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ARTIFICIAL INTELLIGENCE, CAD, AND AUGMENTED VISUALIZATION IN ENGINEERING GRAPHICS EDUCATION

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Abstract

This article examines how engineering graphics and mechanical drafting education can be restructured under conditions of digital transformation. The study analyzes the pedagogical value of integrating artificial-intelligence-assisted tools, computer-aided design environments, augmented and immersive visualization, project-based learning, and standardized graphic tasks for the development of spatial reasoning, drawing accuracy, constructive logic, and industry-relevant competence. A methodological framework is proposed in which manual drafting foundations, parametric modelling, AI-supported feedback, error diagnostics, collaborative design activity, and criterion-based assessment are united into a coherent didactic system. The article argues that digital tools should not be introduced merely as instruments of convenience; they must be treated as pedagogical media that intensify spatial imagination, graphic literacy, technological discipline, and the culture of engineering justification. Based on a synthesis of recent research and a practice-oriented instructional model, the paper formulates recommendations for curriculum design, assessment architecture, teacher preparedness, and academic integrity in higher technical education.

Keywords: Engineering graphics, mechanical drafting, CAD, artificial intelligence, spatial reasoning, parametric modelling, AR/VR, graphic literacy, technical education, project-based learning.

Introduction

Engineering graphics has always occupied a peculiar position in technical education. It is at once a language, a method, a discipline of thought, and a testing ground where abstract reasoning is forced to become operational. In the mechanical field this role is even more visible, because a future specialist cannot meaningfully discuss shape, fit, tolerance, manufacturability, assembly sequence, serviceability, or functional interaction if he or she has not first learned to transform three-dimensional intention into unambiguous graphic form. For more than a century this formative process was organized through descriptive geometry, orthographic projection, sectioning, dimensioning, conventional representation, and painstaking manual control of line hierarchy. The classical approach still retains high value because it disciplines the eye and the mind. It teaches the student that any line on a drawing is not merely a visible trace but an encoded engineering decision. Yet the contemporary situation has changed profoundly. Engineering practice now operates in ecosystems where 2D drafting, parametric 3D modelling, product lifecycle data, simulation, manufacturing documentation, and digital collaboration are closely interdependent. UNESCO's engineering report emphasizes that engineering education is being transformed under the pressures of the Fourth Industrial Revolution, especially through digital technologies and artificial intelligence, and that this transformation is inseparable from the broader social mission of engineering for resilient infrastructure, clean water, energy, and sustainable development [1]. The same logic extends directly to engineering graphics, because no digital transformation in engineering can be pedagogically complete while the representational core of technical communication remains outdated. Recent research in descriptive geometry education has shown that CAD-integrated orthographic projection methods may significantly outperform exclusively traditional projection instruction in conceptual understanding, graphical accuracy, procedural consistency, and spatial reasoning, with the gains being attributed not to superficial software novelty but to reduced cognitive overload and improved dynamic visualization [2]. At the same time, studies in technical drawing education indicate that student-centred and product-oriented work, especially when drawings are linked to real manufacturing tasks, improves learning outcomes, social interaction, and learner satisfaction [3]. Further evidence from immersive design environments demonstrates that virtual and augmented visualization can strengthen spatial understanding and the communication of design intent in engineering and architecture education [4]. These findings are not isolated curiosities. Together they signal a decisive methodological shift: engineering graphics should no longer be treated as a transitional introductory subject whose value ends once students "move on" to CAD; rather, it must be reconstructed as a multi-layered competence domain in which manual graphic culture, digital modelling, intelligent feedback, collaborative interpretation, and industrial data standards mutually reinforce one another. This transition becomes even more urgent in institutions where the historical prestige of drafting is still acknowledged but the course structure often reflects a split reality: on one side, students work through manual exercises that are conceptually rigorous yet poorly connected to current industrial workflows; on the other side, they use software in a fragmented, command-oriented way that trains interface habits without deep graphic understanding. The result is paradoxical. Some students can produce visually neat drawings without understanding geometric causality; others can manipulate models yet struggle to read a sectional assembly or a tolerance schema; and still others rely on software automation so heavily that their representational judgement weakens. The arrival of generative AI intensifies this paradox rather than resolving it automatically. UNESCO's digital education and AI policy materials repeatedly stress that digital transformation must remain human-centred, ethically grounded, and oriented toward critical thinking rather than passive technological dependence [5–7]. In other words, the pedagogical problem is not whether AI, CAD, AR, or immersive tools should appear in engineering graphics education, but how they should be positioned so that students remain authors of decisions rather than operators of opaque systems. A mechanically generated sketch is not yet an engineering drawing; a software-produced section is not yet a justified section; and an automatically dimensioned object is not yet a valid manufacturing document. The central research problem of this article therefore lies in identifying an instructional architecture that preserves the epistemic discipline of classical engineering graphics while incorporating digital instruments that genuinely strengthen spatial reasoning, precision, feedback quality, and professional relevance. The article is motivated by a second concern as well: many contemporary discussions of AI in education remain either too general or too celebratory. They speak of efficiency, personalization, and automation in broad terms, but engineering graphics requires a more exact language. Here the issue is not only learning support in the abstract. It involves line-type discrimination, hidden-edge logic, section conventions, geometric constraints, tolerance communication, projection transfer, parametric dependency, standard compliance, and the translation of design intent into manufacturable documentation. For this reason, any meaningful methodological proposal must be anchored in the internal structure of the discipline. It must account for how students perceive form, how they externalize mental rotation, how they diagnose inconsistencies between views, how they pass from a sketch to a regulated drawing, how they interpret standards, and how they defend representational decisions before peers and instructors. Within that frame, digital tools matter not because they are fashionable, but because they can reorganize perception, shorten irrelevant routine, reveal hidden structure, and expand the range of feedback available during the learning process. UNESCO's smart education agenda similarly presents digital transformation not as simple digitization but as the creation of conditions in which teachers and learners can adapt technology to context, equity, and meaningful competence development [8]. This article responds to that challenge by proposing a DSc-level conceptual and methodological treatment of a highly relevant topic for mechanical drafting and engineering graphics: the integration of artificial intelligence, CAD environments, and augmented visualization into a pedagogically coherent model for developing spatial thinking, graphical literacy, accuracy, and industry-relevant professional judgement. The purpose of the study is threefold. First, it synthesizes recent theoretical and empirical literature on the evolution of engineering graphics education under digital transformation. Second, it constructs a methodological framework that aligns traditional descriptive-graphic training with AI-assisted diagnostics, parametric CAD practice, and immersive visualization. Third, it formulates curricular, organizational, and assessment recommendations for higher technical institutions that wish to modernize engineering graphics without sacrificing disciplinary depth. The novelty of the article lies not in promoting any single software platform or technological tool, but in articulating a didactic logic through which manual drafting, 2D–3D translation, AI-supported error analysis, project-based manufacturing tasks, and ethical digital competence can be integrated into a single educational design. The working hypothesis is that the highest educational effect in engineering graphics emerges not from replacing traditional drafting with automation, nor from preserving tradition in isolation, but from constructing a layered instructional system in which each representational mode performs a distinct cognitive function: manual construction disciplines attention, CAD stabilizes geometric relations and efficiency, immersive visualization intensifies spatial comprehension, and AI expands formative feedback while remaining subordinate to human engineering judgement.

A further point that justifies the chosen topic is the changing status of standards in the machine-building environment. Earlier generations of engineering students often encountered standards as something external to creative work, almost as a final layer applied after the real design had already occurred. In present workflows this separation is no longer tenable. Standardized representation is inseparable from the early stages of modelling, collaboration, version control, and production preparation. When students learn engineering graphics without understanding this integration, they may imitate standards visually without grasping their operational necessity. A line, a hatch, a datum, a surface symbol, or a dimensional reference is not simply a conventional sign but part of the economy of decision-making through which engineers coordinate work across teams, time, and production environments. This is precisely why the pedagogical renewal of engineering graphics cannot be limited to adding more software hours. It requires a change in epistemic emphasis. The student must learn to perceive a drawing as a compressed technical argument. Every projection states something about observable and hidden form. Every section states something about internal necessity and reading economy. Every chain of dimensions states something about function, measurement logic, and manufacturing risk. Every omission creates ambiguity. In this sense engineering graphics is one of the rare disciplines where errors are simultaneously visual, logical, communicative, and technological. That multi-dimensional character makes it an especially fertile field for the careful use of digital tools, because digital tools can reveal hidden dependencies that remain inaccessible or slow to inspect in purely manual settings. Yet the same multi-dimensionality also makes the field vulnerable to shallow modernization. If the curriculum confuses speed with understanding, or interface skill with engineering judgement, then the technology masks weakness instead of curing it. The article therefore approaches digital transformation critically: new tools are accepted only to the extent that they deepen representational awareness, improve the quality of engineering communication, or expand the student's capacity to evaluate the validity of a graphic solution. In this regard, the present study also responds to a broader academic need. Discussions around generative AI in education often concentrate on text production, coding assistance, or assessment security. Engineering graphics has received much less attention, even though it is exactly the kind of domain in which AI may become both highly useful and highly misleading. A system can generate a plausible drawing, infer missing features from partial geometry, or propose a dimension set, yet still fail to account for standard-specific practice, manufacturing sequence, tolerance accumulation, or the practical purpose of the document. The educational risk is subtle. Students may begin to confuse probable-looking output with authoritative engineering representation. That confusion is dangerous not only academically but professionally. In machine-building, a poorly justified drawing is not a harmless classroom mistake; in real production it can produce waste, delay, or safety consequences. This consideration gives the topic immediate relevance for assistant lecturers, curriculum designers, and departments responsible for training future engineers. The proposed article thus speaks not only to theoretical modernization but to quality assurance in technical higher education. Another reason for focusing on this theme is that engineering graphics occupies a transitional location in the student trajectory. It often appears in early semesters, when students are still forming their habits of observation, precision, justification, and independent work. Pedagogical mistakes made at this stage propagate into later courses such as machine elements, strength of materials, production technology, CAD/CAM, mechatronics, and graduation design. If students enter those domains with weak graphic reasoning, they struggle not only to draw but to think through engineering form. Conversely, when engineering graphics is taught as a robust foundation for thinking, students carry its discipline into design reviews, model interpretation, technical communication, and documentation practice. For that reason, the renewal of the graphics course has multiplier effects across the engineering curriculum. It is not a local matter. It is structural. Finally, the topic is relevant because it allows a productive synthesis between international digital-education discourse and the specific needs of mechanical and engineering-graphic education in post-Soviet and Central Asian academic contexts. Many institutions in these contexts inherit strong traditions of descriptive geometry and drafting. That heritage is valuable and should not be discarded. At the same time, graduates are increasingly expected to work in digitally mediated environments shaped by automation, interoperable data, remote collaboration, and AI-supported design assistance. The key challenge is therefore not replacement but translation: how to carry forward the analytic rigour of classical graphic education into a technologically expanded environment. This article treats that challenge as both pedagogical and disciplinary, seeking a model that is rigorous enough for DSc-level discussion and practical enough to inform real course redesign.

Materials and Methods

The methodological basis of the article combines conceptual analysis, structured literature synthesis, comparative pedagogical modelling, and design-based educational reasoning. Because the aim of the study is to formulate an implementable instructional framework rather than to report a single local classroom experiment, the research design follows an integrative methodological logic. First, a corpus of contemporary sources from 2024–2026 and selected foundational educational references was analyzed in order to identify the dominant directions in engineering graphics transformation: CAD-integrated descriptive geometry, immersive visualization, project-based technical drawing, AI-guided digital competence, and data standardization between 2D drawings and 3D workflows. The literature review prioritized recent primary studies and official educational guidance that addressed either engineering graphics directly or the broader pedagogical conditions affecting graphic education in higher engineering institutions. Recent comparative work on CAD-integrated orthographic projection was used to clarify the mechanisms by which digital modelling may lower unnecessary cognitive load while increasing the transparency of geometric relationships [2]. Research on product-oriented and collaborative technical drawing instruction was used to capture the social and practical dimensions of graphics learning when students do not draw merely for submission but for realization in material form [3]. Studies on interactive virtual reality and 3D sketching in engineering and architecture were examined in order to understand how immersive environments affect conceptual design, spatial understanding, and the communication of intention [4]. A 2025 comparative investigation of general-purpose CAD versus specialized toolsets in mechanical drafting was included to highlight the instructional relevance of workflow optimization, tool selection, and creative output under beginner conditions [9]. A 2024 study on standardization of CAD drawing formats and GeoJSON-based extraction of 3D spatial data from conventional plan drawings was also reviewed because it clarifies an increasingly important industrial reality: contemporary engineers must understand not only how to create drawings, but how drawings participate in interoperable data ecosystems [10]. This industrial data perspective matters pedagogically, because it supports a shift from static drafting exercises to documentation-aware graphic reasoning. Second, the study employed comparative pedagogical decomposition. The instructional process of engineering graphics was broken into five interrelated competence clusters: visual-spatial cognition, normative graphic communication, procedural execution, digital model logic, and justificatory reflection. Visual-spatial cognition includes mental rotation, view synthesis, section interpretation, and the capacity to infer hidden geometry from limited projections. Normative graphic communication covers standards of line type, dimensioning, tolerancing, sectioning, symbols, and assembly representation. Procedural execution includes the ordered operations by which students transform a task into a correct graphic result, whether manually or digitally. Digital model logic refers to parametric relations, feature history, constraints, associativity, and the transition between model space and drawing space. Justificatory reflection concerns the student's ability to explain why a representational choice is correct, efficient, standard-compliant, and manufacturable. This decomposition allowed the study to evaluate how different teaching modes contribute distinctively to learning. Manual drafting remains especially strong in normative communication and justificatory reflection because it slows down representation and makes every operation visible. CAD environments strongly support procedural execution, model logic, and geometric consistency through constraint-based construction. Immersive visualization is especially effective in visual-spatial cognition, particularly for students who struggle to map sectional or orthographic representations back to solid form. AI-assisted tools, if carefully framed, can expand feedback loops across all five clusters by helping students detect inconsistencies, compare alternatives, identify missing constraints, or receive adaptive hints. Third, the article adopted a design-based modelling procedure to construct a staged instructional framework for a one-semester or two-semester engineering graphics course in mechanical education. The framework was drafted around three pedagogical phases. The foundation phase emphasizes manual projection, freehand technical sketching, basic descriptive geometry, and standard drawing conventions, but these tasks are paired with digital visualization so that students can immediately compare symbolic representation with spatial objects. The integration phase introduces CAD-based orthographic modelling, section generation, dimensioning, assembly drawing, and tolerance communication while preserving an explicit requirement that students explain each graphical decision in technical terms. The extension phase adds AI-supported review, immersive visualization, data-oriented translation between 2D and 3D representations, and project-based tasks linked to manufacturing or machine element design. At each phase, the balance of teacher guidance, peer collaboration, and independent digital work changes deliberately. The instructor's role is reconceived not as a supervisor of software commands but as an interpreter of representational logic. This aspect is especially important in light of UNESCO's human-centred framing of AI and digital education, which treats technology adoption as an issue of competence, ethics, and agency rather than mere access [5–8]. For this reason, the methodological model incorporates explicit control points designed to prevent uncritical technological dependency. Students are required to submit process evidence, including sketch evolution, view-relation reasoning, feature-tree explanations, and brief oral or written justifications. AI-generated suggestions are allowed only when students annotate whether the suggestion was accepted, corrected, or rejected, and why. Such controls transform AI from an answer-providing mechanism into a reflective instrument. Fourth, criterion-based assessment architecture was built into the model. Instead of grading drawings only by visual neatness or software completion, the framework proposes a multi-dimensional rubric with seven criteria: geometric correctness, standard compliance, dimensioning logic, representational completeness, model-drawing coherence, manufacturability awareness, and justification quality. Geometric correctness measures whether the drawing or model accurately represents the object and whether view relations are internally consistent. Standard compliance addresses adherence to line conventions, sectioning rules, dimension placement, symbols, and notation. Dimensioning logic evaluates whether dimensions are sufficient, non-redundant, functionally meaningful, and production-oriented. Representational completeness assesses whether the set of views, sections, and details is adequate for interpretation. Model-drawing coherence checks the relation between a 3D parametric model and its 2D documentation. Manufacturability awareness examines whether the student understands tolerances, fit, access, assembly sequence, and production constraints. Justification quality measures the student's capacity to explain and defend decisions using appropriate engineering language. This rubric structure was influenced by the finding that effective CAD-integrated instruction improves not only final performance but also confidence, clarity, and procedural consistency [2], and by evidence that project-realization contexts produce stronger engagement and social learning in technical drawing [3]. Fifth, the methodological framework incorporates teacher preparedness as an explicit variable. One of the recurring weaknesses of digital transition in engineering graphics is the mistaken assumption that a teacher who can operate CAD or a visualization tool automatically possesses the pedagogical knowledge required to integrate it effectively. UNESCO's AI and digital competency frameworks emphasize that educators need not only technical familiarity but also critical, ethical, and context-sensitive competence [6–8]. Therefore, the proposed model includes instructor training in four domains: representational diagnostics, digital workflow orchestration, ethical AI use, and multimodal assessment. Representational diagnostics refers to the ability to detect whether a student error is conceptual, perceptual, procedural, or merely interface-related. Digital workflow orchestration means sequencing manual, CAD, immersive, and AI-supported tasks so that one mode prepares the next instead of replacing it mechanically. Ethical AI use includes transparency, authorship, academic integrity, and the avoidance of unverified automated outputs. Multimodal assessment includes evaluating sketches, drawings, models, process logs, and oral defence. Finally, the study employed a relevance-to-practice filter. Every component in the proposed framework was tested conceptually against a practical question: does this element help students produce engineering graphics that are more intelligible, more accurate, more transferable to industrial contexts, and more defensible in professional communication? This filter excluded tools that are visually impressive but pedagogically shallow, as well as tasks that imitate tradition without contemporary applicability. The outcome of the methodological procedure is thus not a software-centred instructional recipe, but a discipline-centred educational model in which technology is selected and sequenced according to the cognitive, normative, and professional structure of engineering graphics itself.

In order to strengthen the validity of the conceptual model, the literature analysis was not performed as an undifferentiated descriptive review. Each source was read against a common analytical matrix consisting of six questions: what competence problem is being addressed; what technological medium is involved; what learning mechanism is proposed; what evidence of effect is reported; what limitations are noted or implied; and how transferable the approach is to a mechanical engineering graphics curriculum. This matrix helped avoid a frequent problem in technology-in-education synthesis, namely the tendency to treat all positive digital results as equivalent. For example, a study may report improved student engagement in a virtual environment, but engagement alone is not enough in engineering graphics unless it translates into stronger projection reasoning, more consistent dimensioning, better section interpretation, or clearer documentation logic. Similarly, a CAD-based study may report faster task completion, yet speed is only educationally valuable when it supports accuracy, understanding, or reflective control. By structuring the source analysis in this way, the study ensured that only those findings with direct methodological relevance informed the proposed framework. Alongside the literature synthesis, a task-ecology perspective was employed. Engineering graphics was treated as an ecology of linked task types rather than as a linear sequence of exercises. These task types include object reading, view generation, error diagnosis, standards interpretation, model revision, assembly communication, and production-oriented annotation. The value of this perspective lies in its capacity to show that no single educational medium is equally well suited for all tasks. Freehand sketching is highly effective for exploratory object reading and quick conceptual externalization. Classical instrument-based drawing is effective for enforcing care, alignment, and rule-following. Parametric CAD is most effective for revisable geometry and associative documentation. Immersive media excel when hidden spatial structure must be mentally unpacked. AI-supported systems are especially useful in tasks involving repeated checking, comparison, and targeted remediation. The proposed pedagogical model therefore allocates media according to task suitability rather than according to institutional habit or novelty appeal. The methodological construction also incorporated a progression principle derived from competence complexity. Simple graphic tasks were not merely placed earlier than difficult ones; rather, tasks were ordered according to the degree of inferential coordination they require. At the entry level, students interpret simple objects and produce basic views where the relationship between surfaces and edges is relatively transparent. Intermediate tasks involve intersection, sectioning, and the coordination of multiple representational conventions. Advanced tasks require students to maintain coherence between functional design intention, parametric model history, assembly logic, and final documentation. AI and immersive tools enter this sequence not as replacements for difficulty but as instruments that can illuminate specific inferential bottlenecks. For instance, when a student fails to understand why a sectional view is preferable to hidden-line overload, immersive visualization can expose internal form more directly, while AI-guided critique can highlight precisely where representational economy has broken down. Another methodological feature of the study is the incorporation of academic integrity as a design parameter rather than as an afterthought. In engineering graphics courses, integrity is often associated narrowly with whether a student copied a drawing. Under digital conditions that definition becomes inadequate. A student may produce original-looking work while depending excessively on opaque automation, peer file inheritance, or AI-generated solutions that are not understood. Therefore, the framework defines integrity in process terms: transparency of workflow, traceability of revisions, declared use of assistance tools, and demonstrable ownership of reasoning. Assessment tasks are designed so that competence must appear in multiple forms—sketches, intermediate files, commentary, peer review, and oral explanation—making it harder for unsupported or borrowed outputs to pass as authentic mastery. The methodological design also assumes variable institutional resources. Not every higher education institution can deploy full VR laboratories, advanced licensed mechanical toolsets, or custom AI platforms. For this reason, the proposed model is scalable. Its core logic does not depend on expensive infrastructure. The essential requirement is pedagogical sequencing and representational clarity. Where immersive hardware is limited, interactive screen-based 3D models and sectional animations may serve similar functions. Where specialized CAD packages are unavailable, general-purpose systems can still support associativity, view extraction, and standards-based documentation if tasks are designed properly. Where AI tools are limited, even semi-structured rule-checking systems or teacher-curated comparative exemplars can reproduce part of the formative-feedback function. Scalability is crucial because the value of a methodological model lies partly in its adaptability. Finally, the methodological stance of the study is explicitly synthetic rather than reductionist. It does not claim that one experimental result or one software comparison can dictate curricular policy. Instead, it builds a coherent pedagogical proposal by integrating convergent findings from multiple directions: spatial cognition research, technical drawing pedagogy, digital transformation guidance, workflow studies, and documentation standardization. Such synthesis is particularly appropriate for DSc-level academic argument because the problem under study—the future of engineering graphics education—is irreducibly multidimensional. It concerns cognition, curriculum, technology, normativity, professional relevance, and ethics at the same time.

Results

The synthesis and modelling procedure led to several results that are theoretically coherent and pedagogically actionable. The first result is the identification of a four-layer architecture for modern engineering graphics education: foundational graphic literacy, digital geometric control, intelligent formative support, and professional documentation transfer. Foundational graphic literacy includes manual sketching, descriptive geometry principles, projection reading, sectional reasoning, and the disciplined use of standards. This layer remains indispensable because it establishes the symbolic grammar of engineering representation. Without it, students often become dependent on software defaults and fail to recognize when a digitally produced output is conceptually wrong. The literature reviewed confirms that descriptive geometry retains a central role in developing spatial reasoning and problem-solving, even when digital tools are introduced [2]. The second layer, digital geometric control, is formed by CAD-based parametric construction, model associativity, constraint management, automated yet critically supervised view generation, and the transition from object modelling to drawing extraction. The significance of this layer lies in the fact that contemporary mechanical work rarely separates geometric ideation from digital operationalization. However, the comparative evidence suggests that CAD yields its strongest educational effect not when students are reduced to command repetition, but when the software environment makes structural relations visible and reduces the burden of routine graphical execution [2,9]. The third layer, intelligent formative support, consists of AI-assisted error detection, adaptive hinting, pattern comparison, variant generation for practice, and feedback analytics. Importantly, this layer is not conceived as a source of authoritative answers. Rather, it extends the feedback ecology of the classroom. In traditional drafting courses, students often wait long intervals before errors in projection transfer, missing dimensions, view inconsistency, or section logic are diagnosed. Intelligent tools can shorten this loop dramatically, provided that feedback remains explainable and contestable. The fourth layer, professional documentation transfer, links the educational act of drawing to industrial data workflows. Here students learn that drawings are not isolated sheet exercises but structured carriers of design intent that may later interact with BIM-like environments, GIS-linked infrastructure models, CAM processes, production documentation, and digital archives. The reviewed study on standardizing CAD drawings with embedded 3D coordinates and attributes demonstrates precisely this wider industrial movement from purely graphic representation toward interoperable data representation [10]. As a result, the educational horizon of engineering graphics must expand beyond “how to draw correctly” toward “how to encode engineering meaning in forms that remain useful across digital systems.” The second major result of the study is the clarification of how different instructional modes affect distinct dimensions of competence. Manual drafting showed the highest conceptual value where slowness, selective attention, and explicit rule internalization are necessary. Students learn line discipline, projection dependency, and section logic more durably when they must construct relations rather than merely select commands. CAD, by contrast, proved strongest where geometric consistency, procedural efficiency, and rapid testing of alternatives are required. Specialized toolsets in mechanical drafting appear especially effective for novice productivity because they reduce unnecessary command search and support task completion with higher workflow efficiency [9]. Immersive visualization contributed most strongly to the interpretation of complex 3D relationships, particularly in conceptual transitions between solid form, exploded arrangement, and sectional or orthographic reduction [4]. Project-based and product-oriented tasks showed their greatest value in motivation, collaboration, and the conversion of drawing from a classroom artifact into a technical means for realizing a tangible object [3]. AI-assisted systems were most useful in repetitive formative operations: identifying missing views, warning about inconsistent dimensions, flagging probable section errors, generating additional practice variants at calibrated difficulty levels, and supporting reflective comparison between student output and standard-compliant alternatives. The third result concerns curricular sequencing. The analysis showed that many weaknesses in engineering graphics learning emerge not because students are incapable of understanding drawing logic, but because institutions often introduce representational modes in an order that fragments rather than integrates cognition. A more effective sequence begins with controlled manual abstraction, proceeds to digitally stabilized geometry, then adds immersive and intelligent support after students possess enough disciplinary vocabulary to critique automated outputs. When AI appears too early, students may confuse generated adequacy with engineering correctness. When CAD appears too late, students may develop manual habits that do not transfer to parametric reasoning. When immersive visualization is treated as a decorative supplement, its strongest cognitive advantage is lost. The proposed sequence therefore moves from hand–eye discipline, to model–projection reciprocity, to explanation-rich digital work, and only then to AI-enhanced optimization and documentation interoperability. The fourth result is the recognition that assessment practices in engineering graphics are frequently too narrow for the actual complexity of the subject. Conventional grading often rewards clean final sheets while underestimating the reasoning process that produced them. The proposed seven-criterion rubric restructures evaluation so that the student's representational judgement becomes visible. In this model, a technically elegant but unjustified drawing cannot receive the highest evaluation, nor can a procedurally clumsy but conceptually sound draft be dismissed without diagnostic credit. This change is especially important in the age of AI, because final appearance alone no longer reliably indicates actual competence. Process evidence, design rationale, revision history, and oral defence therefore become not bureaucratic additions but essential safeguards of validity. The fifth result concerns teacher roles. The analysis indicates that the modernization of engineering graphics is blocked less by lack of software availability than by insufficient pedagogical translation. Where teachers use digital tools merely to accelerate drawing production, students may become faster but not necessarily more competent. Where teachers instead use these tools to make geometric causality, projection reciprocity, and standard logic more discussable, learning deepens. Consequently, teacher expertise in modern engineering graphics must combine three identities: graphic theorist, workflow mediator, and evaluator of machine-supported learning. The sixth result is ethical and epistemic. The introduction of AI into engineering graphics creates a new boundary problem between assistance and substitution. An AI tool may help a student locate a dimensioning inconsistency or propose an alternative sectional view; that can be educationally valuable. But if the student cannot explain why the proposal is correct, the competence has not been formed. UNESCO's emphasis on human agency, ethical use, and critical engagement with AI aligns strongly with this conclusion [5–8]. In engineering graphics, ethical AI use should therefore be defined not only by plagiarism avoidance but by the principle of representational accountability: every accepted automated output must remain intelligible to the student as an engineering statement. The seventh result is a concrete instructional model that can be adapted to mechanical engineering institutions.

In a first module, students engage in freehand technical sketching, view correspondence, line-type logic, and simple solids through manual and digitally visualized tasks. In a second module, they move into constrained CAD construction and generate standard 2D views from 3D models while explicitly labelling projection dependencies. In a third module, they handle sectioning, dimensioning, and simple assembly representations using both manual diagnosis and CAD-based documentation. In a fourth module, students complete a project in which a machine element or small mechanism is sketched, modelled, documented, peer-reviewed, checked with AI-assisted feedback, and finally defended orally as if submitted to production planning. Such a module sequence transforms the course from isolated exercises into a structured rehearsal of professional engineering communication. The eighth result is a revised understanding of what “graphic literacy” means in the present period. It can no longer be reduced to neat drafting or even correct projection. Contemporary graphic literacy in mechanical education includes reading across modalities, tracing the relation between features and views, understanding how standards mediate meaning, managing digital associativity, interpreting automated suggestions critically, and recognizing when a documentation set is insufficient for manufacture or assembly. This broader literacy is both more demanding and more realistic. It treats the engineering drawing not as a static school tradition, but as a live junction between cognition, technology, and industrial action.

A ninth result of the analysis is the identification of recurring error patterns that should guide instructional redesign. Across traditional and digital environments, beginner mistakes in engineering graphics tend to cluster into six categories: object misreading, view mismatch, hidden-feature confusion, section misuse, dimensioning incoherence, and software-driven false confidence. Object misreading occurs when students fail to perceive the hierarchy of primary and secondary forms within a mechanical part, resulting in drawings that reproduce isolated surfaces without grasping the object’s functional structure. View mismatch appears when corresponding elements across front, top, and side projections are not synchronized conceptually. Hidden-feature confusion emerges when students either overuse hidden lines or fail to understand when a sectional solution offers clearer communication. Section misuse includes incorrect cut-plane logic, inconsistent hatching, and failure to distinguish between local, half, offset, and full sections. Dimensioning incoherence involves redundancy, missing reference logic, or dimension placement that does not support manufacturing. Software-driven false confidence arises when students assume that because a view was generated automatically it must be communicatively sufficient. These error categories are important because they show that improvement requires more than increased practice time; it requires targeted diagnostics.

A tenth result is that peer interaction gains a new methodological significance when digital and AI tools are introduced. In conventional settings peer review often remains superficial, focusing on neatness or visible mistakes. In the proposed model, peer review is structured around the same rubric used by the instructor and supplemented by prompts that force students to discuss adequacy of views, logic of section choice, manufacturability, and interpretability for a third-party reader. This practice has two benefits. It externalizes tacit reasoning, and it reduces the passivity that sometimes accompanies digital environments where students interact mainly with screens. The literature on product-oriented technical drawing already indicates that social interaction and collaboration can improve under active learning conditions [3]. The present study extends that insight by showing how digital tools can support, rather than replace, dialogic judgement when peer review is methodically organized. An eleventh result concerns the timing of standards instruction. Many curricula teach standards either too abstractly at the beginning or too incidentally throughout the semester. The analysis suggests a more effective strategy: standards should be introduced at the moment when each convention becomes necessary for solving a meaningful representational problem. For example, students understand sectioning rules more deeply when these rules solve the communicative overload caused by hidden-line representation in a specific object. They understand dimensioning more deeply when dimensions are discussed in relation to functional surfaces, assembly interfaces, or tool access rather than as a detached list of norms. This situational timing increases retention and reduces the impression that standards are arbitrary formalities. A twelfth result is the recognition that the boundary between engineering graphics and adjacent subjects should become more porous. The proposed framework benefits when drawing tasks are linked with introductory machine elements, manufacturing technology, materials, or metrology. When students see how a chamfer affects assembly, how tolerance interacts with fit, or how documentation influences machining, the drawing acquires engineering consequence. That consequence, in turn, intensifies motivation and sharpens judgement. In other words, interdisciplinary linkage does not dilute engineering graphics; it restores its natural habitat within engineering action. A thirteenth result is a set of implementation indicators for institutions. The success of modernization should not be measured only by the number of installed computers or software licenses. More meaningful indicators include reduction in recurring conceptual errors, improvement in student ability to explain drawings orally, increased coherence between 3D models and 2D documentation, better rubric scores for dimensioning logic and manufacturability awareness, and observable changes in student revision behaviour after feedback. A fourteenth result is that course modernization requires administrative realism. Excessively ambitious technological adoption without timetable revision, teacher preparation, or assessment redesign tends to overload both students and staff. Therefore, a staged implementation strategy is preferable: first revise outcomes and rubrics, then align tasks, then introduce digital and AI elements incrementally, and only then expand infrastructure. This order is more sustainable and more academically defensible. A fifteenth result is conceptual: the future-ready engineering graphics course should be understood as a laboratory of representational judgement. Its deepest purpose is not merely the production of compliant drawings but the formation of professionals who can decide what must be shown, how it must be shown, why it must be shown in that way, and how the chosen representation will function within engineering work.

Discussion

The results of the study permit several broader interpretations that are highly relevant for the development of engineering graphics and mechanical drafting as academic disciplines in higher education. The first concerns the persistent false dichotomy between traditional drafting and digital design tools. In many institutions this dichotomy still shapes curricular debates in simplistic terms: either the course remains faithful to manual descriptive geometry and therefore risks obsolescence, or it turns decisively toward CAD, AI, and immersive visualization and therefore risks superficiality. The evidence reviewed here suggests that this opposition is pedagogically unproductive. The real question is not which mode is superior in the abstract, but what cognitive and professional work each mode performs within a coherent sequence. Manual drafting remains irreplaceable where the objective is to make graphic reasoning explicit, slow enough for diagnosis, and visible enough for norm internalization. CAD becomes indispensable where the objective is to stabilize geometric relations, expose constraint logic, increase efficiency, and connect educational tasks to contemporary engineering practice. AR and VR are not merely motivational technologies; properly used, they assist learners who have difficulty reconstructing solids, section planes, and spatial transformations from conventional 2D projections [4]. AI, finally, is most valuable where feedback must become more immediate, comparative, adaptive, and process-sensitive. This layered interpretation restores methodological rationality to a field often pushed by fashion or institutional inertia. A second discussion point concerns cognitive economy. One of the strongest arguments for integrating CAD-based orthographic systems into engineering graphics is that they can reduce unnecessary cognitive expenditure while preserving or even deepening conceptual understanding [2]. This matters because beginners often fail not due to inability to think spatially, but because too many procedural burdens compete for attention at the same time. If a learning environment can reduce low-value routine while keeping representational logic visible, then cognitive resources may be redirected toward higher-order perception and judgement. Yet this argument must be handled carefully. Any simplification that removes the need to understand why a view is necessary, why a section is chosen, or why a dimension chain is wrong becomes harmful simplification. The educational objective is therefore not to minimize difficulty indiscriminately but to separate productive difficulty from nonproductive friction. Productive difficulty exists when the learner must mentally reconcile views, justify a sectional cut, or decide whether a tolerance communicates function. Nonproductive friction exists when routine software search, interface confusion, or redundant redrawing consume effort without adding conceptual value. A well-designed modern course reduces the second while retaining the first. A third issue is the industrial relevance of engineering graphics. The traditional defense of the subject often relies on cultural arguments: graphics trains accuracy, patience, neatness, and engineering discipline. These claims remain partly true, but they are no longer sufficient. In current practice, drawings are embedded in data-rich environments, collaborative platforms, digital archives, and increasingly automated manufacturing or coordination pipelines. The study on standardized CAD drawings linked to 3D spatial data shows how representation is moving toward interoperable documentation structures [10]. In mechanical contexts, similar tendencies appear in model-based definition, parametric revision chains, and digital manufacturing ecosystems. This does not mean that the 2D drawing disappears; rather, its role becomes more strategic. It must be accurate enough to communicate with humans, structured enough to interact with digital systems, and interpretable enough to support inspection, maintenance, and production. Consequently, engineering graphics education should prepare students not only to draw objects but to understand the documentary life of engineering information. A fourth issue concerns the notion of creativity. There is a persistent misconception that strict graphic standards suppress creativity, whereas digital tools or AI somehow liberate it automatically. In reality, engineering creativity is constrained creativity: it emerges through the disciplined negotiation of function, manufacturability, economy, safety, and clarity. The 2025 comparison between general-purpose and specialized CAD toolsets in mechanical drafting suggests that efficiency gains and structured environments may support both productivity and creative outcome when the learner has a meaningful task [9]. Creativity in engineering graphics should therefore be defined not as decorative variation but as the intelligent organization of representation so that design intent becomes clearer, leaner, and more workable. A fifth discussion point is the status of AI-generated content. In many educational settings AI is discussed in moral extremes, either as a threat to academic integrity or as an inevitable productivity enhancer. Engineering graphics requires a more exact norm. Since the subject is intrinsically representational and rule-governed, AI can be highly useful for pattern recognition, anomaly detection, draft critique, hint generation, or multi-variant practice construction. At the same time, because graphic correctness depends on conventions, functions, and context, AI outputs can easily sound or look plausible while remaining technically invalid. For that reason, the article proposes representational accountability as the core principle of acceptable AI use. Under this principle, the legitimacy of AI assistance depends on whether the student can reconstruct the logic of the accepted output, test it against standards and manufacturing intent, and explain it independently. This is consistent with UNESCO's human-centred, ethics-oriented approach to AI in education, which resists replacing agency with dependency [5–8]. A sixth issue relates to equity and differentiation. One of the often overlooked benefits of digital and immersive tools is that they may compensate for uneven prior preparation. Students enter technical universities with widely different backgrounds in school geometry, drawing, and computer use. Some understand spatial relations quickly but work sloppily; others are methodical but slow to visualize; still others are digitally fluent but normatively weak. A multimodal course structure can support these different profiles better than a single-mode course. Immersive visualization can help weaker spatializers; manual sketching can stabilize students who rely too heavily on software; AI-guided feedback can provide additional practice without overloading the instructor; project-based work can sustain motivation among students who struggle with abstract isolated tasks. UNESCO's smart education agenda emphasizes adaptation to context and learner diversity [8], and engineering graphics is an excellent domain in which such adaptation can be concretely operationalized. A seventh issue concerns the teacher. The modernization of engineering graphics is impossible if the teacher's role is imagined only in terms of tool demonstration. The contemporary instructor must interpret errors diagnostically. For example, when a student produces an incorrect sectional view, the teacher should distinguish whether the error comes from weak geometric imagination, misunderstanding of conventions, misuse of a CAD command, or uncritical acceptance of AI-generated advice. Each cause requires a different pedagogical response. This diagnostic sophistication becomes even more important as classrooms become technologically richer. It is easy to adopt software; it is far harder to orchestrate multiple representation modes so that they illuminate one another. Teacher development must therefore include not only software training but representational pedagogy, assessment design, and ethical protocol. An eighth issue is methodological validity in assessment. If higher education continues to evaluate engineering graphics primarily through final printable outputs, then digital tools and AI will distort the measurement of learning. Final outputs are increasingly insufficient proxies for competence. A student can produce a polished sheet with minimal understanding by relying on templates, automation, or borrowed workflows. Conversely, a student with developing but genuine competence may show a weaker final sheet while demonstrating excellent reasoning in process logs or oral defence. Hence the rubric proposed in this article is not a technical detail; it is a methodological necessity. It protects the course from becoming a beauty contest of linework or an interface efficiency contest. A ninth point concerns the status of standardization. Some educators fear that an increased focus on data interoperability, digital standards, and workflow integration may over-technologize the course. Yet standardization has always been at the heart of engineering graphics. What changes today is the scale and visibility of that standardization. Students must understand that a line convention, a dimension scheme, or a coordinate annotation is not a ritual formality but part of a broader system that enables manufacturing, inspection, maintenance, exchange, and traceability. Teaching standards in connection with digital workflows may actually revitalize rather than weaken their meaning. A final discussion point concerns disciplinary identity. Engineering graphics has sometimes been treated as a service course that exists merely to support "real engineering" subjects. The argument of this article is the opposite. Engineering graphics is itself a core epistemic domain because it trains the disciplined transformation of perception into communicable engineering structure. In the age of AI this identity becomes stronger, not weaker. The more software can generate, the more valuable it becomes to educate specialists who can judge, verify, explain, and responsibly use generated representations. The future of engineering graphics therefore does not lie in nostalgia for ink-board culture, nor in surrender to automated visual production, but in a mature synthesis where representation remains a form of thought and technology becomes an amplifier of accountable engineering reasoning.

The discussion may be extended further by considering the historical continuity of the subject. Mechanical drawing and engineering graphics have long been associated with discipline, precision, and objectivity. Yet what counts as precision changes when engineering passes from board-based drafting to linked digital environments. Precision is no longer only the exact placement of lines and dimensions on a sheet; it includes version consistency, parametric robustness, data traceability, and the ability to prevent downstream misinterpretation. This expansion does not invalidate the historical tradition of drafting; rather, it reveals what that tradition was always aiming at in a different technological context: reliable technical communication. Seen from this angle, digital transformation is not a betrayal of engineering graphics but a widening of its original mission. Another important implication concerns student identity formation. Early encounters with engineering graphics often shape whether students begin to perceive themselves as future engineers or merely as course takers completing assignments. A course that emphasizes rote copying, isolated convention memorization, or command-level software training may produce compliance but not professional self-recognition. By contrast, a course that treats students as interpreters and producers of engineering meaning can accelerate identity formation. When students defend why a given set of views is sufficient, why a section is necessary, or why a dimension strategy reflects manufacturing logic, they begin to act like engineers rather than just learners. This identity dimension helps explain why project-realization and collaborative approaches often produce stronger engagement [3]. The student is no longer drawing for the teacher alone but for a plausible technical audience. There is also a governance dimension. Universities increasingly adopt digital tools through centralized procurement or administrative modernization programmes. However, the findings of this article suggest that engineering graphics should not be modernized by procurement logic alone. Software acquisition without curricular logic produces underused infrastructure; AI access without assessment reform produces integrity problems; immersive devices without teacher methodology produce spectacle rather than learning. Institutional leaders should therefore treat engineering graphics as a pilot field for pedagogy-led digital transformation. Because the subject naturally combines visualization, standards, documentation, modelling, feedback, and professional communication, it is ideal for demonstrating whether an institution can align technology, curriculum, and evaluation coherently. Another discussion issue is the danger of over-automation. In advanced industrial settings there is a trend toward model-based definition and increasingly automated documentation generation. Students should be made aware of these trends, yet education must not prematurely erase the interpretive labour from which judgement arises. If automation is introduced as an unquestioned norm, students may never fully encounter the representational problems that the automation is supposed to solve. A strong educational model therefore allows students to experience the necessity of conventions before benefiting from their automation. They should know why a drawing needs a specific section before software creates it, and why a dimension chain is problematic before a checker flags it. Only then does automation reinforce rather than replace understanding. Finally, the article's argument has implications for research. Future empirical studies in engineering graphics should move beyond simple comparisons of "traditional" versus "digital" instruction. More precise questions are needed: which combinations of manual, CAD, immersive, and AI-supported tasks best improve specific sub-competencies; how process-trace data can reveal conceptual development; how oral explanation correlates with drawing quality; which feedback forms most effectively reduce sectioning and dimensioning errors; and how integrity protocols affect student learning cultures in digitally supported drafting courses. In other words, the field now needs second-generation research that studies orchestration rather than isolated tool effects. That research agenda would help transform engineering graphics from a frequently under-theorized service course into a mature site of educational innovation with direct consequences for the quality of engineering formation.

Conclusion

The study has shown that the modernization of mechanical drafting and engineering graphics should be understood as a methodological reconstruction rather than as a simple technical update. Contemporary engineering education requires graduates who are capable of reading, generating, critiquing, and defending graphic information across multiple environments, from manual sketches and standardized 2D drawings to parametric models, immersive visualizations, and AI-supported review systems. On the basis of recent empirical studies and official digital-education guidance, the article demonstrates that the most productive instructional model is a layered one. Manual drafting remains essential for cultivating attentiveness, symbolic discipline, and the ability to reason explicitly about projection and standardization. CAD environments are indispensable for geometric coherence, efficiency, and the connection of educational tasks to current professional workflows. AR/VR tools strengthen difficult transitions between object space and representational space, particularly in the interpretation of complex geometry and sectional relationships. AI tools can substantially enrich formative feedback, task variation, and diagnostic support, but only when their use is governed by the principle of human interpretive responsibility. The major theoretical conclusion is that engineering graphics competence in the present era is not a narrow skill of neat drawing; it is a compound literacy composed of spatial cognition, normative communication, digital model logic, process explanation, and documentation awareness. The major methodological conclusion is that these components should not be taught in isolation. They must be sequenced so that each representational mode contributes its strongest pedagogical function without displacing the others. The major practical conclusion is that institutions seeking to renew engineering graphics should revise not only software infrastructure but also curriculum architecture, teacher training, and assessment logic. A modern course should include manual-to-digital transitions, criterion-based evaluation, project-realization tasks, AI-annotated process evidence, and oral defence of representational decisions. Such a course would better align university training with the realities of contemporary engineering while preserving the intellectual seriousness of the discipline. For higher technical education in Uzbekistan and similar contexts, this approach is especially timely. Many institutions possess the historical tradition of strong drawing instruction but face the challenge of integrating that tradition with rapidly changing digital expectations. The model proposed in this article offers a way to do so without reducing engineering graphics to either a museum of conventions or a software tutorial. Its central message is clear: the future of engineering graphics belongs to educational systems that teach students not merely to produce images, but to encode, examine, and justify engineering meaning through representations that remain accurate, ethical, interoperable, and professionally actionable. At the same time, the article recognizes that modernization is not self-executing. Any institution that attempts to implement such a model must address several practical conditions: the readiness of instructors to teach through multiple representational modes, the revision of learning outcomes to include justification and documentation literacy, the careful definition of acceptable AI use, and the creation of assessment tasks that make authentic competence visible. These conditions are demanding, but they are also realistic. They do not require abandoning established academic strengths; they require reorganizing them. Institutions with strong traditions in descriptive geometry and technical drawing possess an advantage, because they already understand the value of rigour, standardization, and visual thinking. Their task is to connect that foundation to digital workflows, immersive aids, and intelligent feedback in a disciplined manner. If this is done thoughtfully, engineering graphics can become one of the most strategically important subjects in the early engineering curriculum: a place where students first learn what it means to think precisely, communicate responsibly, and use technology without surrendering judgement.

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