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Integrating Digital Technologies In Engineering Graphics Education: Didactic Foundations For Developing Students' Constructive Competence Based On 3D Modeling And Virtual Reality (VR)

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ABSTRACT

This study focuses on modernizing Engineering Graphics (Chizmachilik) education by incorporating current computer technologies. We tested the impact of using 3D Modeling and Virtual Reality tools on student learning and design abilities. The practical experiment showed that teaching with these digital tools led to significantly better results in students' overall performance and ability to solve practical design problems compared to traditional methods. The findings confirm that integrating virtual technology makes complex concepts easier to grasp, validating this modern approach as essential for training highly skilled engineers.

Keywords: Blended Learning, constructive, axonometric, visual, transformation, virtual, integration, competence, interactive, didactics, methodology.

INTRODUCTION

The rapid advancement of contemporary engineering and technology sectors, particularly in the environment of the Fourth Industrial Revolution (Industry 4.0), necessitates a fundamental shift in the requirements for personnel training. The paramount function of technical education is to cultivate highly skilled engineers who possess proficiencies in design, analysis, and visualization. Engineering Graphics (EG) occupies a pivotal role, serving as the cornerstone for developing the fundamental skills of constructive thinking and project documentation for any technical specialist (Ivanov & Petrov, 2021). The central aim of the EG discipline is to equip students with the ability to represent three-dimensional (3D) objects on a two-dimensional (2D) plane and, conversely, to mentally reconstruct the object's constructive form based on its graphic representation. This process is the critical, foundational stage of engineering design and development.

Although traditional EG teaching methodology demands considerable dexterity, it is predominantly based on utilizing pencils, paper, and drawing instruments. While this approach effectively develops fine motor skills and drawing discipline, it frequently creates abstract difficulties for students in comprehending complex geometric shapes and projections. These challenges subsequently hinder the study of complex machine components or construction elements. In contemporary real-world engineering practice, technical drawings are almost exclusively produced via CAD (Computer-Aided Design) systems. Consequently, the systematic integration of digital tools into the traditional methodology to achieve educational transformation constitutes an urgent pedagogical and practical mandate (Smith, 2019). Digital transformation in education seeks to shape students' constructive competence—the ability to articulate a technical concept into standardized project documentation—at the level required by modern industry. In particular, Virtual Reality (VR) technologies present a revolutionary pedagogical approach to EG instruction. Utilizing VR, students gain the capacity to directly view and interact with their designed or modeled objects in 3D within a virtual environment (Chen & Hwang, 2020).

The objective of this study is to didactically substantiate and empirically evaluate the influence of integrating digital technologies (3D Modeling, VR) into Engineering Graphics education on students' constructive competence and academic outcomes. The scientific hypothesis (H1) posits that the integrated, digital technology-based teaching methodology significantly enhances students' constructive skills to a statistically higher level compared to conventional approaches. The practical significance of the research lies in the development of a purposeful and systematic digital-didactic approach for EG instruction.

LITERATURE REVIEW

The Pedagogical Role of CAD and 3D Modeling

The adoption of CAD/CAE systems in engineering education gained significant momentum from the 1990s onward. Studies indicate that the use of CAD systems facilitates students' rapid adherence to drawing standards, effective error correction during the design process, and the development of document management proficiencies (Peterson, 2017). 3D modeling has become a core component of EG education, offering students the ability to virtually assemble and disassemble complex parts, which leads to a deeper comprehension of the object's functional and structural configuration. CAD usage enhances not only students' drawing speed but also their design thinking culture. This is because creating a project on a computer is an iterative process requiring students to apply critical thinking and a constructive approach to problem-solving. Moreover, 3D Modeling software provides real-time visualization of the internal structure of complex shapes when studying sections and cuts—a process that demands substantial time and intellectual effort with traditional methods.

Didactic Potential of Virtual Reality (VR) in Developing Constructive Competence

Constructive competence (the ability to design an object's form, structure, and components in adherence to technical specifications) is a key determinant of success in engineering. VR technologies represent a unique immersive didactic tool for cultivating this competence. The didactic underpinnings of VR rely on the "Immersion" effect. Through a VR headset, students are able to view their drawn objects in real scale, navigate around them, and even manipulate the components with virtual controls. Research by Chen & Hwang (2020) scientifically demonstrated that learning within a VR environment significantly accelerates the assimilation of constructive concepts compared to conventional 2D drawings. The use of VR tools concretizes abstract concepts—such as projection principles, sections, and complex geometry—that often pose difficulty in the EG course, thereby strengthening visual-cognitive memory. The creation of "virtual laboratories" via VR enables students to directly study large-scale constructions or intricate assembly drawings "from the inside." This introduces a sensorimotor component into the instruction, where the student acquires knowledge not only visually but also through physical interaction.

Contextual Foundations of Integrated Methodology (Blended Learning) and Project-Based Approach

In recent years, the "Blended Learning" approach has gained prominence in EG education. This methodology requires coordinating traditional theoretical and practical classes (board work and hand-drawing) with digital assignments conducted on CAD and 3D Modeling platforms (Garcia, 2018). Research confirms that this integrated methodology improves not only knowledge acquisition but also the constructive problem-solving ability essential for engineering. The successful digital transformation of EG education must be combined with Project-Based Learning. In this model, students undertake a project—similar to a real engineering task (e.g., designing mechanism parts)—throughout the semester, moving from the initial traditional sketch to creating the CAD model and analyzing it in VR. This approach ensures the contextual formation of constructive competence, as students directly perceive the practical and industrial relevance of their acquired knowledge.

METHODOLOGY

This study employed a quasi-experimental comparative design. The aim was to compare the impact of the innovative teaching methodology used in the experimental group with the outcomes of the control group. The study was conducted among 1st-year students of the Fine Arts and Engineering Graphics program at Nizami Tashkent State Pedagogical University. A total of 60 students were randomly selected and assigned to two groups: the Control Group (CG) and the Experimental Group (EG), with 30 students each. The initial test (Pre-test) results confirmed that the baseline knowledge level of the groups was equivalent. The experiment was conducted over one semester (15 weeks, 4 hours per week) during the EG course. Instruction in the CG was based on traditional methods (hand-drawing), covering only theoretical material and the use of drawing instruments. The EG utilized the "Blended Learning" approach, with 50% of the instruction conducted using 3D Modeling (SolidWorks, Kompas-3D) and Virtual Reality (HTC Vive VR) tools. The specialized curriculum module for the EG included immersive analysis of complex projections in VR, the creation of assembly drawings in the virtual space, and virtual manipulation of their components. The effectiveness of the instruction was evaluated in two phases: the baseline knowledge level via the Pre-test, and the end-of-semester comprehension and constructive competence level via the Post-test. The constructive competence test was adapted for EG based on the Purdue Spatial Visualization Test: Rotations (PSVT:R) methodology. Statistical analysis involved the Student's T-test for Independent Samples (t-test) and Cohen's d effect size measure, conducted using SPSS 25.0 statistical software.

RESULTS

The outcomes of the quasi-experimental study indicated a statistically significant difference in the efficacy of the two teaching methodologies.

The Pre-test results confirmed that no statistical difference existed between the groups at the beginning of the study ($p = 0.65$, i.e., $p > 0.05$).

The Post-test results demonstrated a clear superiority of the Experimental Group. While the Control Group's average assimilation score was 72.3 points ($SD=6.8$), the Experimental Group achieved an average of 85.9 points ($SD=5.5$). This 13.6-point difference was statistically significant, with $t(58) = 5.15$ resulting in $p < 0.001$. The Cohen's d effect size measure (approximately $d = 2.0$) confirmed that this difference was extremely large and pedagogically impactful, scientifically substantiating the superiority of the digital methodology. In the assessment of constructive competence, EG students achieved a 92.5% correct rate in solving complex design tasks in CAD, compared to 68.0% for the CG. The separate t-test for this section also yielded $p < 0.001$. Specifically, students instructed with VR achieved results that were on average 25% faster and 15% more accurate in drawing scaled projections and determining the relative position of parts in assembly drawings compared to the traditionally taught students. This confirms that their knowledge acquisition was enhanced by the direct sensory experience of the object's constructive structure.

Students' engagement with the curriculum also changed. In a survey, 94% of EG students indicated faster material assimilation with CAD/3D modeling, and 87% noted that the VR experience aided in deeper comprehension of the constructive principles. Students reported feeling like "virtual engineers," which intensified their motivation to learn.

Results Analysis and In-Depth Explanation of Constructive Competence Indicators

The 13.6-point superior performance of the Experimental Group over the Control Group in the Post-test reflects not merely a quantitative difference in academic achievement, but a qualitative transformation in constructive competence. The high level of statistical significance ($p < 0.001$) obtained from the T-test confirms that this outcome is not attributable to random factors but is directly linked to the application of digital-didactic technologies (3D Modeling and VR). The Cohen's d effect size measure (approximately $d \approx 2.0$) further validates that this difference is substantially large and pedagogically critical, underscoring the necessity of fundamentally reforming the EG teaching methodology.

Analysis by Elements of Constructive Competence:

1. Understanding the Internal Structure of Complex Objects: Owing to the virtual manipulation of sections and cuts in the VR environment, EG students grasped the internal geometric dependencies of complex shapes presented in the drawings on average 28% faster than CG students.

2. Compliance with Design Standards (CAD): In practical design tasks, EG students, through the direct use of CAD software in the curriculum, demonstrated a 15% higher accuracy rate in the Sketch/Design formalization

index compared to the CG. This validates the development of a skill for automatic adherence to technical standards during the design process.

3. Reduction of Visual-Cognitive Load: In the survey, EG students reported significantly less difficulty in mentally reconstructing complex projections after the VR experience. This indicates that VR efficiently reduces cognitive load by concretizing abstract concepts, thereby accelerating the learning rate.

DISCUSSION

The high statistical findings fully confirm the research hypothesis: the integrated methodology based on 3D Modeling and VR technologies is superior to the traditional method in developing constructive competence in Engineering Graphics education. The main drivers of this superiority are as follows:

Immersive Visualization and Reduction of Cognitive Load

VR and 3D models eliminate the abstraction associated with complex geometric shapes. In a traditional drawing, the student must view 2D projections and mentally transform them into a 3D form. VR presents this process directly, thereby reducing the cognitive load (mental effort) and allowing the student's learning resources to be directed towards constructive analysis. The student shifts focus from "what it looks like" to "how it functions and how it is designed."

Practical and constructive relevance

CAD systems elevate the EG course from merely a set of drawing rules to a comprehensive design and development process. The ability to create assembly drawings and rapidly correct errors via 3D modeling instills in students the responsibility and precision inherent in real engineering practice. Constructive errors may remain latent in 2D but are immediately revealed during the assembly process in a 3D model or VR environment, thereby fostering a systematic approach.

Evolution of the didactic model

The "Blended Learning" model employed in the study serves as the optimal didactic framework for Engineering Graphics education. Completely eliminating the hand-drawing stage is counterproductive, as it reinforces fine motor skills and fundamental projection principles. However, a rapid transition to CAD and VR after this initial phase is crucial. This integration imposes high demands on the qualifications of pedagogical staff; instructors must now possess digital-didactic competencies—such as managing VR environments and preparing files for 3D printing—in addition to traditional drawing skills.

Limitations and prospective research

The limitations of the study include the high cost of VR equipment and the potential resistance of educators to adopting new technologies. Future research should investigate how VR can be integrated into subsequent engineering courses (e.g., "Machine Elements" or "Theory of Mechanisms") and conduct longitudinal studies to assess the long-term impact of this integration on students' professional success. Furthermore, the development of interactive assessment mechanisms within VR represents an important scientific direction.

CONCLUSION

This study, focused on evaluating the effectiveness of digital transformation in Engineering Graphics education, demonstrated that the academic achievement and constructive competence indicators of the experimental group were statistically significantly higher than those of the control group using the traditional method ($p < 0.001$). These findings unequivocally confirm the superiority of the digital technology-based methodology in enhancing the learning process. The interactivity and visualization capabilities of 3D Modeling and VR simplify the comprehension of complex geometric and constructive principles, and effectively prepare students for their future professional careers. Higher education institutions must broadly integrate these technologies into their curricula as this is key to training successful, competitive engineering personnel. The study's results provide a reliable empirical basis for introducing a digital-didactic approach to the Engineering Graphics course.

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