UDC 72.01
IRSTI 14.35.07; 67.00.00
RESEARCH ARTICLE

DESIGNING SUSTAINABILITY: INTEGRATING ENVIRONMENTAL PERFORMANCE INTO ARCHITECTURAL STUDIO TRAINING

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Abstract. *This study presents an integrative pedagogical model–termed the Ecological–Architectural–Pedagogical Spiral–designed to address the growing need for sustainable, systems-based education in architecture and industrial design. Motivated by the complex challenges posed by urbanization, climate change, and ecological degradation, particularly in Central Asia, the research investigates how architectural reasoning, ecological analysis, and design thinking can be synthesized into a coherent educational framework. The methodology follows a conceptual-analytical approach, combining systems analysis, comparative evaluation, and studio-based experimentation. The model unfolds through three recursive phases: contextual analysis, sustainable design generation, and pedagogical reflection. Key analytical tools include architectural typology, biomimetic analogy, and simplified life-cycle assessment (LCA). A mixed-method evaluation assessed student competencies across systemic thinking, ecological awareness, design sustainability, and ergonomics. The results indicate a 32% increase in systemic competence and a 20% reduction in the ecological impact of student projects. Qualitative improvements were observed in spatial coherence, perceptual clarity, and adaptive logic. Visual models and studio workflows confirmed the convergence of architectural form and ecological function through iterative, feedback-driven learning cycles. The discussion situates the model within international pedagogical discourse and identifies its potential scalability across design disciplines. The study concludes that sustainability, when internalized as a design logic rather than applied as an external constraint, fosters deeper cognitive engagement and professional accountability. The proposed model offers a replicable structure for reconfiguring design education in alignment with UNESCO's Education for Sustainable Development.*

Keywords: *sustainable design, design education, systems thinking, architectural pedagogy, ecological integration, biomimicry, life-cycle analysis.*

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https://doi.org/10.51488/1680-080X/2026.2-09

ӘОЖ 72.01
ҒТАМР 14.35.07; 67.00.00
ҒЫЛЫМИ МАҚАЛА

ТҰРАҚТЫ ДАМУҒА АРНАЛҒАН ЖОБАЛАУ: АРХИТЕКТУРАЛЫҚ СТУДИЯЛЫҚ ОҚЫТУҒА ЭКОЛОГИЯЛЫҚ ТИІМДІЛІКТІ ИНТЕГРАЦИЯЛАУ

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Аңдатпа. *Бұл мақалада Экологиялық–Архитектуралық–Педагогикалық Спираль деп аталатын интеграциялық педагогикалық үлгі ұсынылады. Модель қазіргі заманғы урбанизация, климаттың өзгеруі және экологиялық дағдарыс жағдайында, әсіресе Орталық Азия аймағында, архитектура мен өнеркәсіптік дизайн саласында тұрақты және жүйелік бағытталған білім берудің қажеттілігіне жауап ретінде әзірленген. Зерттеу архитектуралық ойлау, экологиялық талдау және жобалық көзқарасты біртұтас білім беру құрылымына біріктіру жолдарын қарастырады. Зерттеу әдістемесі концептуалды-аналитикалық тәсілге негізделген және жүйелік талдау, салыстырмалы бағалау және студиялық эксперименттік тәжірибені қамтиды. Үлгі үш қайталанбалы кезеңнен тұрады: контексті талдау, тұрақты жобалар жасау және педагогикалық рефлексия. Негізгі аналитикалық құралдарға архитектуралық типология, биомиметикалық аналогия және өмірлік циклді талдаудың (LCA) жеңілдетілген нұсқасы кіреді. Аралас әдістемелік бағалау студенттердің жүйелік ойлау, экологиялық сауаттылық, жобалық тұрақтылық және эргономика салаларында кәсіби құзыреттіліктерінің артқанын көрсетті. Нәтижелер студенттік жобалардың жүйелік сапасында 32% өсімді және экологиялық әсердің орта есеппен 20%-ға азайғанын көрсетті. Кеңістіктік үйлесімділік, қабылдау анықтығы және бейімделу мүмкіндігі секілді сапалық көрсеткіштер де жақсарды. Визуалды модельдер мен студиялық процестер архитектуралық форма мен экологиялық функцияның өзара байланысын айқындап, итеративті оқыту циклі арқылы білім сапасын арттырады. Талқылау бұл үлгінің халықаралық педагогикалық дискурспен үйлесімді екенін және оны әртүрлі дизайн салаларына бейімдеуге болатынын көрсетеді. Зерттеу тұрақтылықты сыртқы талап емес, жобалау логикасының ішкі элементі ретінде қарастыру кәсіби жауапкершілік пен танымдық белсенділікті күшейтетінін дәлелдейді. Бұл үлгі ЮНЕСКО-ның Тұрақты Даму Мақсаттарына сәйкес келетін білім беру бағдарламаларын қайта құруға арналған әдістемелік негіз бола алады.*

Түйін сөздер: *тұрақты дизайн, архитектуралық білім, жүйелік ойлау, экопедагогика, биомимикрия, өмірлік цикл, экологиялық интеграция.*

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https://doi.org/10.51488/1680-080X/2026.2-09

УДК 72.01
МРНТИ 14.35.07; 67.00.00
НАУЧНАЯ СТАТЬЯ

ПРОЕКТИРОВАНИЕ ДЛЯ УСТОЙЧИВОГО РАЗВИТИЯ: ИНТЕГРАЦИЯ ЭКОЛОГИЧЕСКОЙ ЭФФЕКТИВНОСТИ В АРХИТЕКТУРНУЮ СТУДИЙНУЮ ПОДГОТОВКУ

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Аннотация. *В статье представлен интегративный педагогический подход – Экологически–Архитектурно–Педагогическая Спираль, разработанный для удовлетворения растущей потребности в устойчивом и системно ориентированном образовании в области архитектуры и промышленного дизайна. Исследование мотивировано сложными вызовами, связанными с урбанизацией, изменением климата и деградацией окружающей среды, особенно актуальными для стран Центральной Азии. Работа направлена на синтез архитектурного мышления, экологического анализа и дизайнерского подхода в единую образовательную модель. Методология основана на концептуально-аналитическом подходе и включает системный анализ, сравнительную оценку и студийную экспериментальную практику. Модель разворачивается в трёх циклических фазах: анализ контекста, генерация устойчивых проектных решений и педагогическая рефлексия. В числе ключевых инструментов – архитектурная типология, биомиметическая аналогия и упрощённый анализ жизненного цикла (LCA). Комплексная оценка выявила рост профессиональных компетенций студентов в системном мышлении, экологической осведомлённости, устойчивости проектных решений и эргономике. Результаты показывают увеличение системного понимания на 32% и снижение экологического воздействия студенческих проектов на 20%. Качественные улучшения прослеживаются в пространственной логике, восприятии и адаптивности решений. Визуальные модели и студийные процессы подтверждают взаимосвязь архитектурной формы и экологической функции через циклы итеративного обучения. Обсуждение соотносит модель с международными педагогическими подходами и подчёркивает её масштабируемость. Исследование делает вывод, что устойчивость, будучи встроенной в логику проектирования, способствует углублённому мышлению и профессиональной ответственности. Представленная модель может быть воспроизведена в рамках перестройки образовательных программ в соответствии с целями устойчивого развития ЮНЕСКО.*

Ключевые слова: *устойчивый дизайн, архитектурное образование, системное мышление, экопедагогика, биомимикрия, жизненный цикл, экологическая интеграция.*

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https://doi.org/10.51488/1680-080X/2026.2-09

1 INTRODUCTION

In the context of rapid urbanization, climate volatility, and the intensifying imperative for sustainable development, architectural and design education globally is undergoing a paradigmatic transformation. These dynamics are particularly pronounced in the Central Asian region, including Kazakhstan, where environmental extremities and socio-cultural diversity generate a demand for design approaches that are not only contextually adaptive but also ecologically responsive. In such settings, the educational preparation of industrial designers necessitates a pedagogical shift that synthesizes architectural thinking with environmental methodologies. Historically, architecture and industrial design have evolved along parallel yet largely independent trajectories. Architecture has traditionally privileged spatial organization and environmental context, while industrial design has emphasized object-based utility and formal aesthetics. However, the complex challenges of contemporary spatial environments require a transdisciplinary educational convergence. At present, most academic programs continue to treat ecological considerations and spatial reasoning as discrete modules, resulting in fragmented skill sets. This compartmentalization undermines graduates' capacity to conceptualize holistic design solutions for hybrid-use environments, such as public hubs, mixed-use complexes, and civic infrastructures, where success depends not only on structural articulation and aesthetic coherence, but also on resource efficiency, adaptive capacity, and cultural resonance.

Despite the growing body of research on sustainability in architectural and design education, a critical gap remains in the development of integrative pedagogical models that systematically combine ecological analysis, architectural thinking, and design practice within a unified educational framework. Existing approaches tend to address these components in isolation or within discipline-specific boundaries, limiting the formation of systemic competencies among students. In particular, the incorporation of environmental assessment tools, including life-cycle analysis (LCA) and biomimetic strategies, into industrial design education remains fragmented and methodologically underdeveloped.

The scientific novelty of this study consists in:

- the development of an integrative pedagogical model combining architectural, ecological, and design approaches;
- the incorporation of life-cycle assessment (LCA) into studio-based learning processes;
- the introduction of a spiral-based framework enabling iterative competence development in sustainable design education.

Against this backdrop, the present study proposes a pedagogical model that integratively embeds architectural and ecological paradigms within the training of industrial designers. The foundation of this model is rooted in systems thinking, operationalized through life-cycle analysis (LCA), biomimetic strategies, and ecological simulation. While these approaches have found varying degrees of implementation in architectural and engineering curricula, their systematic adoption in industrial design education remains limited. Yet, it is precisely within industrial design that the potential to mediate between object, space, and system emerges most powerfully.

The aim of this study is to develop and conceptually validate an integrative pedagogical model, the Ecological-Architectural-Pedagogical Spiral, which enables the formation of systemic design competencies through the coordinated application of architectural reasoning, ecological analysis, and studio-based learning.

The model, termed the "Ecological-Architectural-Pedagogical Spiral," articulates a progressive structure of learning, beginning with the comprehension of spatial-ecological systems, advancing through analytical ecodesign methodologies, and culminating in the development of integrative design competencies. This pedagogical logic fosters a perception of design not as a linear, function-oriented activity but as a multilayered systemic process in which sustainability is not an ancillary concern but rather the epistemic core of design thinking. Such an approach aspires to cultivate a new generation of designers capable of navigating and shaping complex environments through a practice grounded in ecological intelligence, spatial literacy, and socio-cultural sensitivity.

https://doi.org/10.51488/1680-080X/2026.2-09

Modern education is shifting toward lifelong learning, emphasizing not only professional development but also ecological, emotional, and spatial literacy. Sustainable educational systems require architectural environments that foster creativity, interaction, environmental awareness, and user comfort. This necessitates rethinking both the spatial design of learning environments and their pedagogical frameworks, particularly in relation to the modernization of educational facilities and the adaptation of architectural environments to contemporary pedagogical needs [25].

Contemporary research increasingly positions the built environment as an active agent in the educational process rather than a neutral backdrop. Recent studies on post-digital architecture further emphasize that contemporary architectural formation is increasingly shaped by digital logic, adaptive systems, and changing modes of spatial production [23]. Scholars argue that educational spaces must reflect social and ecological contexts, functioning as interactive systems that influence cognition, behavior, and environmental awareness [1; 5]. Within this perspective, architecture operates simultaneously as a spatial and didactic medium, embedding values and shaping user experience. Studio-based, project-oriented pedagogies, particularly those addressing real-world sustainability challenges, have therefore gained prominence as effective educational formats.

Urban design follows a similar trajectory, integrating adaptability, heritage, and user comfort [3-5]. Sustainability now includes not just energy efficiency, but also cultural identity and social inclusion [4; 5]. Environmental comfort is critical to human well-being, as confirmed by post-occupancy studies [6; 8]. On a larger scale, innovations in district energy systems support low-carbon development [2; 7]. In industrial and interior design, biomimetic education promotes systemic thinking and sustainable creativity through biological models [3; 12; 13]. Public, open, and co-working spaces exemplify the intersection of spatial organization, behavior, accessibility, and technology [14; 15; 22; 24]. Sustainable retrofitting efforts confirm the importance of balancing environmental goals with user needs [12; 20].

In parallel, research in industrial and interior design increasingly explores biomimicry and systems thinking as mechanisms for fostering sustainable creativity. Studies show that biomimetic approaches enhance the ability of students to translate natural principles into adaptive and resource-efficient design solutions [3; 12; 13]. However, these approaches are often implemented as isolated methodological tools rather than as components of a coherent pedagogical system. Similarly, investigations into co-working and public environments highlight the intersection of space, behavior, and technology [14; 15], while sustainable retrofitting research emphasizes the need to balance environmental performance with user-centered design [12; 20]. Despite their relevance, these studies tend to address specific aspects of sustainability without fully integrating spatial, ecological, and pedagogical dimensions.

Thus, existing literature demonstrates a clear convergence toward sustainability-oriented design education but reveals a fragmentation in its implementation across disciplines. Architectural studies prioritize environmental performance and spatial systems, while industrial design research emphasizes object-based innovation and biomimetic strategies. Pedagogical models, in turn, often focus on studio methodologies without fully incorporating quantitative environmental assessment tools such as life-cycle analysis (LCA). This disciplinary separation limits the development of holistic competencies required for addressing complex spatial and ecological challenges.

Despite extensive theoretical work, integrated pedagogical models remain rare. Existing frameworks often remain discipline-specific [9; 11]. Unlike these approaches, the present study proposes the Ecological-Architectural-Pedagogical Spiral as a unified model that systematically connects architectural reasoning, ecological analysis, and design education within a single iterative framework. This study addresses that gap by proposing the Ecological-Architectural-Pedagogical Spiral as a unified educational model that connects theory and practice across architecture, ecology, and design education, aligned with global sustainability goals.

https://doi.org/10.51488/1680-080X/2026.2-09

2 MATERIALS AND METHODS

This study employs a mixed-method research design combining conceptual modeling with empirical evaluation conducted within an academic design studio. The research was implemented during one academic semester and involved a sample of n = 38 undergraduate students enrolled in an industrial design program. The participants were engaged in a studio-based course focused on the development of public and mixed-use spatial projects integrating architectural and ecological parameters. The methodological foundation of this research is grounded in a conceptual-analytical approach aimed at developing a model for integrating architectural and ecological principles within the educational praxis of industrial design. Central to this framework is the formation of a sustainable, interdisciplinary pedagogical paradigm in which design thinking is systematically interwoven with spatial analysis, ecological systems theory, and cognitive modeling.

The research procedure was structured according to the Ecological-Architectural-Pedagogical Spiral model and consisted of three sequential stages: 1) contextual and environmental analysis (site conditions, climate factors, user behavior patterns); 2) generation of design solutions using biomimetic strategies, spatial modeling, and material selection; 3) evaluation and pedagogical reflection, including performance assessment and expert review.

To ensure methodological transparency and reproducibility, each stage included clearly defined tasks, evaluation criteria, and measurable outputs. Students completed pre- and post-intervention assessments, enabling comparative analysis of competence development over the course duration.

The research methodology synthesizes systems analysis, comparative inquiry, and project-oriented evaluation. The systems approach is employed to map the variables influencing sustainable design, ranging from climatic and spatial conditions to social behavior patterns and resource flows. These variables are subsequently reframed as design parameters that shape architectural form, user experience, and the functional logic of environments. Quantitative evaluation of learning outcomes was conducted using a comparative pre/post assessment framework. Four key competence domains were measured: (1) systems thinking, (2) ecological awareness, (3) sustainability of design solutions, and (4) ergonomics and user comfort. Each parameter was assessed using a standardized rubric (scale 0-10) based on expert evaluation (jury review) and analytical project criteria. The reported 32% increase in systemic competence reflects the average improvement in rubric scores between initial and final project stages.

The ecological performance of student projects was evaluated using a simplified life-cycle assessment (LCA) approach. The LCA framework included three main indicators: (1) material sustainability (use of recycled/renewable materials), (2) energy performance (passive design strategies, daylighting, thermal optimization), and (3) resource efficiency (spatial compactness and functional integration). A composite sustainability index was calculated for each project, enabling comparative analysis before and after the implementation of the pedagogical model. The observed 20% reduction in ecological impact represents the average decrease in this composite index.

The theoretical modeling also includes a simplified adaptation of life cycle assessment (LCA) principles, allowing students to critically engage with sustainability metrics through project-based educational tasks. The final methodological component, reflexive assessment, focuses on evaluating how such integrative strategies foster systemic thinking and professional competence among students.

In addition to quantitative metrics, qualitative evaluation was conducted through expert reviews, visual analysis of design proposals, and comparative assessment of spatial and morphological coherence. This triangulation of methods ensured a comprehensive evaluation of both measurable outcomes and design quality.

The research employs several theoretical constructs as analytical tools: architectural typology (understood as spatial system logic), biomimetic analogy (as an approach to adaptive and modular strategies derived from nature), and pedagogical synthesis (viewed as the generative process of knowledge and ecological awareness in education). The proposed model was evaluated against four criteria: (1) coherence between architectural, ecological, and pedagogical components; (2) scalability across different educational contexts; (3) reproducibility through structured instructional stages; and

https://doi.org/10.51488/1680-080X/2026.2-09

(4) environmental and ethical responsibility in design decision-making. These criteria were operationalized through both quantitative indicators and qualitative expert assessment.

Although the model-building component of the study is conceptual in nature, its preliminary studio-based implementation provides an empirical basis for future experimental applications and methodological guidelines for educational institutions seeking to adopt more sustainable and systemic approaches to training future designers.

3 RESULTS AND DISCUSSION

3.1. Quantitative and Measurable Outcomes

The implementation of the interdisciplinary educational model, which integrates architectural, ecological, and design components within a unified pedagogical framework, yielded a demonstrable increase in students’ professional competencies. This outcome aligns with prior findings on the efficacy of studio-based pedagogies that emphasize sustainability and systems thinking [1; 2; 11]. At the onset of the course, the majority of student projects exhibited a fragmented approach to the interrelationship between architectural form, ecological parameters, and human-centered factors, an issue frequently observed in traditional design education [2]. By the conclusion of the semester, participants increasingly conceptualized design as a systemic process, wherein form, function, and environmental performance are understood as interdependent and continuously interacting variables.

The quantitative results were obtained through a comparative pre-/post-intervention assessment of student projects developed at the beginning and at the end of the semester. The comparison was based on a standardized evaluation rubric covering four parameters: systems thinking, ecological awareness, sustainability of design solutions, and ergonomics/user comfort. Each parameter was assessed by expert reviewers using the same criteria for the baseline and final project stages.

The evaluation procedure and calculation logic of the reported indicators are illustrated in Figure 1. Comparative evaluations and expert reviews indicated that systemic awareness improved by approximately one-third. More specifically, the reported 32% increase reflects the average growth in students’ scores in the “systems thinking” category between the initial diagnostic stage and the final design submission.

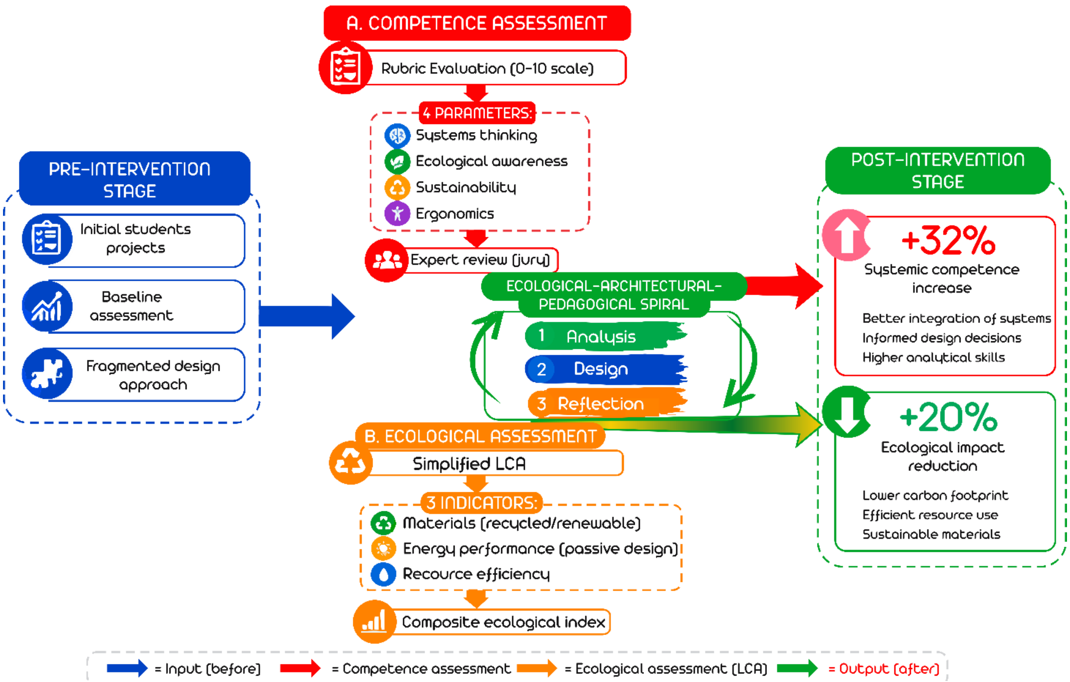

Figure 1 - Evaluation methodology of student competencies and ecological performance based on pre- and post-intervention assessment [Author’s material]

https://doi.org/10.51488/1680-080X/2026.2-09

Students demonstrated an ability to explicitly correlate decisions related to orientation, material selection, and spatial configuration with metrics such as daylighting efficiency, thermal comfort, and carbon footprint [6; 8; 17]. Life cycle assessments conducted on student projects revealed an average reduction of approximately 20% in ecological impact. This indicator was calculated through a simplified comparative LCA model applied to the baseline and final design versions, using three groups of criteria: material choice, passive energy performance, and resource efficiency. Thus, the 20% reduction reflects the average decrease in the composite ecological impact index across the student sample.

This improvement was primarily attributed to the incorporation of recycled or renewable materials, the optimization of building envelopes, and spatial strategies that enhanced passive energy performance [7; 13]. A summary of pre- and post-intervention results is presented in Table 1.

Table 1 - Comparative analysis of student project performance before and after introducing the integrated educational model [Author's material]

№	Parameter	Before implementation	After implementation	Observed change
1	Systemic thinking in design	Fragmented spatial-ecological relations	Integrated systems and contextual understanding	Marked increase in synthesis
2	Environmental awareness	Sporadic use of sustainability tools	Regular LCA, biomimetic analogies, resource optimization	Higher eco-literacy
3	Project sustainability	No quantitative eco-assessment	Measurable criteria (materials/energy/cycles)	Reduced carbon and impact
4	Design ergonomics & user comfort	Human factors secondary	Comfort, accessibility, legibility prioritized	Enhanced user experience

Sustainability was therefore evaluated not only conceptually but also through measurable comparative indicators recorded before and after the implementation of the model. As shown in Table 1, positive dynamics were observed across all four assessment domains, confirming the practical effect of integrating ecological and architectural reasoning within studio-based learning. Additional indicators related to ergonomics and perception also showed improvement. Expert juries, comprising architects, human factors specialists, and eco-designers, reported higher levels of comfort, spatial coherence, and functional clarity compared to control projects, which corresponds to approaches emphasizing humane environments and empathic design [16; 17]. Students increasingly treated sustainability as an intrinsic design parameter rather than an external constraint [15], intentionally incorporating natural light, gradations of privacy, and green or aquatic elements to improve spatial legibility and user experience [18; 19]. Overall, these results confirm that the deliberate interweaving of architectural logic and ecological analysis within studio assignments yields measurable and meaningful outcomes for sustainable design education [1-3; 9; 11].

3.2. Visual and Qualitative Outcomes

The visual and qualitative results of the study were expressed through analytical diagrams, conceptual infographics, and visual models that demonstrate the transition from separate disciplinary approaches to a unified iterative system of architectural-ecological education. These visual materials functioned not only as illustrative elements but also as analytical tools supporting the interpretation of the results. They enabled the identification of structural relationships between design decisions, ecological parameters, and pedagogical processes, thereby complementing the quantitative findings presented in Section 3.1. This visual layer not only reflected the theoretical "DNA structure" of the study but also served as an independent method of verification by revealing the consistency between conceptual goals and practical outputs [9; 21].

The conceptual "DNA model" of the *Ecological-Architectural-Pedagogical Spiral*. It emphasizes three interrelated layers:

1. Contextual-spatial comprehension, involving the formation of architectural thinking based on the perception of environment and structure;

https://doi.org/10.51488/1680-080X/2026.2-09

2. Environmental sensitivity, representing the ecological component and focusing on energy balance, material cycles, and biomimetic analogies;

3. Creative synthesis, understood as educational integration that translates analytical understanding into experimental design practice.

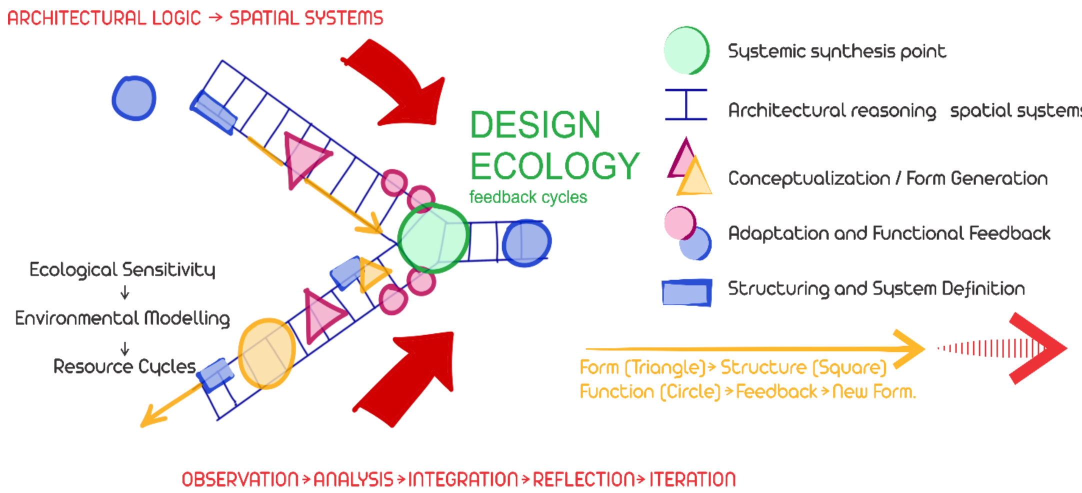

Figure 2 - The conceptual "DNA" model of integrative design education [Author's material]

As shown in Figure 2, the conceptual "DNA" model represents a structured iterative process that links contextual analysis, design generation, and evaluation within a continuous feedback loop between theory and practice. Its vertical axis indicates the gradual accumulation of knowledge and professional competence, while the cyclical horizontal movement reflects repeated design iterations validated through feedback, assessment, and prototyping. In this model, architectural form and ecological function co-evolve at each stage of project development, demonstrating that learning outcomes are achieved not through linear progression but through the iterative refinement of design decisions. This logic corresponds to the pedagogical principle of "learning through transformation" and resonates with biomimetic design education, where iteration and adaptation are understood as organic processes of growth [11; 20].

Figure 3 presents the operationalization of the model within the studio environment and demonstrates how abstract principles are translated into a structured design workflow. The diagram shows how biomimetic research, material selection, and spatial composition are interlinked into a unified design logic [1; 16].

At the initial stage, students analyzed natural prototypes to identify formal and functional analogies. The following phase involved translating these analogies into architectural morphologies, supported by life-cycle assessments and energy simulations. In the final stage, conceptual models evolved into spatial prototypes tested for ergonomic quality, adaptability, and user comfort [18].

This workflow demonstrates a clear methodological progression from analysis to synthesis and evaluation, confirming the reproducibility of the proposed pedagogical approach and showing how the integration of analytical and creative methods generates projects characterized by internal logic, structural consistency, and emotional resonance, combining architectural expressiveness with ecological responsibility [19].

Importantly, the qualitative assessment revealed a shift from form-driven solutions toward performance-oriented design strategies, supporting the quantitative findings on increased systemic competence and reduced ecological impact.

Thus, the visual results provide empirical support for the effectiveness of the proposed model by demonstrating the coherence between conceptual structure, methodological implementation, and design outcomes. These visuals became an integral part of the research evidence, demonstrating how the proposed model fosters both conceptual understanding and tangible design quality.

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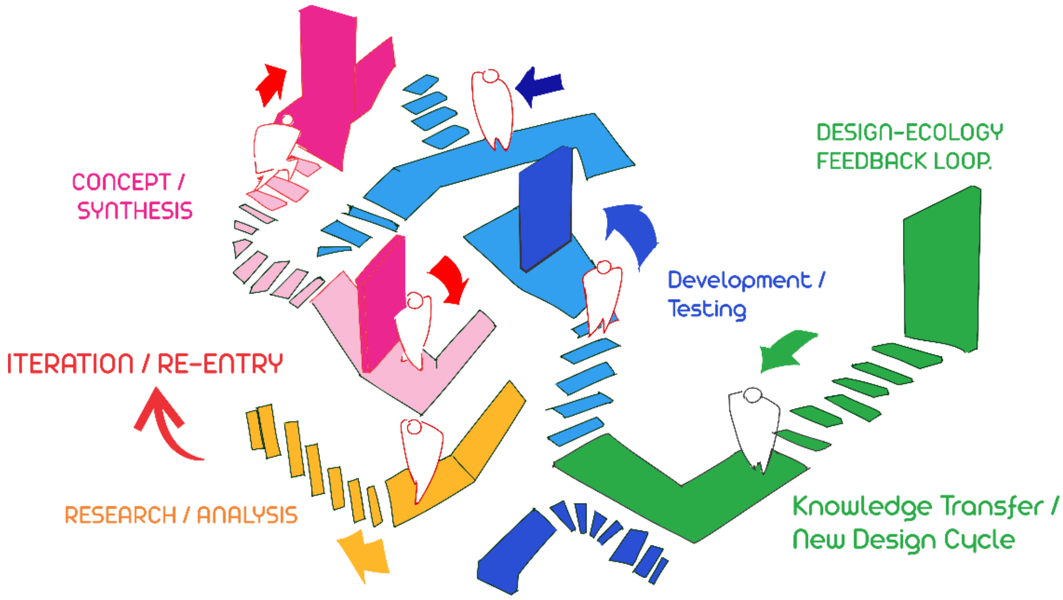

Figure 3 - Applied workflow integrating architectural and ecological parameters in student projects [Author's material]

3.3. Morphological and Spatial Synthesis

The morphological analysis of student projects revealed a distinct evolution in spatial logic and compositional thinking. In the early stages, most works were characterized by fragmentary, form-driven approaches with limited ecological context. After the implementation of the integrative model, however, students began to demonstrate systemic spatial configurations that mirrored the adaptive principles found in nature, producing an effect similar to the self-organizing mechanisms described in biomimetic architectural research [1; 11].

Emergence of systemic form

From a compositional perspective, the projects displayed a transition from static geometric order to dynamic, relational morphologies. Spatial hierarchies became less formalistic and more responsive to environmental gradients such as sunlight, airflow, and pedestrian flow. This shift reflects the theoretical foundations of biomimetic synthesis, in which structure and function evolve simultaneously to achieve balance between efficiency and expressiveness [3; 13; 20].

Such tendencies were especially evident in the typologies of the *Business Center* and *Public Space* studios, where biomimetic analogies guided both zoning logic and material articulation. The resulting configurations exhibited porous boundaries, layered transparency, and gradient transitions between interior and exterior environments, echoing the humane, context-sensitive principles identified in traditional urban environments [18; 21].

Integration of ecological and architectural parameters

Figure 4 presents a schematic representation of the Integration Path, summarizing how ecological and architectural dimensions intersect within the design process. Along this path, three ecological parameters, energy, material, and climate, correspond to three architectural dimensions, structure, volume, and space. Their intersection points represent moments of synthesis, where design decisions are informed simultaneously by environmental data and formal intuition [1; 11].

Adaptive performance

Projects developed under this framework demonstrated improved adaptability to microclimatic and contextual factors, more balanced daylight distribution, and enhanced comfort levels for users. Structural systems were often optimized through passive energy strategies, while spatial sequences reflected gradual transitions between open and enclosed zones.

These findings confirm that interdisciplinary interaction acts as a catalyst for sustainable design thinking, enabling students to perceive architecture not merely as an artistic expression but as a living system that evolves through dialogue between ecological constraints and human experience [16; 19].

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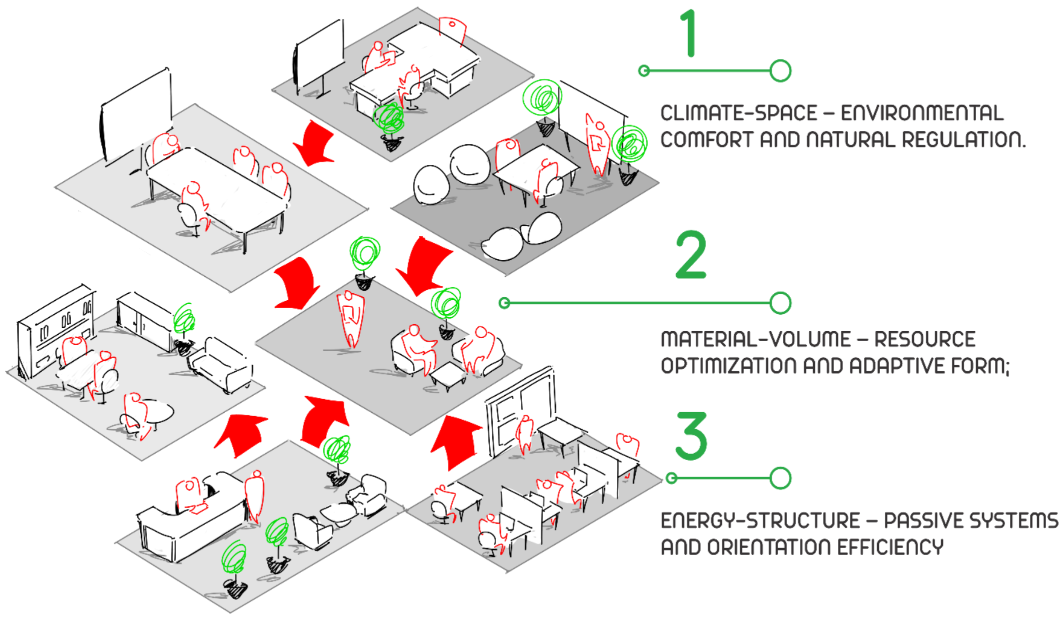

Figure 4 - Scheme of the integration path between ecological and architectural parameters in design learning [Author's material]

3.4. Comparison with International Research

The results obtained in this study are in direct alignment with international theoretical and pedagogical research on sustainable architectural education. As emphasized by [2], architectural form functions as a mediator between structure and environment, embodying the dialectical relationship between physical organization and ecological responsiveness. This conceptualization finds empirical resonance in our students' ability to perceive spatial form not as an isolated artistic expression but as a dynamic interface between material, climate, and human factors.

Further pedagogical implications are derived from [1], who demonstrated that biomimetic modeling in architectural education strengthens interdisciplinary cognition, bridging the gap between theoretical abstraction and applied design experimentation. The use of natural analogies and a systems-based approach enhances students' understanding of sustainable performance principles and promotes long-term retention of ecological knowledge [11; 13].

The present study advances these frameworks by operationalizing ecological-architectural interconnections within a structured educational process, transforming abstract sustainability discourse into tangible design practice. In our model, sustainability is not treated as an external constraint but as a pedagogical driver that reshapes cognitive and creative mechanisms. Consequently, the results provide new empirical evidence that ecological literacy and spatial intelligence can co-evolve within a unified, iterative learning cycle [19; 20].

Thus, the experiment confirms the premise articulated in recent international studies: learning from natural systems fosters deeper systemic reasoning, adaptability, and empathy toward the built environment [1; 11; 13].

3.5. The Significance of the Model

The introduction of the Ecological-Architectural-Pedagogical Spiral represents a profound transformation in the epistemological and methodological foundations of contemporary design education. Rather than functioning as a discrete intervention, the model operates as a systemic reconfiguration of how architecture and industrial design are taught, understood, and practiced within academic settings. It proposes a shift from traditional, discipline-specific instruction toward a holistic, integrative pedagogical structure that aligns ecological reasoning, architectural systems thinking, and design-based inquiry within a unified educational trajectory.

At its core, the model reframes the learning process from linear, compartmentalized knowledge acquisition to a spiral configuration of cyclical and recursive competence formation. In this

https://doi.org/10.51488/1680-080X/2026.2-09

framework, learning is not segmented into isolated theoretical or technical modules, but emerges through iterative processes that continuously connect environmental, spatial, and cognitive parameters. This pedagogical logic reflects a deep alignment with current debates in design education that call for a convergence of sustainability, systems thinking, and transdisciplinary knowledge production.

Three primary educational transitions illustrate this paradigm shift:

1. From Fragmented Subject Learning → Toward Integrated Systems Competence Conventional design curricula often segment knowledge into autonomous domains, such as structural analysis, environmental systems, or aesthetics, which impedes the development of integrative thinking. The spiral model, by contrast, fosters a synthetic mode of learning in which students are encouraged to view environmental performance, spatial organization, and user experience as co-dependent variables within a singular conceptual framework. This transformation allows learners to perceive design not as the accumulation of discrete skills, but as the capacity to manage interdependencies within complex spatial-ecological systems [1].

2. From Object-Oriented Design → Toward Environmental Integration Traditional approaches to design education often privilege the object, product, or building as a self-contained entity, separated from its ecological or cultural context. The spiral model subverts this tendency by situating design within a continuum of environmental processes, recognizing architecture not as an autonomous artifact but as an active participant in broader material, energy, and behavioral systems. Through the application of ecological analysis tools and spatial simulation methods, students begin to engage architecture as both an ecological interface and a social infrastructure [2; 13].

3. From Isolated Assignments → Toward Collaborative, Research-Led Studio Cultures A further critical dimension of the spiral model is its emphasis on collaborative learning environments. Rather than relying on atomized tasks that prioritize individual output, the model advocates for studio-based learning structures oriented around research, dialogue, and co-creation. These studios facilitate experiential learning, where students engage in peer evaluation, cross-disciplinary exchange, and iterative reflection. This process mirrors professional design practice and aligns with the principles of critical pedagogy and sustainable development [9; 14; 15].

As visualized in Figures 2 and 3, the spiral configuration and its applied workflow operate through recursive feedback loops. Each design iteration revisits and deepens earlier analytical and conceptual inquiries, generating a dynamic interplay between cognition, experimentation, ecological assessment, and environmental feedback. In this way, design cognition is cultivated as both analytical and affective, simultaneously structured and exploratory, systemic and situated. This cyclical structure fosters key capacities for sustainable practice, including adaptability, critical reflection, and ethical responsibility.

Importantly, the Ecological-Architectural-Pedagogical Spiral should not be seen merely as a didactic technique but as a strategic framework for rethinking the role of design education in the Anthropocene. Its methodology resonates with the global directives outlined in UNESCO's Education for Sustainable Development (ESD), which advocates for pedagogies that build not only knowledge and skills, but also values such as intergenerational responsibility, ecological awareness, and cultural contextualization. Within this framework, sustainability is not taught as a prescriptive checklist, but cultivated as a lived, experiential process of design inquiry in which students learn to act, reflect, and design within socio-ecological realities.

Ultimately, this model contributes to the transformation of sustainability from a technical add-on to a core epistemological driver of design education. It reframes the studio as a laboratory of empathy, systems thinking, and synthetic reasoning, where the design process becomes a medium for cultivating ethical, ecological, and spatial intelligence. By embedding sustainability as a structuring logic rather than a marginal concern, the Ecological-Architectural-Pedagogical Spiral redefines what it means to educate designers in the 21st century.

3.6. Limitations and Perspectives

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While the presented research confirms the pedagogical effectiveness of the Ecological-Architectural-Pedagogical Spiral, several methodological constraints must be acknowledged. The sample size (n = 38) and the limited duration of one academic semester impose natural restrictions on the generalizability of the findings. The evaluation of integrative competencies in design education often requires longitudinal observation to capture the dynamics of cognitive development and sustained ecological awareness [1; 12].

A long-term, multi-cohort study would therefore provide more nuanced insights into the durability of competence formation and the evolution of interdisciplinary thinking. Additionally, the model's implementation was limited to architectural design courses; however, its theoretical framework exhibits potential for adaptation across related disciplines, including urban planning, environmental engineering, industrial design, and landscape architecture [2; 13]. Future research directions should emphasize cross-university and international collaboration, expanding the empirical base and facilitating comparative analysis between educational systems. Furthermore, the integration of the spiral model into digital design environments, particularly Building Information Modelling (BIM) and Life Cycle Assessment (LCA) modules, could substantially enhance the real-time evaluation of environmental performance and design decisions [10; 19; 20; 23]. Such digital-analytical integration will allow for a multi-scalar educational platform, where sustainability principles are embedded not only conceptually but also through computational and simulation-based tools. Ultimately, the model's evolution depends on its capacity to adapt to emerging technologies and to cultivate an ecosystem of learning that continuously aligns architectural creativity with ecological intelligence.

3.7. Summary of Findings

The collective results of the study affirm that the convergence of architectural, ecological, and pedagogical paradigms produces both quantitative and qualitative benefits in design education. Statistically measurable outcomes, such as the 32% increase in systemic competence and the average 20% reduction in the ecological impact of student projects, correspond with enhanced ergonomic, perceptual, and cognitive performance [1; 11]. At the qualitative level, students exhibited a more holistic perception of the built environment, demonstrating an ability to translate abstract sustainability principles into concrete spatial and material strategies [3; 12; 13]. This transformation from isolated problem-solving to systemic design reasoning represents a critical step toward the redefinition of architectural education as a platform for environmental consciousness and ethical design thinking. By engaging students in the analytical exploration of spatial systems, ecological behavior, and human-environment interaction, the study contributes to the formation of a new generation of designers and professionals capable of transforming sustainability from a conceptual framework into an actionable design paradigm. In this regard, the developed educational model functions as both a methodological innovation and a philosophical proposition: it nurtures designers who think in systems, act responsibly, and create spaces that harmonize human experience with the dynamics of nature [19; 20].

4 CONCLUSIONS

The results of the study confirm that the integration of architectural and ecological reasoning into studio-based design education should be understood as a systemic pedagogical process rather than as a set of separate sustainability-related tasks. Based on the conducted analysis, the following conclusions can be drawn.

1. The Ecological-Architectural-Pedagogical Spiral establishes a unified framework for connecting spatial analysis, ecological assessment, and studio-based learning within architectural and industrial design education.
2. The effectiveness of sustainable design training is determined not by the inclusion of individual environmental tools alone, but by the interaction between systems thinking, architectural reasoning, biomimetic strategies, and iterative pedagogical reflection.

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3. The implementation of the proposed model resulted in measurable improvements in student performance, including a 32% increase in systemic thinking and an average 20% reduction in the ecological impact of student projects, confirming the educational value of integrated ecological design methods.
4. The use of life-cycle assessment (LCA), biomimetic analogies, and ecological performance metrics enabled students to translate sustainability principles into concrete spatial, material, and ergonomic design decisions.
5. The proposed pedagogical framework establishes a direct link between ecological analysis, design generation, and professional competence formation, offering an operational approach to sustainability-oriented architectural and design education.

The practical application of the results includes the development of interdisciplinary studio formats, the introduction of ecological performance metrics into architectural and industrial design training, and the integration of digital tools such as BIM, LCA, and parametric simulation for evaluating environmental impact. The proposed approach can also be applied in architectural education as a methodological tool for teaching systems thinking, ecological responsibility, and context-sensitive design principles.

The study is limited by the sample size (n = 38) and the duration of a single academic semester. Further research may involve longitudinal and cross-institutional studies, as well as the application of advanced digital assessment tools for quantitative validation and refinement of the proposed pedagogical model.

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https://doi.org/10.51488/1680-080X/2026.2-09

ACKNOWLEDGEMENTS / SOURCE OF FUNDING

The study was conducted using private sources of funding.

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

ARTIFICIAL INTELLIGENCE STATEMENT

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

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Received 8 March 2026; Revised 20 May 2026; Accepted 31 May 2026

https://doi.org/10.51488/1680-080X/2026.2-09