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DIGITALIZATION AND ENERGY EFFICIENCY IN THE TRAINING OF FUTURE CONSTRUCTION PROFESSIONALS: CHALLENGES AND PROSPECTS

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Abstract

Relevance. Accounting for approximately 39% of global carbon dioxide emissions, the construction industry is currently at the epicenter of radical transformations (changes). Contemporary scholarship views these shifts through the prism of the "Twin Transition"—the synergy between digitalization and greening (environmental sustainability). Within this multidimensional context, the vocational education and training (VET) system faces an existential challenge, grappling with obsolete curricula and institutional barriers that restrict teacher agency. The contemporary labor market demands a workforce capable of designing and implementing energy-efficient solutions within the innovative paradigm of Construction 4.0.

Purpose. To provide a theoretical and empirical substantiation for a comprehensive model integrating energy-efficient and digital technologies into the vocational training system of future construction professionals, and to conduct an in-depth analysis of the effectiveness of innovative pedagogical strategies (specifically immersive simulations and BIM technologies) amidst the global climate transition and the urgent demands of Ukraine's post-war infrastructure reconstruction (particularly under the Ukraine Facility program).

Methods. The study is grounded in systemic and interdisciplinary approaches. It utilizes a systematic review following the PRISMA protocol, structural-functional analysis to evaluate labor market skill gaps, comparative pedagogical modeling to contrast traditional and innovative educational paradigms, and a meta-analysis of empirical data regarding the efficacy of immersive virtual environments.

Results. The findings demonstrate a critical education-work transition mismatch (qualification gap) between high-tech market expectations and graduate competencies. The transition to the Education 4.0 paradigm via a multidisciplinary approach and Life Cycle Assessment (LCA) is substantiated as imperative (having no alternative). Furthermore, the unprecedented efficacy of immersive technologies (VR/AR) in fostering safety behavior is statistically confirmed (accelerating learning rates fourfold). The prospects of utilizing sustainable materials are detailed, and institutional strategies for Ukraine's post-war reconstruction are proposed, focusing on project localization, the establishment of Centers of Vocational Excellence (CoVEs), and the expansion of dual education.

Conclusions. The effective implementation of green technologies cannot be achieved through superficial (cosmetic) modifications; it demands surmounting institutional barriers and empowering teacher initiative. Only a profound, synergistic integration of digital twins, sustainable materials science, and localized public-private partnerships can supply the industry with the qualified workforce needed to realize the "Build Back Better" vision.

Keywords: *Construction 4.0, energy efficiency, Building Information Modeling (BIM), Twin Transition, immersive learning, green building, dual education.*

Introduction. The Architecture, Engineering, and Construction (AEC) industry, which has historically been among the most conservative sectors of the global economy, now finds itself at the epicenter of radical macroeconomic and technological transformations. This existential pressure is primarily driven by environmental factors: the sector is one of the largest consumers of resources and a critical source of greenhouse gas emissions, accounting for approximately 39% of total global carbon dioxide (CO_2) emissions (Clemente de Souza & Debs, 2023; Marinelli, 2023). In light of international climate commitments, maintaining the status quo in construction technologies is no longer viable (sustainable).

Today, European academia and policy view these challenges through the prism of the "Twin Transition" concept—a process that organically integrates environmental greening (the Green Transition) and digital transformation (the Digital Transition). Within this paradigm, digital innovations (such as artificial intelligence, BIM, and the Internet of Things) serve not merely as automation tools, but as an indispensable means to achieve global climate goals and ensure sustainable development.

In this context, national and international vocational education and training (VET) systems face an existential challenge. Supported by strategic documents such as the European Green Deal and the Digital Education Action Plan, the twin transition concept demands a fundamental reimagining of the workforce training system. The ability of future specialists to thoroughly comprehend the nature of energy processes, design complex cyber-physical systems, and implement energy-efficient technologies has transformed from an optional competitive advantage into a rigorous qualification requirement (Noguera et al., 2024; Radkevych & Pryhodii, 2024).

Presently, the level of proficiency in these green and digital competencies determines the overall macroeconomic capacity of economies to compete effectively on the global stage and comply with European directives, such as the Energy Performance of Buildings Directive (EPBD) (Noguera et al., 2024; Radkevych & Pryhodii, 2024). Traditional approaches to building construction, which relied on the extensive use of cheap raw materials, have completely exhausted their economic potential (Abera, 2024; Svyrydiuk, 2025). Modern engineering thought treats energy efficiency as a highly complex, multi-tiered set of measures that must be seamlessly integrated across all stages of a facility's life cycle—from early building information modeling to final environmental disposal and recycling (Abera, 2024; Svyrydiuk, 2025).

Such a holistic approach demands that specialists possess an entirely new level of epistemological understanding of the laws of building physics and the circular economy (Abera, 2024; Svyrydiuk, 2025). Concurrently, the global construction sector faces an acute (pervasive) shortage of a workforce capable of productively operating high-tech equipment (Bhattarai et al., 2025). To successfully overcome this labor crisis, a powerful synergy is required between innovative constructivist pedagogical methodologies and the direct implementation of green building principles into qualification frameworks. This issue is of paramount importance for Ukraine, which stands on the precipice of the largest post-war infrastructure reconstruction campaign in Europe's modern history.

The purpose of the article is to provide a comprehensive theoretical and empirical substantiation of an innovative model for the management and development of the vocational education system, based on the deep integration of energy-efficient and digital technologies (Twin Transition) into the training process of future construction professionals.

To achieve this overarching goal, the following specific objectives were formulated:

- to conduct a structural-functional analysis of qualification gaps (education-work transition mismatch) during the transition to the Construction 4.0 paradigm;
- to investigate systemic barriers in teaching practices and evaluate the effectiveness of implementing multidisciplinary energy-efficient pedagogical technologies (EEPT);
- to evaluate the cognitive mechanisms underlying the impact of immersive technologies

(VR/AR/XR) on the rate of engineering material acquisition (learning speed);

- to develop recommendations for adapting education to the demands of using sustainable (carbon-negative) building materials and methods of modular prefabricated construction;
- to propose effective institutional strategies to optimize Ukraine's post-war infrastructure reconstruction process (specifically within the framework of the Ukraine Facility program) through project localization and the development of Centers of Vocational Excellence (CoVEs).

Research Methods. The study is grounded in a comprehensive, multi-tiered, interdisciplinary approach. At the first (theoretical-exploratory) stage, systematic literature review methods were applied using the standardized PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to ensure transparency and objectivity in selecting relevant sources. A critical analysis of the regulatory framework and industry reports was conducted, enabling the conceptualization of the core nature of the Twin Transition and the Construction 4.0 paradigm.

At the second stage, the structural-functional analysis method was employed to identify the qualification gap in the labor market. The assessment of the epistemological mismatch was carried out by comparing graduates' self-assessment profiles with objective competence audit data from employers. To visually contrast the training models, comparative pedagogical modeling was applied.

At the third stage, a meta-analysis of existing empirical data regarding the implementation of digital tools was conducted. To evaluate the effectiveness of immersive technologies (VR/AR), statistical indicators from regression models were analyzed. The impact of green materials was assessed through the lens of the Life Cycle Assessment (LCA) concept. All quantitative and qualitative data were synthesized to formulate institutional recommendations.

Artificial intelligence tools (Perplexity AI, Gemini, DeepL) were utilized in this work solely for technical proofreading purposes (spelling and punctuation checks, stylistic editing of selected text fragments, and automated verification of bibliographic citation formatting). No scientific content was generated by AI. The scientific propositions, conclusions, and results constitute solely the author's own intellectual contribution.

Results and Discussion. The transition of the global construction industry to the Construction 4.0 paradigm marks an evolutionary, multidimensional transformation in the methods of engineering design and physical construction of assets. It conceptually relies on the pervasive deployment of cyber-physical systems, the Industrial Internet of Things (IIoT), generative artificial intelligence algorithms, automated robotics, and additive manufacturing.

Within the specific context of the urban environment, this paradigm aims to drastically increase labor productivity, guarantee an unprecedented level of safety (Vision Zero), and ensure maximum operational energy efficiency of assets (Clemente de Souza & Debs, 2023). Modern infrastructure facilities are transforming into complex, dynamic energy nodes. The use of sensor systems allows for the collection of Big Data regarding the building's life cycle, which is then analyzed by neural networks for the predictive optimization of resource consumption (Munianday et al., 2024). A prime example is the smart buildings concept, which involves integrating IoT sensors with heating, ventilation, and air conditioning (HVAC) systems. These systems autonomously adapt operational parameters to the physiological needs of occupants, weather conditions, and solar radiation in real time, minimizing energy losses. From the perspective of vocational workforce training, this implies a radical shift in worker skill sets: qualified workers are now required to understand programmable logic controller (PLC) programming, routing protocol architecture, and network integration (Adi Sucipto et al., 2024).

Next-generation frontline workers are expected to interact with "digital twins" of buildings, utilize ruggedized mobile terminals, and wear mixed-reality glasses to read building information models directly at the job site (Clemente de Souza & Debs, 2023). However, the large-scale adoption of innovations is critically hindered by a systemic lack of digital competencies across all levels, underscoring the urgent need to institutionalize a philosophy of lifelong learning (Marinelli, 2023).

Despite technological progress, empirical studies reveal a critical mismatch between employer expectations and the quality of VET graduate training. Engineering companies impose stringent requirements on personnel, expecting specialists to possess fundamental engineering hard skills, an advanced environmental consciousness, and highly developed interpersonal soft skills. In practice, recruiters observe the phenomenon of an education-work transition mismatch (Bhattarai et al., 2025).

Psychometric analysis demonstrates a cognitive bias among graduates: they tend to overestimate their own soft skills while underestimating or displaying measurable incompetence in solving specialized engineering tasks (Bhattarai et al., 2025). Employers record unsatisfactory levels of proficiency in computer-aided design (AutoCAD) and Building Information Modeling (BIM) systems (Bhattarai et al., 2025; Herliand, 2025). A worrying symptom is the presence of gaps in understanding building physics (thermodynamics, dew point migration), which constitutes the immutable foundation for ensuring actual energy efficiency.

When environmental standards and technologies are taught as isolated theoretical disciplines, it catastrophically hinders the formation of a holistic vision among students. A graduate may mechanically know the installation technology for insulation, yet fail to realize that leaving gaps (thermal bridges) will exponentially affect the overall energy balance, leading to heat loss and the formation of toxic mold (Radkevych & Pryhodii, 2024; Svyrydiuk, 2025).

It is crucial to emphasize that the primary burden of implementing green and digital skills falls directly on teachers and vocational instructors. According to the teacher agency mediation model, educators are not merely passive executors of educational policies. They act as key mediators who are forced to navigate complex institutional constraints on a daily basis. The successful integration of innovations faces three systemic barriers: an acute gap between declared policy and actual practice on the ground, a chronic lack of resources alongside obsolete curricula, and insufficient or fragmented collaboration with industry representatives. Furthermore, many vocational instructors objectively lack contemporary practical experience with state-of-the-art technologies, meaning that the success of greening education often relies solely on personal initiative, informal networks, and the unpaid labor of individual enthusiastic educators.

To provide a clear understanding of the scale of the required changes, Table 1 presents a comparison of the training paradigms.

Table 1

Comparative analysis of traditional and innovative vocational training models for future construction professionals

Analysis Parameters of the Educational Model	**Traditional (Inertial) Vocational Training Model**	**Innovative Vocational Training Model (Twin Transition & Construction 4.0)**
Core characteristics of professional skills	Narrowly specialized, strict standardization of mechanical operations	Interdisciplinary, with well-developed critical, spatial, and systems thinking
Environmental component	Fragmented, isolated theoretical subjects without practical reinforcement	Comprehensively (pervasively) integrated, incorporating Life Cycle Assessment (LCA)
Digital toolkit	Absent or limited (reliance on paper-based/2D drawings)	Full immersion: BIM, IoT, AR/VR, cloud data management
Role of the educator	Transmitter of static theory according to a pre-approved plan	Innovative educator, facilitator (moderator) of practical case studies
Understanding of building physics	Superficial, oriented toward the rote memorization of state regulations (building codes)	In-depth (profound), centered on thermodynamic and algorithmic modeling

Compiled by the author based on the sources: Clemente de Souza & Debs, 2023; Munianday et al., 2024; Latif et al., 2024; Kruchek & Subina, 2025; Svyrydiuk, 2025.

Overcoming this gap represents an existential challenge that can only be resolved through the large-scale retraining of teaching staff, their empowerment, and the direct, institutionalized involvement of technology companies in shaping educational standards (Clemente de Souza & Debs, 2023).

To successfully cultivate environmentally responsible specialists, the widespread implementation of energy-efficient pedagogical technologies (EEPT) is imperative. These technologies entail a departure from a passive, transmissive teaching style in favor of interactive, problem-based, and constructivist methodologies that compel students to engage with real-world, multifaceted operational challenges (Drozich, 2025).

Instead of treating ecology as an isolated, tedious theoretical subject, contemporary European educational practice unequivocally demands the implementation of multidisciplinary curricula. These programs must organically and pervasively integrate the principles of sustainable development, systems thinking, and mandatory Life-Cycle Assessment (LCA) of materials and buildings directly into core professional disciplines. Through the LCA methodology, students learn to evaluate the environmental and energy footprint of a structure from raw material extraction to its final disposal (recycling).

Case-based learning serves as a highly effective tool. For instance, students are tasked with developing an energy modernization (retrofitting) plan for a Soviet-era residential building, incorporating renewable energy sources (solar thermal collectors, heat pumps, solar panels), designing ventilated facades, and selecting carbon-negative materials. By analyzing the root causes of heat loss using thermal imaging, students develop analytical thinking and the ability to make engineering decisions based on objective calculations, thereby transforming from blind executors into conscious co-creators of the technological process (Kalamas Hedden et al., 2017; Drozich, 2025).

Cross-level integration is equally vital, exemplified by the "Talent Plan 2+3" model, which combines the applied skills of a worker with the managerial capabilities of an engineer (Farran & Nunez, 2025). Dual-degree tracks are further enhanced by micro-credentials—highly specialized certificates (e.g., in configuring IoT protocols) that facilitate flexible adaptation to rapid labor market dynamics and validate the graduate's contemporary competencies (Farran & Nunez, 2025).

The digitalization of the construction industry and the attainment of energy efficiency are impossible without the implementation of Building Information Modeling (BIM). BIM has evolved into the industry's "gold standard"—a complex digital metamodel that integrates spatial architecture, engineering, economics, and operational schedules into a single cloud-based data environment in real time (DPC, 2018).

The educational focus must shift from tool-oriented training (button-pressing) to developing "project intelligence" within interdisciplinary BIM studios (Shin & Kang, 2026). Students must understand cause-and-effect relationships: how altering a wall's thickness or a building's orientation within a digital model instantaneously impacts heat loss and overall energy efficiency. Even at the conceptual design stage, BIM enables computer-based thermodynamic simulations, solar gain (insolation) optimization, and material carbon footprint assessment (Meterelliyöz & Önder, 2022; Shin & Kang, 2026).

However, the large-scale adoption of BIM is hindered by a deficiency in teachers' digital competencies. To address this, the corporate sector initiates "growing together" strategies (Shojaei et al., 2023), funding training programs for subcontractors and VET institutions. Special attention is dedicated to soft skills—the ability to work collaboratively in a digital team and resolve spatial clashes within a Common Data Environment (CDE) (Adi Sucipto et al., 2024; Shojaei et al., 2023).

The widespread integration of immersive technologies (VR/AR/XR) fundamentally reshapes the neurobiological paradigm of training, facilitating a transition to a profound, fully immersive kinesthetic experience. This is critically important for learning occupational safety regulations and practicing complex motor operations at heights or with hazardous equipment (Patka et al., 2025; Zia Ud Din et al., 2024).

Studies demonstrate the unprecedented efficacy of VR training: the index of positive change in safety behavior is consistently higher by 0.593 points compared to traditional lectures, while in the cultivation of subjective experiential knowledge (experiential outcomes), the difference reaches 0.777 points (Man et al., 2024). The virtual environment allows for the repeated, risk-free, and cost-effective practice of emergency scenarios, building durable muscle memory and automaticity of reflexes. The learning rate for complex material increases fourfold in VR, and the concentration level rises by 400% due to isolation from external distractions (Almeida et al., 2023; Man et al., 2024).

However, the risk of "cybersickness"—a physiological discomfort that frequently affects older workers—must be considered, along with the hazard of cognitive overload. This necessitates the development of ergonomic adaptation programs and specialized metaverses tailored to the specific characteristics of different age groups (Al-Khiami & Jaeger, 2023; Chellappa, 2025).

The transition to a green economy requires a transformation of the material foundations of construction, replacing carbon-intensive materials (clinker cement, steel) with eco-friendly alternatives. These include fly ash, the biocomposite hempcrete, bamboo composites, and geopolymers. Incorporating active mineral admixtures into concrete mixes allows for a significant reduction in cement content, while simultaneously enhancing the ultimate strength and chemical resistance of structures.

Table 2

Ecological and Technological Profile of Innovative Construction Materials

Sustainable Construction Material	Origin / Environmental Impact	Key Properties and Applications in Energy-Efficient Construction
Hempcrete	Renewable biomass / Carbon-negative, biodegradable	High thermal insulation, vapor permeability, moisture regulation (walls)
Fly ash	Industrial byproduct of thermal power plants (TPPs) / Hazardous waste utilization	Active mineral admixture, partial cement replacement, enhanced sulfate resistance
Recycled concrete / plastic	Recycling of construction and demolition waste / Reduction of landfill volumes	Use as a coarse aggregate in non-critical applications (non-structural elements)
Bamboo composites	Rapidly renewable bioresource / Carbon sequestration	High tensile strength, replacement for steel reinforcement (rebar) and lightweight structural elements
Geopolymers	Synthesized aluminosilicate materials / CO2 emissions reduced by 80%	Production of concrete without the use of traditional Portland cement

Compiled by the author based on: Abera, 2024.

Hempcrete is a carbon-negative material that sequesters carbon dioxide (CO_2) during plant growth, providing excellent thermal insulation and natural moisture regulation (Abera, 2024). The incorporation of fly ash and metallurgical slag into concrete mixes enables the effective utilization of industrial waste, thereby enhancing the sulfate resistance and structural strength of components (Abera, 2024). Future professionals must study the Material Sustainability Performance Score (MSPS) to analyze the viability (feasibility) of material utilization throughout the entire life cycle (Hailu, 2025; Latif et al., 2024). Engaging students in the hands-on fabrication (self-construction) of eco-materials from construction and demolition waste serves as an effective pedagogical strategy that dismantles stereotypes and fosters environmental responsibility (Botella et al., 2022).

Beyond materials, the spatial macromodel of assembly (erection) is undergoing a transformation as the industry transitions toward modular, prefabricated construction (Off-Site Construction—OSC) (European Commission, 2025; McKinsey & Company, 2019). Shifting the lion's share of operations to controlled factory environments ensures millimeter-level engineering precision, significantly shortens construction timelines, and minimizes construction dust and waste in urban areas. This modular approach creates ideal conditions for the high-precision integration of green building technologies (GBTs), such as multi-pane (multi-chamber) windows, solar panels, and heat recovery (recuperation) systems (European Commission, 2025; Yun et al., 2026).

Amid the imperatives of Ukraine's large-scale post-war reconstruction—compounded by catastrophic infrastructure damage and an acute demographic crisis—dual education is emerging as a critical instrument for macroeconomic stabilization (Braun & Melnyk, 2023). International donors, most notably the multi-billion-euro Ukraine Facility framework, have set a stringent condition: new infrastructure must be designed in accordance with the "Build Back Better" principle and comply with the strictest EU energy efficiency standards.

Notably, the Ukraine Facility explicitly underscores its role in generating new "green" jobs and the necessity for large-scale investments in skills development (including vocational training) to cultivate a workforce equipped for the twin digital and green transition. Furthermore, the post-war reconstruction process must be highly localized, directly addressing the specific needs of local territorial communities, which serve as the primary beneficiaries and frontline implementers of recovery initiatives on the ground. Experts emphasize that the creation of local green jobs within regions will serve as the most potent socio-economic catalyst for encouraging the repatriation of Ukrainian citizens from abroad. Public engagement and decision-making transparency at the community level constitute the foundational principles of sustainable economic development in the post-war era.

Despite the ongoing war, state investments in Ukraine's educational sector increased by nearly 22% in 2024, targeting the development of modern vocational training (educational-practical) centers (Bilan, 2025). The developed managerial model for integrating dual education views it as a strategic tool for human capital management, designed to rapidly cultivate a loyal talent pool and mitigate labor shortages at construction sites (Bilan, 2025). By combining classroom theory with practical apprenticeships (internships) at state-of-the-art sites, the dual system helps overcome the technological lag of state-run laboratories and ensures the synchronization of skills with industry demands (Bilan, 2025; Marynchenko & Kucher, 2025).

A key system-building role is played by Centers of Vocational Excellence (CoVEs)—local innovation hubs that align the efforts of the state, business, and startups through public-private partnerships (Giunipero, 2025). CoVEs provide access to state-of-the-art infrastructure (industrial 3D printers, laser scanners, and BIM software) and focus heavily on energy-efficient construction and waste management. Graduate certification via VOC-Test Centers guarantees investors that skills and qualifications comply with international standards. To rapidly respond to reconstruction demands in de-occupied regions, mobile training units equipped with portable VR simulators are being effectively deployed; these enable novices to safely practice complex operations under field conditions, thereby minimizing workplace injuries and the wastage of expensive eco-materials (Kruchek & Subina, 2025; Marynchenko & Kucher, 2025).

Conclusions. The multi-criteria systems analysis conducted demonstrates that the effective integration of energy-efficient technologies into the professional practices of construction workers cannot be achieved through superficial modifications to obsolete curricula. The current crisis demands a large-scale paradigm shift that incorporates the challenges of the Construction 4.0 era, the global "Twin Transition" strategy, and the unique specificities of Ukraine's massive post-war reconstruction.

First, the inertial training model must give way to a competency-based approach grounded in multidisciplinarity and systemic Life Cycle Assessment (LCA). However, the success of these transformations depends critically on surmounting the institutional barriers that educators encounter daily. Only by liberating instructors from outdated bureaucratic constraints and equipping them with resources and contemporary practical experience through industry collaboration can energy-efficient pedagogical technologies (EEPT) be effectively implemented (Drozich, 2025; Radkevych & Pryhodii, 2024).

Second, pervasive digitalization must become the cornerstone of education. Shifting toward the development of "project intelligence" through the widespread deployment of BIM studios will supply the industry with a workforce capable of independently optimizing building energy efficiency (Shin & Kang, 2026). This digital transformation must be supported by corporate mentorship programs, micro-credentials, and cutting-edge immersive technologies (VR/AR) that radically accelerate cognitive processes and elevate occupational safety standards (Almeida et al., 2023; Farran & Nunez, 2025; Man et al., 2024; Shojaei et al., 2023).

Ultimately, within the context of Ukraine's Euro-integration modernization, the deployment of dual education and Centers of Vocational Excellence (CoVEs) serves as the primary mechanism for the rapid alignment of education with real economic needs (Bilan, 2025; Braun & Melnyk, 2023). Incorporating the Ukraine Facility framework's philosophy of generating localized "green" jobs at the territorial community level, coupled with the widespread adoption of sustainable biomaterials, will enable the domestic construction sector to achieve a quantum leap. This alignment will facilitate a swift recovery from the post-war demographic crisis and ensure the realization of the "Build Back Better" vision under the most rigorous principles of sustainable development (Abera, 2024; European Commission, 2025).

Conflict of Interest

The author certifies that no conflict of interest (financial, professional, or personal) exists that could have influenced the objectivity of the research results or conclusions. The integrity of the double-blind peer review process was ensured through a mandatory declaration of the absence of conflict of interest submitted via the journal's editorial system. This protocol guaranteed complete author anonymity and the independence of the expert evaluation throughout the entire editorial cycle.

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ЦИФРОВІЗАЦІЯ ТА ЕНЕРГОЕФЕКТИВНІСТЬ У НАВЧАННІ МАЙБУТНІХ БУДІВЕЛЬНИКІВ: ВИКЛИКИ ТА ПЕРСПЕКТИВИ

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Реферат:

Актуальність. Будівельна індустрія, на яку припадає приблизно 39 % глобальних викидів діоксиду вуглецю, опинилася в епіцентрі радикальних змін. Сучасна наука розглядає ці зміни через призму «Подвійного переходу» (Twin Transition) – синергії цифровізації та екологізації. У цьому багатовимірному контексті система професійної (професійно-технічної) освіти постає перед екзистенційним викликом, стикаючись із застарілими навчальними програмами та інституційними бар'єрами, що обмежують агентність викладача. Сучасний ринок потребує робітників, здатних проєктувати та впроваджувати енергоефективні рішення в рамках інноваційної концепції Construction 4.0.

Мета: теоретичне та емпіричне обґрунтування комплексної моделі інтеграції енергоефективних і цифрових технологій у систему професійної підготовки майбутніх фахівців будівельної галузі, а також глибокий аналіз ефективності інноваційних педагогічних стратегій (зокрема імерсивних симуляцій та BIM-технологій) в умовах глобального кліматичного переходу та нагальних потреб повоєнного відновлення інфраструктури України (зокрема програми Ukraine Facility).

Методи: дослідження базується на системному та міждисциплінарному підходах; застосовано методи систематичного огляду за протоколом PRISMA, структурно-функціонального аналізу для оцінки кваліфікаційних розривів на ринку праці, порівняльне педагогічне моделювання для зіставлення традиційної та інноваційної освітніх парадигм, а також метааналіз емпіричних даних щодо ефективності імерсивних віртуальних середовищ.

Результати: доведено наявність критичного кваліфікаційного розриву (education-work transition mismatch) між очікуваннями високотехнологічного ринку та компетенціями випускників; обґрунтовано безальтернативність переходу до освітньої парадигми Education 4.0 через мультидисциплінарний підхід та аналіз життєвого циклу (LCA); статистично підтверджено безпрецедентну ефективність імерсивних технологій (VR/AR) у формуванні безпекової поведінки (пришвидшення засвоєння матеріалу в 4 рази); деталізовано перспективи використання сталих матеріалів; запропоновано інституційні стратегії для повоєнної відбудови України через локалізацію проєктів, створення Центрів професійної досконалості (CoVEs) і розвиток дуальної освіти.

Висновки: ефективне впровадження зелених технологій неможливе шляхом косметичних змін; воно вимагає подолання інституційних бар'єрів та підтримки ініціативи викладачів; лише глибока синергетична інтеграція цифрових двійників, екологічного матеріалознавства та локалізованого державно-приватного партнерства здатна забезпечити індустрію кадрами для реалізації концепції «Build Back Better».

Ключові слова: *Construction 4.0, енергоефективність, інформаційне моделювання будівель, подвійний перехід, імерсивне навчання, зелене будівництво, дуальна форма здобуття освіти.*

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