completion, ability to independently select an appropriate solution, ability to identify and correct errors, compliance with safety requirements, quality of the final practical product or service, digital competence, ability to transfer theoretical knowledge into practical situations.

An integral competency indicator can be represented as:

$$C_p = \sum_{i=1}^{n} w_i K_i$$

where C_p represents the overall practical competency level, K_i represents an individual competency indicator, and $w_i$represents its weighting coefficient, with:

$$\sum_{i=1}^{n} w_i = 1.$$

This model allows institutions to adapt the evaluation system to specific professional fields.

Results. One of the main pedagogical possibilities of digital prototyping is the visualization of professional objects and processes. Many vocational concepts are difficult to understand through

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verbal explanations or static illustrations alone. A digital prototype can represent the structure, components, connections, movements, and operating principles of a technical object. For example, in mechanical engineering education, students can examine a three-dimensional model of a machine, analyze the interaction between components, and simulate possible operational conditions. In construction education, digital prototypes can represent buildings, structural elements, and technological sequences. In electrical engineering, digital models can demonstrate circuits and system behavior. Visualization therefore contributes to the transition from abstract knowledge to concrete professional understanding.

Safe Repetition of Practical Activities. Practical competence develops through repeated performance and reflection. However, repeated practice using real equipment may be limited by costs, equipment availability, time, and safety considerations. Digital prototyping creates an environment in which students can repeatedly perform professional operations before moving to physical equipment. Students can test different actions, observe the consequences, identify mistakes, and repeat the procedure.

This creates a pedagogical sequence:

perform → observe → identify error → correct → repeat → master.

The possibility of repeated practice is particularly important for students who require additional time to acquire a particular professional operation.

Early Detection and Correction of Errors. Digital prototypes enable students to identify potential errors before implementing a solution in the physical environment. For example, a student may construct a digital model, run a simulation, identify an incorrect connection or inappropriate parameter, and modify the model before beginning physical production. This changes the pedagogical role of error. Instead of being considered only as a negative outcome, an error becomes a source of feedback and learning.

The process can be expressed as:

Action→Feedback→Error Identification→Correction→Improved Action.

Such a cycle contributes to reflective learning and problem-solving competence.

Development of Independent Decision-Making. Professional competence requires more than the mechanical reproduction of instructions. Students must be able to select appropriate solutions in changing situations. Digital prototyping allows teachers to create alternative scenarios in which students must choose among several possible solutions. The consequences of each decision can then be simulated and analyzed. For example, students may be asked to select an appropriate material, technological parameter, production sequence, or system configuration. The digital environment can provide immediate feedback regarding the consequences of their decisions.

This supports the development of: analytical thinking, problem-solving, professional decision-making, creativity, responsibility for decisions.

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Individualization of Practical Training. Students differ in their prior knowledge, learning speed, practical experience, and digital competence. Traditional practical training may have difficulty addressing these differences within a limited amount of instructional time. Digital prototyping can support individualized learning trajectories. A digital learning environment can record students' performance and identify areas where additional practice is needed. For example, one student may need additional training in equipment operation, while another may require more practice in planning or troubleshooting.

Thus, digital prototyping can support the principle:

diagnosis → individualized task → practice → feedback → correction → reassessment.

Formative Assessment and Digital Monitoring. Digital prototyping can also transform practical assessment. Instead of evaluating only the final result, teachers can analyze the entire process of task completion.

Potential indicators include:

Indicator	**Pedagogical significance**
Task completion time	Measures efficiency
Number of errors	Indicates accuracy
Number of repeated attempts	Indicates learning dynamics
Independent decisions	Measures autonomy
Compliance with technological sequence	Indicates procedural competence
Safety compliance	Measures professional responsibility
Final product quality	Measures practical performance
Ability to correct errors	Indicates reflective competence

Such monitoring provides more detailed information for formative assessment and pedagogical intervention.

Integration of Digital and Physical Practice. The results of the conceptual analysis demonstrate that digital prototyping should not replace real practical training. Its greatest pedagogical value emerges when digital and physical environments are integrated.

An effective learning sequence can be represented as:

Theory→Digital Prototype→Simulation→Real Practice→Monitoring→Reflection.

The digital environment prepares students for real practice, while physical practice provides authentic experience that cannot always be reproduced virtually.

Discussion. The findings demonstrate that the pedagogical potential of digital prototyping extends beyond visualization. Its main contribution lies in integrating several pedagogical functions within one learning process. First, digital prototyping connects theoretical knowledge with practical action. Students are able to observe how theoretical principles influence the behavior of real or simulated systems. Second, it creates conditions for experiential learning. Students can experiment with different solutions and immediately observe their consequences. Third, digital prototyping strengthens

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formative assessment. Teachers can obtain information not only about the final product but also about the process through which students reached that result. Fourth, it supports individualized instruction. Data collected during digital activities can be used to determine the specific learning needs of individual students. The findings are consistent with recent research on mixed reality and virtual reality in vocational education, which emphasizes the potential of immersive digital environments for cognitive, behavioral, and affective learning outcomes. At the same time, the present conceptual model extends this perspective by incorporating digital prototyping into a broader quality-management cycle. The effectiveness of digital prototyping depends on several pedagogical conditions. Technology itself does not automatically produce better learning outcomes. The digital environment must be aligned with learning objectives, professional competencies, assessment criteria, and authentic vocational tasks. Teacher digital competence is another important condition. Teachers need to be able not only to operate digital tools but also to design meaningful learning scenarios, interpret digital performance data, provide feedback, and connect virtual activities with real professional practice. Infrastructure is also important. Effective implementation requires suitable hardware, software, digital content, and technical support. In resource-constrained institutions, gradual implementation may therefore be more realistic than immediate large-scale digitalization. Another limitation concerns the difference between virtual and physical environments. A student may successfully complete a simulated task but experience difficulties when working with real equipment. Therefore, digital prototyping should function as a preparatory and complementary environment rather than a complete substitute for authentic practical training.

Conclusion. Digital prototyping provides significant pedagogical possibilities for developing students' practical competencies in vocational education. Its value is associated not only with three-dimensional visualization or virtual simulation but also with its ability to connect theoretical knowledge, practical action, feedback, assessment, and individual learning. The study demonstrates that digital prototyping can contribute to the development of practical competencies by providing opportunities for repeated practice, safe experimentation, early error detection, independent decision-making, individualized learning, and continuous formative assessment.

The proposed model — diagnosis → digital modeling → simulation → physical practice → monitoring → correction → reassessment — provides a systematic framework for integrating digital technologies into practical training.

At the same time, digital prototyping should not be regarded as a substitute for authentic professional practice. Its pedagogical effectiveness is greatest when digital and physical learning environments complement one another. Successful implementation requires appropriate infrastructure, teacher digital competence, relevant digital content, authentic professional tasks, and competency-oriented assessment. Future empirical studies should test the proposed model in specific vocational specialties and compare students' competency development before and after systematic implementation of digital prototyping. Such research could provide quantitative evidence concerning the effects of digital

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prototyping on practical performance, learning efficiency, error reduction, and professional decision-making.

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