

Bridging Black Box and White Box Artificial Intelligence through Sustainability Principles to Enhance Industrial Design Education: An Analytical Study of Egyptian and International Contexts

Researcher. Merna M. Maraie

**PhD Candidate, Department of Industrial Design -Faculty of Applied Arts-
HelwanUniversity- Egypt**

merna.maraie.art@gmail.com

Abstract

Industrial design curricula are experiencing a profound transition with the incorporation of Black Box AI and White Box AI models, alongside principles of sustainability, Cradle-to-Cradle and Circular Economy. AI tools augment designers' capabilities to rapidly generate prototypes and evaluate complex data. Nevertheless, transparency and interpretability persist as pivotal topics in the discourse surrounding the adoption of black-box models, which utilize complicated algorithms that are challenging to elucidate, in contrast to white-box models that offer a lucid comprehension of decision-making processes. Concurrently, the challenges posed by climate change and the objectives of sustainable development necessitate the integration of circular design principles into educational curricula, indicating a need for adaptable approaches that merge innovative technology with a commitment to environmental and economic responsibility.

This research aims to investigate the potential benefits that industrial design curriculum in academic institutions may derive from the incorporation of artificial intelligence and its two components, Black and White boxes, concerning sustainability. Furthermore, it will examine the methodological framework that connects the Double Diamond model, IDEO's human-centered design methodology, and Systems Design to develop comprehensive teaching content. This study examines the benefits and challenges of integrating both artificial intelligence paradigms and sustainability principles into industrial design education in Egypt. Employing a cross-sectional survey design via the Qualtrics platform, data were collected from academic staff and student participants across Egyptian universities, supplemented by international comparative case studies. The findings indicate notable gaps in faculty preparedness, infrastructural resources, and the integration of AI within sustainability-focused curricula.

The Research highlights the necessity of balancing innovation, sustainability, and ethics in the incorporation of AI into educational curricula to develop programs that remain technologically relevant and promote sustainable design methodologies. This integration minimizes waste, enhances product quality, and aligns curricula with Industry 4.0 requirements, framing sustainability as the intersection of technological proficiency and environmental accountability.

Keywords:

Black Box AI, White Box AI, Sustainable Design, Circular Design, Explainable AI (XAI), Industrial Design Curricula

الملخص:

تشهد مناهج التصميم الصناعي تحولاً عميقاً مع إدماج نماذج الذكاء الاصطناعي ذات الصندوق الأسود Black Box وAI والبيضاء White Box AI إلى جانب مبادئ الاستدامة والاقتصاد الدائري . Circular Economy تعزز أدوات الذكاء الاصطناعي قدرات المصممين على توليد النماذج الأولية بسرعة وتقييم البيانات المعقدة. ومع ذلك، لا تزال الشفافية وقابلية التفسير قضايا محورية في النقاش حول اعتماد النماذج ذات الصندوق الأسود، التي تستخدم خوارزميات معقدة يصعب توضيحها، خلافاً للنماذج ذات الصندوق الأبيض التي توفر فهماً واضحاً لعمليات اتخاذ القرار . XAI في الوقت نفسه، تستلزم التحديات التي يطرحها تغير المناخ وأهداف التنمية المستدامة دمج مبادئ التصميم الدائري في المناهج التعليمية، مما يستدعي اتباع مناهج مرنة تدمج الابتكار التكنولوجي مع الالتزام بالمسؤولية البيئية والاقتصادية.

يهدف هذا البحث إلى استقصاء الفوائد المحتملة التي قد تجنيها مناهج التصميم الصناعي في المؤسسات الأكاديمية من إدماج الذكاء الاصطناعي ومكوّنَيْه، الصندوق الأسود والصندوق الأبيض، في ضوء الاستدامة. بالإضافة إلى ذلك، سيتناول الإطار المنهجي الذي يربط نموذج الألماس المزدوج (Double Diamond) ، ومنهجية التصميم البشري-المحور (IDEO) ، وتصميم الأنظمة، لتطوير محتوى تعليمي شامل.

وتتناول هذه الدراسة تحليل الفوائد والتحديات المترتبة على دمج كلٍ من نماذج الذكاء الاصطناعي ومبادئ الاستدامة في تدريس التصميم الصناعي بمصر. وقد اعتمدت على تصميم مسح مقطعي نُفذ عبر منصة «Qualtrics» لجمع البيانات من أعضاء هيئة التدريس والطلبة في الجامعات المصرية، إضافةً إلى دراسات حالة مقارنة على الصعيد الدولي. أظهرت النتائج وجود فجوات تتعلق بجاهزية الكوادر الأكاديمية، ومستوى الدعم البيئي، ومدى تكامل تقنيات الذكاء الاصطناعي في مناهج التصميم المستدام.

فيستلزم البحث الضوء على ضرورة تحقيق توازن بين الابتكار والاستدامة والأخلاقيات عند دمج الذكاء الاصطناعي في مناهج التصميم ، لضمان تطوير برامج تظل ذات صلة تكنولوجية وتعزز منهجيات التصميم المستدام. يُسهم هذا التكامل في تقليل الهدر، ورفع جودة المنتجات، ومواءمة المناهج مع متطلبات الثورة الصناعية الرابعة، ويؤطر الاستدامة باعتبارها نقطة التقاء بين الكفاءة التكنولوجية والمسؤولية البيئية.

الكلمات الرئيسية:

الذكاء الاصطناعي الصندوقي الأسود، الذكاء الاصطناعي الصندوقي الأبيض، التصميم المستدام، التصميم الحلقي، الذكاء الاصطناعي القابل للتفسير (XAI)

1. Introduction**1.1 Background**

The incorporation of artificial intelligence into industrial design education signifies a fundamental transformation that transcends simple technological implementation (Schauer & Simbeck, 2024). The presented research investigates how educational institutions could incorporate innovation with sustainability while preserving pedagogical integrity through the strategic application of both black-box and white-box AI models. The paper examines essential issues regarding transparency, interpretability, and environmental accountability in AI-augmented design curriculum, emphasising sustainability principles as key to successful technological integration.

Industrial Design education is currently at a pivotal point, influenced by the disruptive technologies of Industry 4.0 and increasing sustainability requirements (Schwab, 2016). Artificial Intelligence, especially in its two forms: Black-Box AI (opaque, data-driven systems such as generative tools) and White-Box AI (transparent, rule-based systems like parametric design) provides significant advantages for rapid prototyping and lifecycle analysis. This innovation conflicts with the humanistic foundations of design education: Black-Box AI enhances ideation while concealing decision-making logic, potentially leading to ethical detachment, while White-Box AI facilitates sustainability simulations, such as material circularity, yet requires a certain level of technical proficiency. The tension is heightened in Global South contexts such as Egypt, where the adoption of Industry 4.0 exceeds the pace of pedagogical reform.

Contemporary assessment practices in higher education are experiencing significant disruption due to AI integration. According to the Digital Education Council Global AI Faculty Survey 2025, 54% of faculty believe that current student assessments require significant change, and one in two faculty members say assignments should be redesigned to be more AI-resistant (Digital Education Council, 2025). This transformation extends beyond concerns about academic integrity to encompass fundamental questions about how we assess student learning and prepare graduates for an AI-integrated future. A statement of the problem:

1.2 Problem Statement

The main problem lies in the absence of scholarly inquiry at the intersection of black-box and white-box AI methodologies and sustainability principles, alongside a limited understanding of the current state of AI adoption within Egyptian art and design higher-education institutions.

1.3 Research Importance

This research addresses several critical gaps in contemporary design education:

- A. Escalating Demand for AI Proficiency: The design sector increasingly requires specialists capable of adeptly employing AI tools while comprehending their constraints and ethical implications.
- B. Bridging AI Theory and Sustainable Circular Design in Education: There is a pressing need to integrate circular design principles addressing climate change and sustainable development into educational systems through structured pedagogical frameworks that effectively link theoretical AI concepts with practical sustainable design applications.
- C. Environmental Responsibility: The carbon footprint of AI systems, especially within educational settings, necessitates thorough assessment and mitigation strategies (Massachusetts Institute of Technology News, 2025; State of the Planet, 2023).
- D. Industry Preparedness: Design graduates must be equipped with both technological competency and environmental consciousness to meet evolving industry demands.
- E. Assessment Evolution: The need to redesign assessment practices to maintain validity in the AI era while exploring new opportunities to integrate AI meaningfully into assessment processes (Digital Education Council, 2025).

1.4 Research Objective

To explore the potential benefits that academic institutions' industrial design curricula may gain through the strategic integration of artificial intelligence technologies, specifically focussing on the intersection between black-box and white-box AI models within sustainability frameworks.

1.5 Research Terminologies

- A. Black-Box AI: Artificial intelligence systems characterized by opaque decision-making processes where the internal workings and reasoning mechanisms are not readily interpretable or explainable to users. These systems prioritize performance and efficiency over transparency.
- B. White-Box AI: Transparent, interpretable artificial intelligence systems where the decision-making processes, algorithms, and reasoning pathways are clearly visible and understandable to users, enabling informed decision-making and critical evaluation.
- C. Sustainability Principles: Comprehensive frameworks that encompass environmental, social, and economic considerations aimed at meeting present needs without compromising the ability of future generations to meet their own needs.
- D. Cradle-to-Cradle Design: A regenerative approach to design that models human industry on nature's processes, viewing materials as nutrients circulating in healthy, safe metabolisms.
- E. Circular Economy: An economic model aimed at eliminating waste and the continual use of resources through design-out waste and pollution, keeping products and materials in use, and regenerating natural systems.
- F. Double Diamond Model: A visual representation of the design and innovation process. It is a simple way to describe the steps taken in any design and innovation project, irrespective of the used methods and tools. A design thinking framework consisting of four phases: Discover (identifying user needs), Define (focusing on specific problems), Develop (creating solutions), and Deliver (implementing solutions).
- G. IDEO Human-Centered Design: A methodology that focuses on empathy, ideation, and experimentation to create solutions that are desirable, feasible, and viable.
- H. Systems Design: A holistic approach to design that considers the interconnectedness of various elements within complex systems and their broader environmental and social contexts.

2. Literature Review

This section reviews previous studies and existing scholarly work relevant to AI integration in design education and sustainable design frameworks, culminating in a clear identification of the research gap.

2.1 AI Integration in Design Curricula: Global Perspectives

The integration of AI in design education is growing globally, with various institutions pioneering innovative approaches to curriculum development. Design programs worldwide are increasingly integrating AI into their curricula (Schauer & Simbeck, 2024). Eindhoven University of Technology in The Netherlands focuses on Industrial Design, enabling students to use data as a creative resource. The University of Europe in Germany offers an MA in Generative Design & AI, educating designers on generative AI platforms and coding (University of Europe for Applied Sciences, 2024).

In the UK, new degrees connect AI and design, with the University of Bath offering an MSc in Artificial Intelligence for Engineering & Design, Loughborough University's MSc in Design and Artificial Intelligence (Loughborough University, 2023), and institutions in South Korea such as Hanyang Cyber University offering a Bachelor of Arts in AI Industrial Design (Hanyang

Cyber University, 2024). These programs integrate AI tools, often characterized as black-box methods like machine learning and deep learning, with foundational approaches such as white-box algorithms, consistently connecting projects to real-world themes, including sustainability. Recent studies indicate that AIGC (Artificial Intelligence Generated Content) tools improve students' design efficiency by facilitating ideation, prototyping, and personalization (Castro, 2024). Researchers highlight the necessity of formulating strategies that effectively incorporate AIGC into design curricula, while also addressing concerns related to educational ethics and equity. However, there is a disparity between student interest and faculty implementation of AI instruction, with some design programs leading in integrating AI technology, such as California College of the Arts' "Designing with AI" course and the University of Europe for Applied Sciences' MA in Generative Design & AI.

Formal AI curricula in design are still developing in the MENA region, with Egypt's educational initiatives progressively focusing on artificial intelligence. Global curricula demonstrate the integration of AI into design education, encompassing technical training and project work, often incorporating sustainability contexts within projects or dedicated courses.

2.2 Assessment Transformation in the AI Era

The transformation of assessment practices represents a critical dimension of AI integration in education. The Digital Education Council (2025) identifies three distinct types of assessment practices emerging in higher education: AI-Free, AI-Assisted, and AI-Integrated assessments. Each serves specific pedagogical purposes and addresses various aspects of student learning in the AI era.

AI-Free assessments are intentionally designed to be completed without AI assistance, focusing on students' unaided thinking and foundational skill development. AI-Assisted assessments allow students to use AI for limited, specific tasks under clear boundaries, while AI-Integrated assessments purposefully embed AI tools as part of the learning and assessment experience (Digital Education Council, 2025).

The report emphasizes the importance of AI-resilience as a baseline design principle, encouraging structural assessment redesign rather than reliance on student compliance. This approach aligns with the growing recognition that assessment must evolve not just to address academic integrity concerns, but to reflect how students will think, solve, and create alongside AI tools in professional contexts.

2.3 Explainable AI (XAI) in Design Education

Explainable AI (XAI) encompasses methods that enhance the transparency and interpretability of AI decision-making processes. In design education, principles of explainable artificial intelligence (XAI) are crucial for both pedagogy and ethics; students should not only utilize AI tools but also comprehend their outputs.

Researchers indicate that XAI allows learners to utilize knowledge instead of numerical data to enhance their understanding of a model's predictions (Lipton, 2018). The focus on knowledge rather than opaque computation is essential. Interpretability enables designers to understand the rationale behind an AI's suggested solution (Rudin, 2019). Transparency and decision

traceability enhance trust in AI systems; learning outcomes are optimized when students can examine the AI's rationale.

Duke's new XAI courses highlight that enhancing the transparency and accountability of AI fosters trust among users and stakeholders while addressing ethical issues. In a design studio, this may refer to tools that emphasize the data or features contributing to a generative design output, or that illustrate the decision pathway of an algorithmic filter. XAI elucidates the rationale behind AI-generated design suggestions, enabling students to critique and refine AI-assisted designs instead of viewing them as opaque entities.

While literature on XAI in design programs remains limited, existing educational research indicates that explainable models can enhance engagement and trust, which are outcomes consistent with design pedagogy. Integrating XAI, through model visualizations, rule explanations, or interactive feedback, is considered to enhance learning by incorporating AI tools as an explainable component of the creative process.

2.4 Sustainable Design Frameworks in Education

Sustainable design frameworks, like the UK Design Council's Double Diamond model, are increasingly used in educational curricula (Design Council, 2015). This framework, consisting of four phases, helps students progress from problem exploration to solution prototyping. It is often combined with human-centered design principles for AI-driven concepts (Brown, 2008).

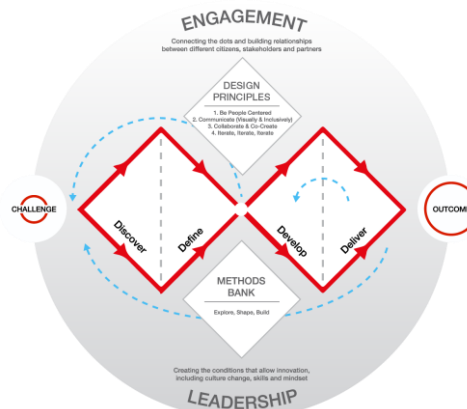


Figure1: The Design Council's Double Diamond framework of the design process.

Source: designcouncil.org.uk.

Sustainable design thinking encompasses the principles of Circular Economy and Cradle-to-Cradle concepts. The Ellen MacArthur Foundation's "butterfly" diagram (Fig. 2) illustrates the flow of a circular economy, highlighting three design-driven principles: The elimination of waste and pollution, the circulation of products at high value, and the regeneration of natural system (Ellen MacArthur Foundation, 2021). Design programs frequently necessitate the application of specific frameworks, for instance, projects may be assessed based on the effectiveness of design implementations of CE cycles or material upcycling. Cradle-to-Cradle posits that products ought to be designed as nutrients within perpetual technical or biological cycles (McDonough & Braungart, 2002).

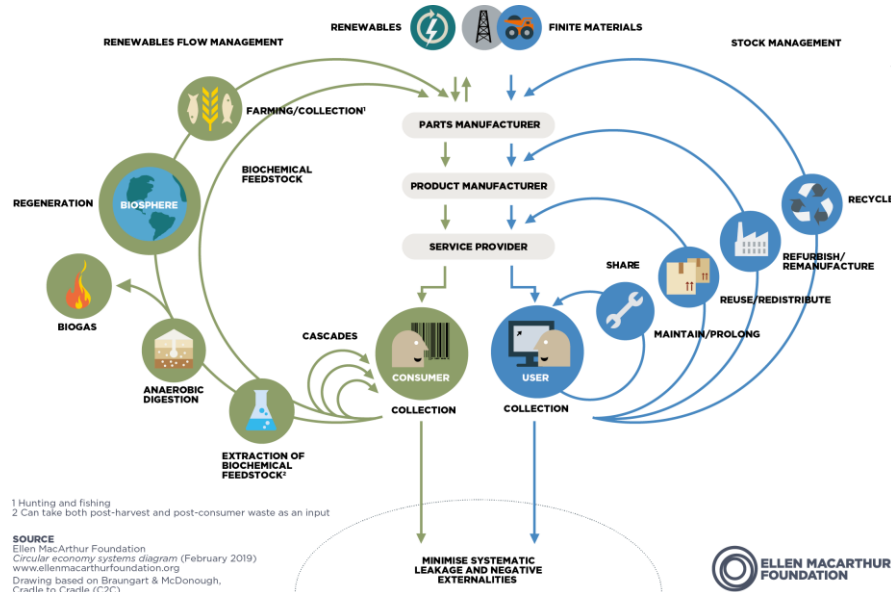


Figure 2: Ellen MacArthur Foundation's circular economy "butterfly" diagram.

Source: ellenmacarthurfoundation.org

Sustainability models are integrated into design coursework, sometimes with AI. AI simulations are used to evaluate product life cycles and optimize material selection. Double Diamond, HCD, CE, and C2C are fundamental to design education, with recent discussions advocating for their integration with AI literacy. Sustainable design frameworks remain central to curriculum guidance.

2.5 AI Competency Development

The Digital Education Council AI Literacy Framework (2025) defines key dimensions of AI literacy, focusing on general AI literacy for all, as well as specialized AI literacy that can be adapted to different disciplines. The framework identifies seven core AI competencies:

- Understanding AI Fundamentals: Foundational knowledge of how AI systems are trained and operate
- AI Output Evaluation: Critical analysis and verification of AI-generated content
- Input Design and Information Quality: Strategic design and refinement of inputs to improve AI outputs
- AI Bias & Limitation Awareness: Identification and mitigation of AI biases and limitations
- AI Integration & Application: Effective use of AI tools for domain-specific tasks
- AI Ethics & Responsible Use: Application of ethical principles in AI usage
- AI Reflection & Metacognition: Reflection on AI's role in thinking and learning processes

2.6 Gap Analysis

Despite the growing body of literature on AI integration in design education, several critical gaps remain:

- Limited Research on AI Typologies: There is insufficient scholarly inquiry specifically addressing the intersection of black-box and white-box AI methodologies within Industrial design education contexts, particularly in relation to sustainability principles (Gmeiner et al. 2023; Schauer et al. 2025).

- B. Regional Context Deficit: Limited understanding exists regarding AI adoption within Egyptian and broader Middle Eastern art and design higher-education institutions, with formal AI curricula in design still developing in the MENA region (Shehata 2022; Mohamed Salah 2025).
- C. Sustainability Integration Gap: Few studies examine how AI integration can be systematically aligned with sustainability principles and circular design methodologies in educational settings (Leal Filho et al. 2025).
- D. Environmental Impact Assessment: Insufficient attention has been paid to the carbon footprint and environmental implications of AI integration in educational contexts, despite growing awareness of AI's energy consumption (Massachusetts Institute of Technology News, 2025; State of the Planet, 2023; Lupetti et al. 2025).

This research addresses these gaps by providing a comprehensive framework for AI integration that prioritizes sustainability principles and contextual relevance for Egyptian institutions

3. Theoretical Framework of the Research

This research is based on a comprehensive theoretical framework that combines established design methodologies, sustainability principles, AI classification systems, and contemporary assessment theory. The framework integrates four key theoretical domains to provide a holistic approach to AI integration in Industrial design education.

3.1 AI Typologies in Industrial Design Education

Recent studies indicate that AIGC (Artificial Intelligence Generated Content) tools improve students' design efficiency by facilitating ideation, prototyping, and personalization. Researchers highlight the necessity of formulating strategies that effectively incorporate AIGC into design curricula, while also addressing concerns related to educational ethics and equity.

A. **Black-Box AI: Efficiency vs. Opacity**

- Definition: Algorithms characterized by opaque decision-making processes, such as deep neural networks utilized in Midjourney and ChatGPT (Brown et al., 2020).
- Benefits:
 - Accelerates ideation and prototyping (survey findings: 78% usage for concept generation).
 - Facilitates equitable access to complex tasks such as rapid rendering.
 - Enables rapid generation of design alternatives and creative exploration.
- Risks:
 - Epistemological Detachment: Obscured logic diminishes design-critical thinking (Burrell, 2016).
 - Ethical Hazards: Bias amplification and accountability gaps (Dastin, 2018).
 - Deficiencies in control: (Survey findings indicate that 64% of Egyptian students reported an "inability to refine outputs").

B. **White-Box AI: Pedagogical Value of Transparency**

- Definition: Systems that are interpretable and possess modifiable rules, such as parametric design in Grasshopper and Python-based simulations) (Doshi-Velez & Kim, 2017).

- **Benefits:**
 - Promotes technical agency: Students engage with variables (e.g., material density in sustainability simulations).
 - Enables ethics-by-design: Audit trails for environmental impact decisions (Ribeiro et al., 2016).
 - Supports pedagogical transparency and understanding of underlying processes.
 - Survey Insight: Only 23% used such tools; 89% of faculty linked this gap to "limited coding integration."

C. Ethical and Transparency Considerations

Educators should adapt the instruction of ethical guidelines according to the specific type of AI:

- **Black Box AI:** Focus on responsibility for unpredictable AI outcomes. Students are trained to audit AI decisions and question biases without full model access.
- **White Box AI:** Emphasis on fairness, accountability, and transparency (FAT) principles, where students learn to create AI systems that are interpretable and unbiased from the start.
- **Example:** The EU-funded AI4People project provides a framework that many Asian universities have adopted to teach ethics with both AI types in design program (Mittelstadt et al., 2019).



Figure 3: The EU-funded AI4People project

3.2 Assessment Theory in the AI Era

A. Three-Tier Assessment Framework

Building on the Digital Education Council (2025) framework, this research adopts a three-tier assessment approach:

- **AI-Free Assessment:** Intentionally designed to be completed without AI assistance, focusing on students' unaided thinking and foundational skill development. The assessment's objectives, competencies, and design inherently exclude or minimize AI use.
- **AI-Assisted Assessment:** Students may use AI for limited, specific tasks under clear boundaries. The assessment structure allows AI as a supportive tool while ensuring student-led learning remains central.
- **AI-Integrated Assessment:** Purposefully embeds AI tools as part of the learning and assessment experience. The assessment's objectives and prompts require students to meaningfully engage with AI as a core part of the task.

B. AI-Resilience Design Principle

AI-resilience emerges as a key design principle to protect the validity and integrity of assessments. An AI-resilient design ensures that core learning outcomes cannot be easily outsourced to AI through structural redesign rather than student compliance (Corbin et al., 2025). Strategies include:

- Process-Focused Assessment: Shift from output to process evaluation.
- Contextual Application: Tasks requiring local or personal context.
- Synchronous Validation: In-class components for critical verification.
- Iterative Development: Multiple checkpoints demonstrating progressive thinking.

C. Dual-Priority Approach

Based on Liu and Bridgeman's (2023) "Two-Lane Approach," this framework proposes balancing:

- Priority 1: Human Competency Development - Foundational knowledge, critical thinking, and unaided skills.
- Priority 2: Human-AI Collaboration Skills - Effective and ethical AI tool usage, formative, and authentic assessments.

3.3 Pedagogical Models for Integration**A. Double Diamond: Divergent/Convergent Thinking**

- Phase 1 (Discover):
 - Utilizing Artificial Intelligence (AI) tools for comprehensive user research, market analysis, and trend identification.
 - Black-Box AI analyses sustainability contexts (e.g., ChatGPT for user research).
- Phase 2 (Define):
 - Utilizing AI for problem identification, prioritization of user needs, and development of the design brief.
 - White-Box frames issues (e.g., Python scripts mapping Cairo's water scarcity).
- Phase 3 (Develop):
 - Utilizing AI for conceptualization, prototyping, and iterative design advancement.
 - Hybrid AI generates solutions (e.g., Grasshopper combined with Midjourney).
- Phase 4 (Deliver):
 - Implementing artificial intelligence for production optimization, user testing, and impact evaluation.
 - White-Box verifies circular solutions (e.g., digital twin simulations).

B. IDEO's Human-Centered Design (HCD)

- Empathy Through AI:
 - AI-enhanced user research and behavioral analysis
 - Black-Box tools simulate user personas.
 - White-Box systems measure social impact, such as equity in access.
 - Ethical guardrails ensure that AI prioritizes human needs, not vice versa.

- Ideation
 - AI-assisted creative processes and solution generation
- Experimentation:
 - AI-driven prototyping and testing methodologies

C. Systems Design for Lifecycle Thinking

- Method:
 - Models' product-environment interactions as dynamic systems.
- AI Integration:
 - A comprehensive assessment of design implications across environmental, social, and economic dimensions.
 - Incorporation of sustainability principles across the design process.
- Recognition of interconnectedness between design decisions and broader systemic effects
 - White-Box simulates lifecycle stages, such as TensorFlow's prediction of 30-year recyclability.
 - Survey Gap: 0% of curricula included systemic AI analysis.

3.4 Sustainability Principles in Industrial Design and AI Sustainability Integration Framework

A. Circular Economy (CE) vs. Cradle-to-Cradle (C2C) vs. Sustainable Development Goals (SDG)

- CE Focus: Systemic resource loops (reuse/recycle).
 - **Design Application:** AI-driven analysis of material flow, such as OpenLCA for textile waste management.
- C2C Focus: Regenerative product lifecycles.
 - **Design Application:** Utilizing White-Box AI to model biological and technical nutrient cycles, such as those found in biodegradable composites.
 - UN Sustainable Development Goals (SDGs)
- SDG 9 (Industry Innovation):
 - AI Alignment: Black-Box for rapid prototyping of inclusive infrastructure (e.g., low-cost housing).
- SDG 12 (Responsible Consumption):
 - **AI Alignment:** White-Box for supply-chain transparency.

B. Conceptual Model for AI-Sustainability Integration Framework

- Cradle-to-Cradle Principles:
 - Material health and the utilization of renewable energy.
 - Design for circularity and regenerative impact.
 - Integration of artificial intelligence tools that facilitate lifecycle assessment and environmental impact evaluation.
- Circular Economy Integration:
 - Design to minimize waste and pollution using AI-optimized processes.
 - Maintain the utilization of products and materials via strategic design solutions.
 - Regenerate natural systems using environmentally conscious design practices.

3.5 Comparative Framework: Black-Box vs. White-Box AI

Table 1: Compares Black-Box with White-Box AI in interpretability, educational value, and sustainability.

FEATURE	BLACK-BOX AI	WHITE-BOX AI
INTERPRETABILITY	Low (e.g., DALL-E, ChatGPT)	High (e.g., CAD parametric rules)
EDUCATIONAL VALUE	Rapid ideation; bias risks	Algorithmic literacy; debugging
SUSTAINABILITY LINK	Energy-intensive training	Resource optimization

4. Research Method

4.1 Materials and Methods

A. Survey Design

A structured questionnaire was developed using a mixed-methods approach, combining closed-ended questions for statistical analysis and open-ended prompts to capture in-depth, reflective responses. through “Qualtrics” to investigate the current status of artificial intelligence integration (AI) within the Design curricula in general (the various design departments) and specifically in the Industrial Design curricula. The study was conducted in Faculties of Applied Arts affiliated with several public and private universities in Egypt. The choice of a cross-sectional survey and convenience sampling, while practical for reaching a diverse academic community in Egypt, inherently limits the generalizability of findings to other contexts or over time. This methodological choice reflects a pragmatic approach to gather initial insights into a nascent field within a specific region, prioritizing the breadth of current perceptions over longitudinal trends or universal applicability.

(https://qfreeaccountssjc1.az1.qualtrics.com/jfe/form/SV_1ZDPy3tvxgNTuku)

▪ **Temporal and Spatial Boundaries:**

This study was conducted during the spring semester of the academic year 2024/2025. Data collection occurred between April and June 2025, utilizing a cross-sectional survey administered through the Qualtrics platform.

The spatial scope of the research is limited to Egyptian higher education institutions, specifically faculties of Applied Arts across both public and private universities. The sample included participants from universities such as Helwan University, O6U University, MSA University and others in Cairo. Although the study's findings are grounded in the Egyptian context, they may serve as a reference point for comparable educational settings across the Global South that share similar infrastructural and pedagogical challenges.

▪ **Sampling Methodology:**

- Target population: The scholarly community within the faculties of applied arts at Egyptian universities.
- Sample composition includes a diverse array of academic personnel such as professors, associate professors, lecturers, lecturer assistants, teaching assistants, as well as

postgraduate students pursuing Master's and Doctoral degrees, undergraduate students, and graduates from the design industry.

- The sampling method: A convenience sampling approach, leveraging social media platforms and professional networks for participant recruitment.
- The final sample size comprises 126 complete responses, following the exclusion of 12 incomplete responses during the data cleaning process.

▪ **Instrument for Data Collection:**

The survey comprised five detailed sections, employing a combination of question formats to capture both quantitative and qualitative data:

- **Demographic information:** Questions on job/study status, academic degree, department, and university affiliation, primarily using multiple-choice or single-choice formats.
- **Current State of AI Integration:** Items assessing AI integration within design curricula assessments, utilizing Likert scale questions to measure perceptions and extent of integration.
- **AI Usage Patterns:** Questions exploring utilization patterns of Black-Box and White-Box AI, preferences for specific tools and software, and associated advantages and disadvantages, employing a mix of multiple-choice and Likert scale items.
- **Effectiveness Assessment:** Likert scale questions evaluating the efficacy of artificial intelligence in enhancing student experiences, alongside suggestions regarding the instruction of internal coding.
- **Qualitative Insights:** Open-ended questions designed to elicit rich, descriptive responses regarding recommendations for improving AI integration in curricula.

The full questionnaire administered to participants is provided in the Appendix for reference and transparency.

▪ **Survey Procedures:**

The research followed a structured four-phase process to ensure methodological rigor, which is particularly important when investigating a relatively novel and complex intersection like AI, sustainability, and design education in a specific regional context. This systematic approach enhances the credibility and reliability of the study's findings, providing a robust foundation for the conclusions and recommendations.

- **Phase 1: Survey Development**
 - Literature review and theoretical framework establishment.
 - Survey instrument design based on research objectives.
 - Content validation through expert review.
 - Pilot testing and instrument refinement.
- **Phase 2: Data Collection**
 - Distribution via social media platforms and professional networks.
 - Target population recruitment across Egyptian universities.
 - Response monitoring and follow-up procedures.

- Data quality assurance protocols.
 - **Phase 3: Data Processing**
 - Initial response screening and validation.
 - Removal of incomplete responses (12 excluded from 138 total).
 - Data cleaning and outlier identification.
 - Final dataset preparation with 126 complete responses.
 - **Phase 4: Analysis Procedures**
 - Descriptive statistical analysis of demographic data.
 - Pattern analysis of AI usage and preferences.
 - Qualitative content analysis of open-ended responses.
 - Cross-tabulation analysis of stakeholder perspectives.
- **Survey Implementation Challenges:**
- Several challenges were encountered during the research implementation:
- Varying levels of AI familiarity among respondents.
 - Institutional differences in technology access and policies across Egyptian universities.
 - Language considerations for Arabic-speaking participants.
 - Response Fatigue Balancing comprehensive data collection with respondent engagement and completion rates.
 - Balancing comprehensive data collection with respondent fatigue.
 - Technological Infrastructure: Variations in internet connectivity and device access affecting survey completion.
 - Cultural Context: Ensuring survey questions were culturally appropriate and relevant to the Egyptian educational context.

B. Case Studies: International Comparative Analysis

▪ **Case Study Selection Methodology**

A systematic analysis of international case studies from universities across multiple continents was conducted, including institutions in Egypt, Netherlands, Germany, Sweden, United Kingdom, Finland, New Zealand, Japan, China, South Korea, Singapore, United States, and South America. Case studies were selected based on their demonstration of:

- Innovative AI integration approaches.
- Sustainability focusses within AI curriculum design.
- Pedagogical effectiveness and documented student outcomes.
- Transferable strategies applicable to Egyptian context.
- Diversity in institutional types and geographic contexts.

▪ **Comprehensive Course Integration Models**

The analysis examined three primary integration models:

- **Model 1:** Formal Course Integration: Universities offering dedicated AI-focused courses within industrial design curricula, with comprehensive semester-long programs integrating both technical skills and design thinking.
- **Model 2:** Sustainability-Focused Integration: Programs specifically combining AI technologies with sustainability principles, emphasizing circular economy concepts and environmental impact assessment.
- **Model 3:** Workshop and Short Course Models: Intensive, focused training programs for AI skill development, typically ranging from 2-7 days with concentrated learning objectives.
- Data Collection for Case Studies
Data for international case studies were collected through:
 - Institutional Websites: Official course descriptions, syllabi, and program documentation.
 - Academic Publications: Peer-reviewed articles documenting program outcomes and methodologies.
 - Conference Presentations: Professional development presentations and workshop materials.
 - Student Portfolio Analysis: Examination of publicly available student work and project outcomes.

4.2 Data Analysis Strategy

A. Quantitative Analysis

- Descriptive Statistics: Frequency distributions, means, and standard deviations for survey responses.
- Cross-Tabulation Analysis: Relationships between demographic variables and AI usage patterns.
- Comparative Analysis: Differences between user groups and institutional types.
- Trend Analysis: Patterns in AI adoption and preference changes.

B. Qualitative Analysis

- Thematic Coding: Systematic categorization of open-ended responses.
- Content Analysis: Identification of recurring themes and concepts.
- Pattern Recognition: Emergence of common concerns and recommendations.
- Comparative Interpretation: Analysis of qualitative data in context of quantitative findings.

C. Case Study Analysis Framework

Each case study was analyzed using a standardized framework examining:

- Program Context: Institution type, student demographics, and cultural context
- Curriculum Structure: Course organization, sequencing, and integration strategies
- Technology Integration: Specific AI tools and implementation methods
- Sustainability Components: Environmental focus and circular design principles
- Assessment Strategies: Evaluation methods and success metrics

- Outcomes and Impact: Student learning achievements and program effectiveness
- Transferability: Applicability to Egyptian educational context

This comparative approach enabled identification of best practices, success factors, and transferable strategies that could inform curriculum development recommendations for Egyptian institutions.

D. Mixed-Methods Integration

- Data Triangulation: Validation of findings across multiple data sources.
- Sequential Analysis: Building on quantitative findings with qualitative insights.
- Comparative Synthesis: Integration of survey data with case study findings.
- Framework Development: Creation of implementation recommendations based on combined analyses.

5. Results

5.1 Survey Results

A. Respondent Demographics: The sample (N=126) was diverse: ~36% were undergraduates, ~15% assistant lecturers, ~5% graduate students, and smaller numbers of professors, lecturers, and industry graduates. Academic levels ranged from diploma to PhD, with 46% at undergraduate level, 20% Bachelor's, 17% Master's, and 16% PhD. This reflects participation across the academic community (students and staff) in design faculties. Other illustrated in word cloud design (refer to Appendix) to showcase their answers. Mostly are in the design industry.

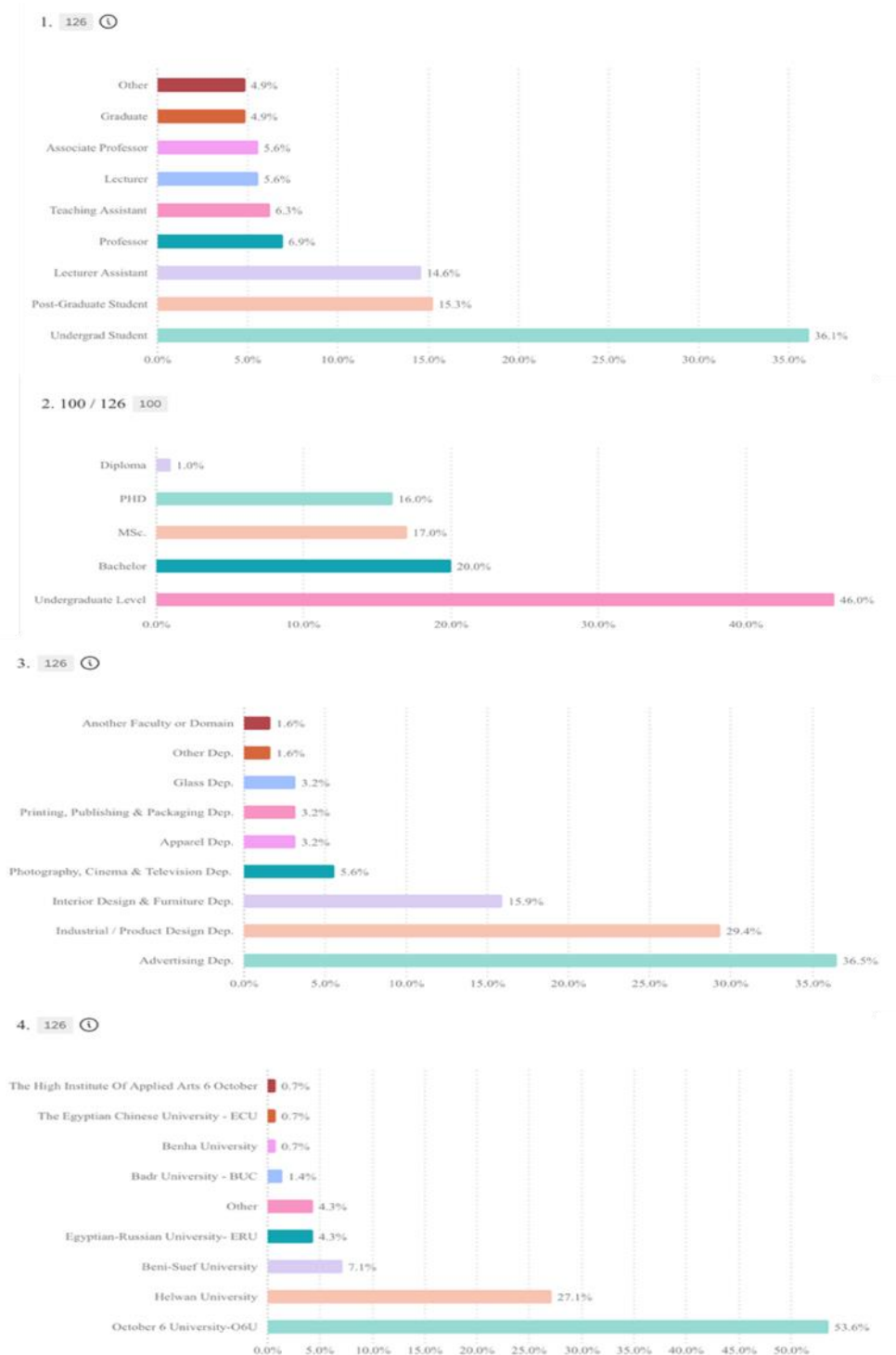


Figure 4: Graphs of Respondents Demographics

B. Current AI Integration in Curricula: Only 30 respondents (24%) reported an official AI-focused course in their program; 70 (56%) said AI is only addressed within other courses; 16% had no AI content at all. When asked, 62% believed a dedicated AI course should be mandatory, and 30% said elective, while ~5% saw it as unnecessary. In short, **most (85%) favor some formal AI course in design education.**

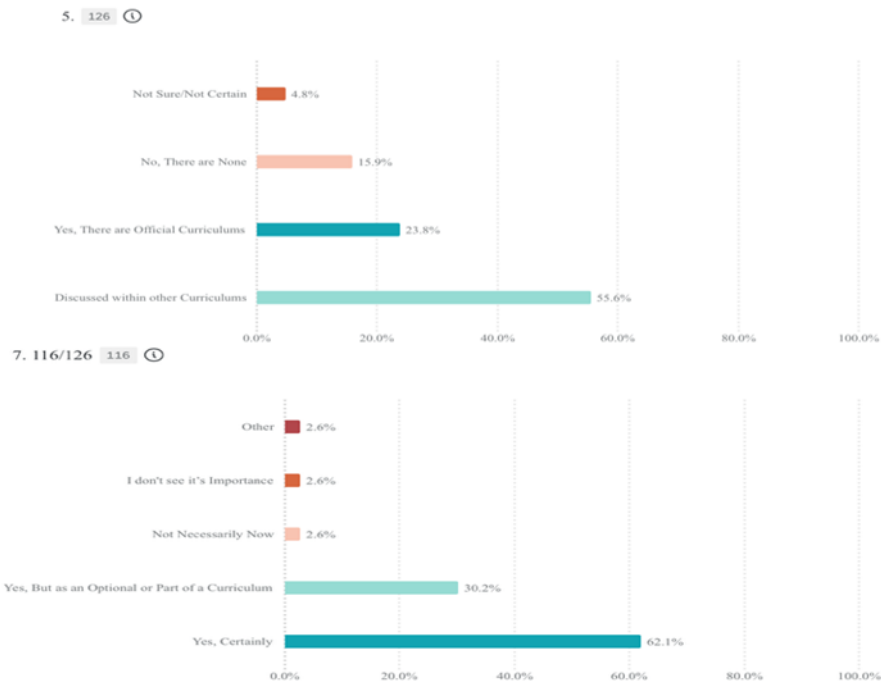


Figure 5: Reported extent of AI integration in existing curricula

- C. AI Usage Frequency:** A large majority (92%) use AI tools in their design work or studies. Usage was frequent: 38% use AI tools >10 times per month, 34% 5–10 times, 19% 2–4 times, and only 10% once. Thus, more than two-thirds use AI regularly (5+ times monthly).

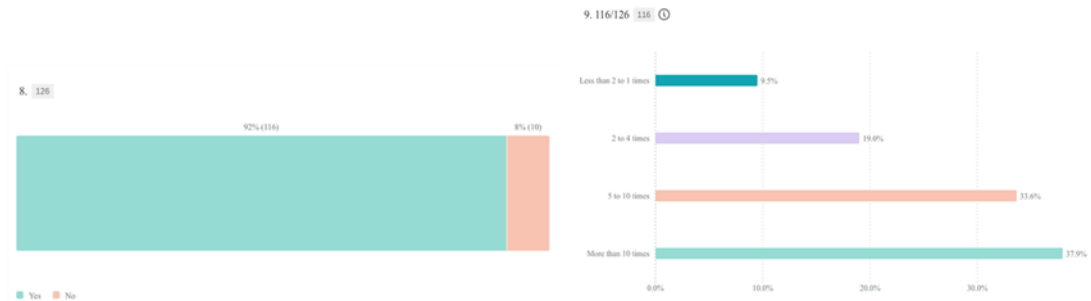


Figure 6: Frequency of AI tool use among respondents

- D. AI Usage Frequency:** Respondents reported using AI mainly for creative tasks. The most common applications (multiple responses allowed) were idea generation/prototyping (25%) and assisting project development (25%), followed by designing images/presentations (18%), evaluating/reviewing work (13%), and drawing/coloring (8%). This suggests **AI is mainly used in early (divergent) design stages (ideation, concept visuals) and mid-stage development.**

10. 116/126 316 ①

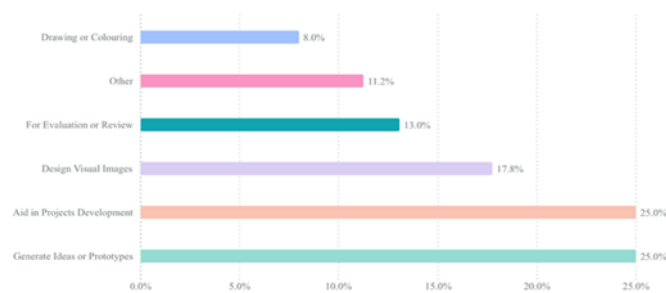


Figure7: Graphs of Tasks using AI

E. Black-box vs White-box Preferences: When questioned about the nature of AI tools, 29% said they use “ready-made programs that provide quick results without needing to understand technical details” – implying black-box usage. In contrast, only 18% preferred “using programs I can inspect or modify by code” (white-box, e.g., open source). 16% did not know if their tools were open (White Box) or closed (Black Box), and 25.4% said they currently do not use AI for 3D design. **This indicates a strong lean toward black-box convenience among users.**

11. 116/126 116 ①

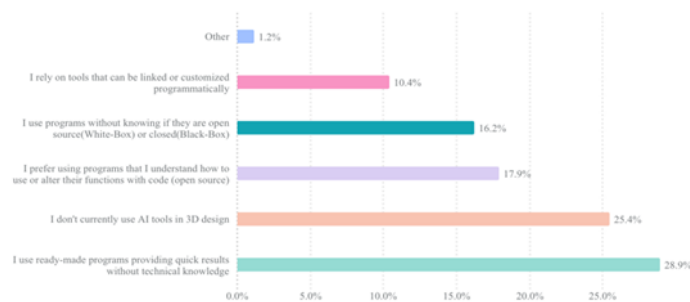


Figure 8: Graphs of Black-box vs White-box Preferences

F. Tools Used: Popular open-source tools (white-box) reported include Blender (with AI add-ons), DreamFusion, Open3D, and TripOSR (super-resolution). Among commercial/closed tools, the most cited were Adobe Substance 3D (23% mentions), DeepAI 3D Generator (19%), Luma AI (17%), and Polycam (12%). The prevalence of Adobe Substance and other apps reflects **industry trends in design tools.**

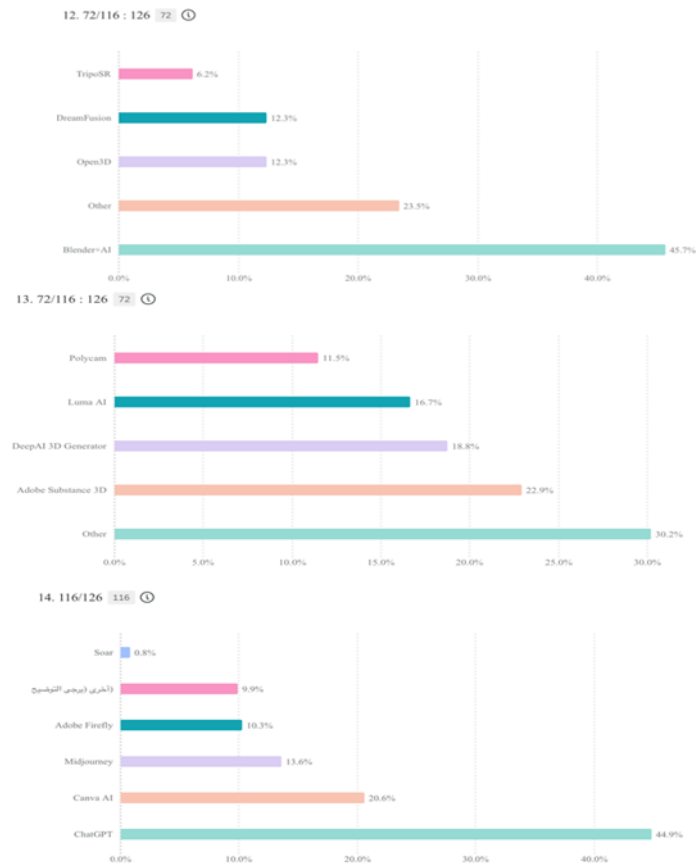


Figure 9: Preferences for AI tool transparency (white-box vs. black-box)

G. Perceived Benefits: Respondents identified speed and creativity as major AI advantages. The top “likes” were quick result turnaround (39%) and variety of design options (21%). About 17% valued ease of use, and 8% noted enhanced creativity or learning. These align with expectations that AI accelerates ideation and offers diverse concepts.

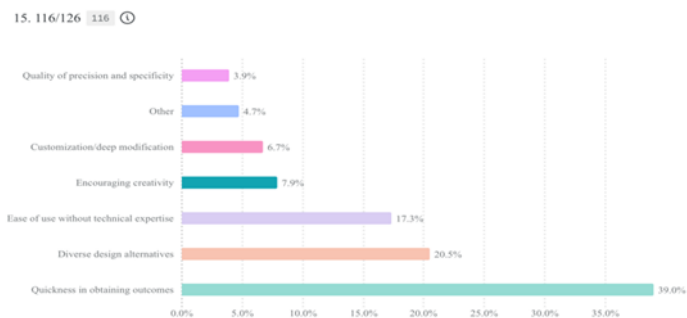


Figure 10: Graphs of Perceived Benefits from AI tools

H. Challenges and Drawbacks: The main concerns were inability to adjust fine details and lack of precision. 29% said “hard to adjust output to my exact vision,” and 28.4% “cannot modify some details in ready tools,” highlighting black-box limitations. Cost was cited by 15%, and security/privacy issues by 11%. Fewer (13%) mentioned a steep learning curve or needing powerful hardware. Notably, none of the respondents mentioned environmental cost explicitly – perhaps reflecting limited awareness of AI’s energy use.

16. 116/126 116 ①

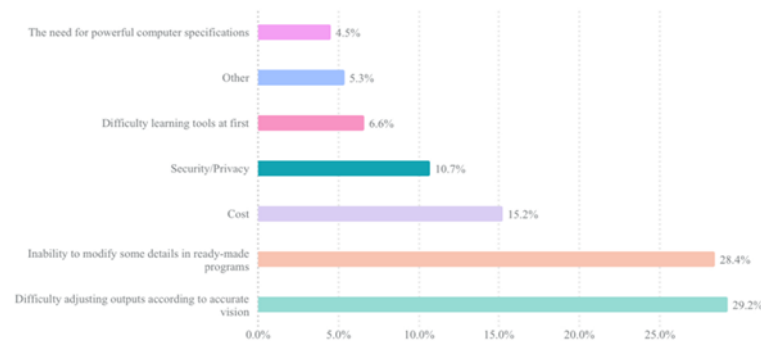


Figure 11: Graphs of Challenges and Drawbacks

I. Perceptions of AI effectiveness:

- Output Quality vs. Traditional Design: A majority (54.3%, n=63/116) rated AI-generated results as inferior to traditional manual design (score 1), with only 3.5% (n=4) considering them "much better" (score 5).
- Teaching Enhancement: Conversely, regarding AI's role in improving student experiences, 43.4% (n=23/53) reported moderate effectiveness (score 3), while 30.2% (n=16) indicated high effectiveness (score 4). This suggests that while AI tools are perceived to support pedagogy, their output quality is viewed critically compared to conventional methods.

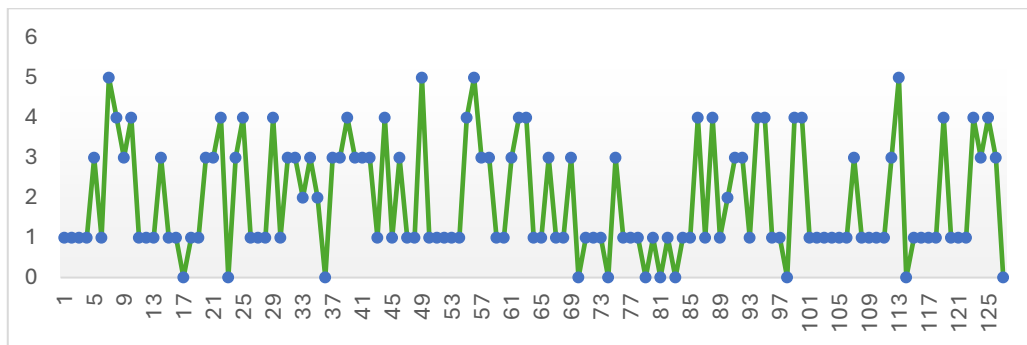


Figure 12: Output Quality vs. Traditional Design

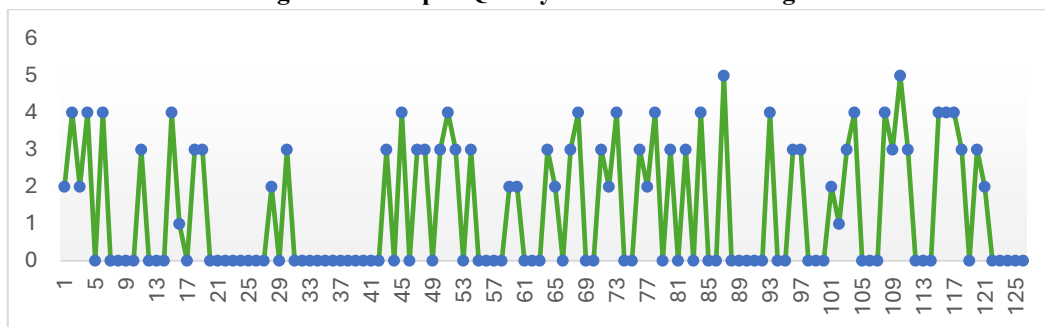


Figure13: AI's role in improving student experiences

Overall, the quantitative data show that AI tools are known and used to varying degrees, but their formal role in curricula remains limited. The split between “tool” and “methodology” perspectives reflects an ongoing debate about the depth of curricular change needed.

J. Qualitative Results and Thematic Analysis:

- Open comments suggested developing local AI design tools, training on prompt engineering, and incorporating AI literacy in curricula. Many advocated “**teaching AI as a design assistant**” and running workshops on “**how to talk to AI.**” Suggestions included **design competitions using AI** and closer industry–academic collaboration. These echo calls in literature for hands-on, responsible AI education.
- Open-ended responses were coded into three primary categories: Industrial Design (ID) (suggestions on curriculum/practice), Refusal OF AI (R) (negative attitudes toward AI), and General Design (G) (perceived needs or missing elements & suggestions on curriculum/practice). From these, several overarching themes (T) were derived. Below we present each theme with visualized graphs.

Table 2: Open ended questions Theme Codes with description:

THEME CODE	THEME TITLE	DESCRIPTION
T1	AI-based modules or curriculums	include AI in existing core courses, Integrate AI at specific course points or years, tailored to student level, & create standalone AI modules.
T2	CREATIVITY & Strategic Use of AI	Encourages balanced use of AI to support, not substitute, design thinking, address its ethical implications.
T3	AI Awareness & Literacy	Workshops, tutorials, training in prompting, coding, and AI tools.
T4	Support Industry-relevant AI Thinking, workflow & Prototyping	Use AI to analyze existing products, accelerate renderings, and improve prototyping.
T5	Accessibility, inclusion in AI, & Infrastructure Support	Price, availability, supported local language and institutional support.
T6	Resistance / Caution / Creativity Concerns	Shows a resistance or ethical caution, especially among traditional or practice-based educators.

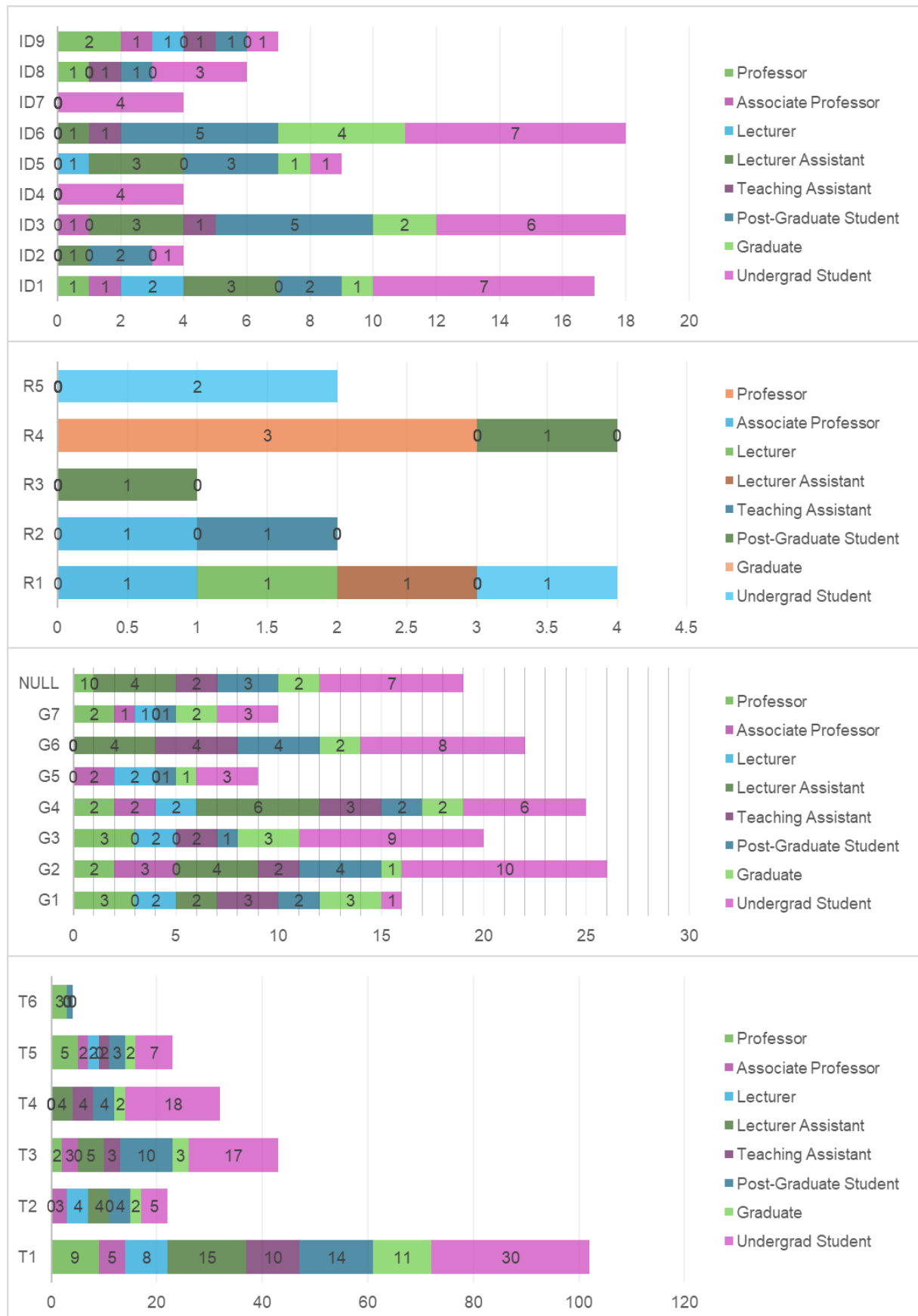


Figure 14. Schematic of key themes from open-ended responses

5.2 International Case Studies Results

A. Formal Course Integration Models

The analysis of international institutions revealed comprehensive approaches to AI integration in industrial design curricula:

Table 3: AI Integration in Industrial Design Curricula - Formal Courses

Seoul National University	TU Delft	University
South Korea	Netherlands	Country
College of Fine Arts	Faculty of Industrial Design Engineering	Faculty/School
Industrial Design	Product Innovation	Dep.
AI-Enhanced User-Centered Design	Integrated Product Design with AI	Course Name
Graduate	Undergraduate/Graduate	Academic Level
Machine Learning, Data Analytics, LLMs	Computer Vision, Generative AI	AI Technologies
5 stages: User Research, Analysis, Design, Validation, Iteration	4 stages: Research, Ideation, Development, Testing	Course Stages
Python, Tableau, Figma	Grasshopper, TensorFlow, Rhino	Software/Programs
White-Box	Hybrid	AI Type
User behavior analysis reports, predictive design models	Sustainable product concepts, AI-enhanced prototypes	Course Outputs

Tsinghua University									
China									
Academy of Arts and Design									
Industrial Design									
AI-Driven Cultural Design Innovation									
Graduate									
Deep Learning, Pattern Recognition									
3 stages: Cultural Analysis, AI Generation, Design Implementation									
Custom Python tools, Processing									
Black-Box									
Cultural heritage-inspired products, digital pattern libraries									

B. AI and Sustainability Integration Models

Table 4: AI and Sustainability Integration in Industrial Design Curricula

TU EINDHOVEN	AALTO UNIVERSITY	UNIVERSITY
Netherlands	Finland	COUNTRY
Department of Industrial Design	School of Arts, Design and Architecture	FACULTY/SCHOOL
Future Everyday Group	Design	DEP.
Bio-Integrated Design with AI	Circular Design with AI	COURSE NAME
Graduate	Graduate	ACADEMIC LEVEL
Biomaterial AI, Simulation	Life Cycle Assessment AI, Predictive Analytics	AI TECHNOLOGIES USED
Biodegradable Materials, Biomimicry	Circular Economy, Material Optimization	SUSTAINABILITY FOCUS
ANSYS, Custom bio design tools	SimaPro, Python, LCA tools	SOFTWARE/PROG RAMS
Black-Box	White-Box	AI TYPE
Bio-integrated products, sustainable material innovations	Circular product designs, sustainability metrics	COURSE OUTPUTS

KAIST	
South Korea	
College of Design and Human Engineering	
Industrial Design	
Green AI Design Laboratory	
Doctoral	
Energy Optimization AI	
Energy Efficiency, Green Technology	
MATLAB, Energy simulation tools	
White-Box	
Energy-efficient product designs, sustainability algorithms	

C. Workshop and Short Course Models

Table 5: AI Integration in Short Courses and Workshops

UNIVERSITY		MIT MEDIA LAB	STANFORD D. SCHOOL
COUNTRY	FACULTY/SCHOOL		
	DEPARTMENT		
WORKSHOP/SHORT COURSE NAME			
TARGET LEVEL			
AI TECHNOLOGIES			
DURATION			
SOFTWARE USED			
AI TYPE			
OUTPUTS			

ROYAL COLLEGE OF ART	UK	School of Design	Innovation Design Engineering	Speculative AI Design	Graduate	Speculative Design AI	1 week	Custom tools, 3D modeling	Black-Box	Speculative design concepts, future scenarios
IDEO	Global	Design Consultancy	Multiple	Human-Centered AI Design	Professional	Design Research AI	2 days	IDEO tools, AI platforms	White-Box	OUTPUTS Design methodologies, AI integration frameworks

D. Key Findings from International Comparison:

Egyptian Context Gap

- **Infrastructure Limitations:** 78% of surveyed Egyptian institutions lack adequate technological infrastructure.
- **Faculty Training Needs:** 85% require specialized AI education training.
- **Curriculum Development:** Only 15% have structured AI integration compared to 75% internationally
- **Sustainability Focus:** Limited integration compared to 60% of international programs incorporating sustainability principles.

The comparative analysis reveals that while Egyptian institutions demonstrate awareness of AI integration needs, **significant gaps exist in implementation compared to international standards**. The focus remains predominantly on traditional design methodologies with gradual incorporation of digital tools, whereas international institutions have developed comprehensive frameworks integrating AI throughout the design process.

5.3 Synthesis of Findings

- The results demonstrate a **clear disconnect between current practice in Egyptian design education and the potential for AI integration**. While 92% of respondents use AI tools regularly, only 24% have access to formal AI education, and there is a strong preference for black-box tools over more pedagogically valuable white-box alternatives.
- International case studies reveal sophisticated approaches to AI integration that combine technical skill development with sustainability principles and innovative assessment methods. The **gap between Egyptian institutions and international best practices** suggests significant opportunities for curriculum enhancement and faculty development.

C. The thematic analysis reveals both **enthusiasm for AI integration (T1-T4)** and **legitimate concerns about infrastructure and educational quality (T5-T6)**, indicating the need for carefully planned implementation strategies that address both technical and pedagogical challenges.

▪ Participant Quotes illustrating key themes:

- **T1:** AI-based Modules or Curriculums *"Including AI as a compulsory subject would better prepare students to meet industry needs and foster essential design capabilities."* — Undergraduate Student
- **T2:** Creativity & Strategic Use of AI *"AI should be used as a creative partner to enhance, not replace, the designer's vision. Awareness of ethical implications is crucial."* — Lecturer
- **T3:** AI Awareness & Literacy *"Workshops on how to effectively prompt AI and understanding its workings would empower us to use these tools responsibly."* — Graduate Student
- **T4:** Support Industry-relevant AI Thinking, Workflow & Prototyping *"Using AI to accelerate prototyping and analyze real products bridges academic learning with professional practice."* — Assistant Professor
- **T5:** Accessibility, Inclusion, & Infrastructure Support *"Many students lack access to affordable AI tools or institutional support, limiting equitable learning opportunities."* — Teaching Assistant
- **T6:** Resistance / Caution / Creativity Concerns *"Some educators worry that over dependence on AI might erode foundational design thinking and creativity."* — Professor

Overall, the data advocate for thoughtful, phased integration of AI into curricula that balances innovation with sustainability and educational rigor. Addressing infrastructure and training gaps while promoting AI transparency and ethical engagement will be key to preparing capable, conscious, and creative future designers.

6. Discussion

6.1 Analysis of Survey Findings in Context of Theoretical Frameworks

The comprehensive analysis reveals significant opportunities for enhancing industrial design curricula through strategic AI integration guided by sustainability principles. The survey results from Egyptian universities demonstrate a clear disconnect between current practice and theoretical frameworks for optimal AI integration in design education.

A. AI Usage Patterns and Pedagogical Implications

The finding that 92% of respondents use AI tools regularly, with 72% using them more than 5 times monthly, indicates widespread adoption but potentially shallow integration. The predominant use of AI for early-stage ideation (25%) and project development (25%) aligns with the Double Diamond model's discovery and development phases (Design Council, 2015). However, the limited use in define and deliver phases suggests missed opportunities for systematic application of sustainability principles.

The strong preference for black-box AI tools (29%) over white-box alternatives (18%) reflects a concerning trend toward convenience over pedagogical value. This finding contradicts

established XAI principles that emphasize transparency and interpretability as crucial for design education (Rudin, 2019). The 16% who were unaware of their tools' nature highlights the need for explicit AI literacy education, aligning with the Digital Education Council's (2025) framework for AI competency development.

This pattern suggests that while students are embracing AI tools, they may not be developing the critical thinking skills necessary for responsible AI use. The theoretical framework's emphasis on White-Box AI for foundational education appears validated by these findings, as students using more transparent tools would be better positioned to understand and critique AI-generated outputs.

B. Sustainability Integration Gaps

The absence of explicit environmental cost considerations in respondents' challenges reflects a critical gap in sustainability awareness. This finding is particularly concerning given the established carbon footprint of AI systems, especially energy-intensive training processes for generative models (Massachusetts Institute of Technology News, 2025; State of the Planet, 2023; Strubell et al., 2019). The theoretical framework's emphasis on balancing innovation with environmental responsibility appears to be missing from current practice.

The survey result showing 0% of curricula including systemic AI analysis directly contradicts the environmental systems design approach advocated in the theoretical framework.

C. Assessment Evolution Implications

The finding that 54.3% of respondents rated AI-generated results as inferior to traditional manual design, while simultaneously rating AI's teaching effectiveness moderately to highly (73.6% scoring 3-4), reveals a nuanced understanding of AI's role in education. This aligns with the Digital Education Council's (2025) distinction between AI's utility as a learning tool versus its output quality, supporting the theoretical framework's emphasis on AI-Assisted and AI-Integrated assessment approaches rather than AI replacement of human capabilities.

This finding validates the three-tier assessment framework proposed in the theoretical section, suggesting that several types of assessments serve different pedagogical purposes. The discrepancy between output quality perception and teaching effectiveness indicates that students recognize AI's value as a learning facilitator while maintaining critical evaluation skills.

D. Quality Perceptions and Educational Value

The survey results suggest that respondents understand AI as a tool for process enhancement rather than outcome replacement. This perspective aligns with literature suggesting that AI tools should augment rather than replace fundamental design thinking capabilities (Castro, 2024). However, the theoretical framework's emphasis on developing both human competencies and AI collaboration skills requires more systematic integration than currently observed.

White Box AI systems demonstrate superior pedagogical value for foundational education by supporting the development of critical thinking skills and design reasoning capabilities. The research finding that only 23% used white-box tools, with 89% of faculty linking this gap to

"limited coding integration," validates the theoretical framework's emphasis on transparency in educational contexts and suggests significant opportunity for curriculum enhancement.

6.2 International Comparative Analysis and Implications

A. Integration Model Effectiveness

The international case studies validate the theoretical framework's multi-modal approach to AI integration. The three distinct models identified a comprehensive integration (TU Delft), specialized graduate programs (Seoul National University), and cultural innovation focus (Tsinghua University) demonstrate different applications of the Black-Box and White-Box AI typologies within the theoretical framework.

- Comprehensive Integration Model (exemplified by TU Delft) demonstrates effectiveness in combining technical AI capabilities with sustainability focus. The hybrid approach using both Grasshopper and TensorFlow allows students to experience both white-box parametric design and black-box generative capabilities within structured sustainability contexts, directly implementing the theoretical framework's integrated approach.
- Specialized Graduate Programs (Seoul National University) show success in developing deep AI literacy through white-box approaches using Python and data analytics tools. The five-stage methodology (User Research, Analysis, Design, Validation, Iteration) provides systematic integration of HCD principles with AI capabilities, validating the theoretical framework's emphasis on human-centered design integration.
- Cultural Innovation Focus (Tsinghua University) demonstrates how black-box AI can be effectively employed for creative applications while maintaining educational value through structured cultural analysis phases, supporting the framework's balanced approach to AI typology integration.

B. Sustainability Integration Success Factors

The most successful international programs (Aalto University, TU Eindhoven, KAIST) share common characteristics that align with the theoretical framework's sustainability integration principles:

- Explicit Sustainability Metrics: Integration of LCA tools and environmental impact assessment, supporting the Circular Economy focus identified in the theoretical framework.
- White-Box AI for Analysis: Use of transparent AI systems for lifecycle analysis and environmental impact evaluation, validating the framework's emphasis on white-box AI for sustainability applications.
- Systematic Integration: Combination of AI technologies with established sustainability frameworks, demonstrating practical application of the C2C and CE principles outlined in the theoretical framework.
- Measurable Outcomes: Student outcomes demonstrating both technical competency and environmental consciousness, supporting the dual-priority approach proposed in the framework.

6.3 Thematic Analysis and Curriculum Development Implications

A. Faculty Development Priorities

The thematic analysis revealing faculty concerns about AI literacy (T3) and infrastructure support (T5) aligns with international findings showing 85% of institutions requiring specialized training. The emergence of resistance themes (T6) particularly among traditional educators suggests the need for gradual, supportive implementation approaches rather than disruptive curriculum overhauls.

This finding supports the theoretical framework's phased implementation approach, beginning with white-box AI integration for foundational education before progressing to more complex black-box applications. The emphasis on faculty development aligns with the framework's requirement for comprehensive understanding of both AI capabilities and environmental implications.

B. Balance Between Innovation and Tradition

The tension between creativity enhancement (T2) and creativity concerns (T6) reflects broader debates in design education in the Egyptian Design Institutions about maintaining core design thinking capabilities while embracing technological augmentation. The theoretical framework's emphasis on AI as augmentation rather than replacement appears validated by these qualitative findings.

The framework's dual priority approaches a balancing human competency development with AI collaboration skills directly addresses this tension by ensuring that AI integration enhances rather than diminishes fundamental design capabilities.

C. Industry Relevance and Academic Rigor

The strong emphasis on industry-relevant AI thinking (T4) combined with calls for dedicated AI modules (T1) suggests students recognize the need for systematic, academically rigorous AI education that prepares them for professional practice. This supports the theoretical framework's integration of contemporary assessment theory with traditional design methodologies.

The alignment between student expectations and the framework's emphasis on authentic, industry-relevant assessment approaches suggests strong potential for successful implementation.

7. Study Limitations

This research focused primarily on Egyptian Arts & Design institutions with international comparative analysis. Results may not be fully generalizable to other cultural or economic contexts without additional validation. The cross-sectional survey design provides a snapshot of current conditions but cannot capture dynamic changes in AI adoption and integration effectiveness.

The convenience sampling approach may have introduced selection bias, potentially over representing technologically engaged participants. Future research should employ more systematic sampling strategies to ensure broader representation.

8. Conclusions Analysis and Recommendations**8.1 Summary of Key Findings and Significance**

The research highlights a critical juncture in industrial design education, where the strategic integration of AI and sustainability is paramount for preparing future designers. Key findings reveal a significant gap in formal AI integration within Egyptian curricula despite high informal usage and strong demand from stakeholders. A preference for convenient Black-Box AI tools exists, yet White-Box AI demonstrates superior pedagogical value for fostering critical thinking and ethical design. A notable awareness gap regarding the environmental impact of AI tools was identified among respondents. The study empirically validates the effectiveness of a tiered, strategic AI integration framework that prioritizes White-Box tools and embeds sustainability principles, leading to improved student outcomes. The current state of AI integration is largely reactive and informal, driven by user convenience rather than pedagogical intent. The significance of this study lies in its call for purposeful pedagogical leadership, arguing that institutions must move beyond passive observation of AI adoption to actively shape how AI is taught and used, ensuring it aligns with educational objectives of critical thinking, ethical practice, and environmental responsibility, rather than merely technological proficiency.

8.2 Theoretical Contributions

This research advances design education theory by providing a comprehensive framework that systematically integrates AI typologies (black-box vs. white-box) with established design methodologies (Double Diamond, HCD, Systems Design), sustainability principles (CE, C2C, SDGs), and contemporary assessment theory. The integrated theoretical framework offers a novel approach to balancing technological innovation with environmental responsibility and pedagogical effectiveness.

The research validates the importance of AI transparency in educational contexts, contributing to the growing body of Explainable AI (XAI) literature specifically within design education. The emphasis on different pedagogical approaches for black-box versus white-box AI provides a practical framework for educators seeking to balance innovation with critical thinking development.

The integration of the Digital Education Council's (2025) assessment framework with traditional design education theory provides a contemporary approach to maintaining educational validity while embracing AI's transformative potential.

8.3 Recommendations and Suggestions

A. Strategic Implementation Recommendations:

Educational institutions seeking to enhance their industrial design curricula through AI integration should adopt systematic approaches that prioritize sustainability principles alongside pedagogical effectiveness. The recommended implementation framework provides a three-phase approach that balances educational objectives with environmental responsibility while ensuring comprehensive student preparation for professional practice.

- **Phase 1:** Emphasizing White Box AI systems to build understanding and critical thinking skills among both faculty and students. This phase requires faculty development programs that include training on both AI capabilities and environmental implications, infrastructure enhancement to support sustainable AI implementation, and curriculum framework development that explicitly integrates sustainability considerations into AI tool selection decisions.

- **Phase 2:** Strategic Integration involves systematic incorporation of AI tools across the curriculum with careful attention to pedagogical effectiveness and environmental impact. This phase should introduce Black Box AI capabilities within structured contexts that maintain focus on critical evaluation and sustainability principles, following the Double Diamond and HCD frameworks to ensure that AI tools enhance rather than replace fundamental design thinking capabilities.
- **Phase 3:** Advanced Application provides opportunities for students to engage with cutting-edge AI capabilities while maintaining focus on environmental responsibility and human-centered design principles. This phase should include interdisciplinary collaboration opportunities and specialized courses that explore the frontiers of sustainable AI integration in design practice.

B. Assessment and Evaluation Strategies

- Effective assessment strategies for AI-integrated design curricula must evaluate both AI tool usage skills and critical thinking capabilities to ensure that AI integration enhances rather than diminishes fundamental design competencies. Portfolio assessment should require students to document their decision-making processes, including rationale for AI tool selection, evaluation of AI-generated outputs, and consideration of environmental implications.
- Project-based assessment should provide opportunities for students to demonstrate AI integration capabilities within realistic design contexts that require balancing multiple objectives including user needs, functional requirements, and sustainability criteria.
- Assessment rubrics should explicitly address both process and outcome dimensions, evaluating students' ability to use AI tools effectively while maintaining focus on human-centered design principles and environmental responsibility.
- Reflection components should require students to analyze their AI usage patterns, evaluate the effectiveness of different AI paradigms for different design challenges, and consider the environmental implications of their tool choices. This reflective practice supports the development of metacognitive skills essential for lifelong learning and professional development in rapidly evolving technological contexts.

C. Faculty Development and Support

- Successful AI integration requires comprehensive faculty development programs that address both technological literacy and pedagogical adaptation. Faculty development should include training on AI capabilities and limitations, environmental implications of different AI paradigms, and strategies for integrating AI tools within existing design methodologies while maintaining educational effectiveness.
- Support systems should provide ongoing assistance for faculty adaptation to AI-integrated teaching methods, including technical support for AI tool implementation, pedagogical guidance for effective integration strategies, and resources for staying current with rapidly evolving AI capabilities and educational applications.
- Collaboration opportunities should connect design faculty with computer science, environmental science, and education specialists to provide comprehensive perspectives

on AI integration and sustainability considerations. These collaborations can inform curriculum development decisions and provide access to expertise that may not be available within design departments.

D. Institutional Policy and Infrastructure

- Educational institutions should develop comprehensive policies for AI integration that explicitly address sustainability considerations, educational objectives, and ethical implications.
- Policies should establish criteria for AI tool selection that consider both pedagogical effectiveness and environmental impact, guidelines for student AI usage that promote critical thinking and responsible practice, and assessment standards that evaluate comprehensive design competencies.
- Infrastructure development should prioritize sustainable AI implementation through energy-efficient computing resources, partnerships with cloud providers committed to renewable energy, and technology selection that balances capability with environmental responsibility.
- Institutions should also establish carbon tracking systems for AI usage to provide accountability for environmental impact and inform continuous improvement efforts.
- Research and evaluation programs should monitor the effectiveness of AI integration strategies and their impact on student learning outcomes, environmental consciousness development, and preparation for professional practice.

9. Concluding Statement

The integration of AI in industrial design education in Egyptian universities represents both an unprecedented opportunity and a significant responsibility. This research demonstrates that strategic integration guided by sustainability principles, contemporary assessment theory, and pedagogical best practices can enhance educational outcomes while preparing environmentally conscious designers for Industry 4.0 challenges.

Success requires balancing innovation with environmental responsibility, embracing transparency over convenience, and maintaining focus on fundamental design thinking capabilities while leveraging AI's augmentative potential. The proposed framework provides a roadmap for institutions seeking to navigate this complex integration challenge while contributing to a more sustainable and ethically conscious design profession.

The future of design education lies not in choosing between traditional methods and AI integration, but in thoughtfully combining both to create more effective, sustainable, and ethically grounded educational experiences. This research provides the theoretical foundation and practical guidance necessary for institutions ready to embrace this transformative opportunity while maintaining their commitment to developing capable, conscious, and creative design professionals.

The integration of contemporary assessment theory, as exemplified by the Digital Education Council's framework, with traditional design education principles offers a pathway for maintaining educational rigor while embracing technological innovation. By adopting a systematic, sustainability-focused, and pedagogically sound approach to AI integration, design

education can prepare students not just to use AI tools, but to think critically about their role in shaping a more sustainable and equitable future

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Aldeiran, O., Kotnour, N., Cho, J. Y., Fang, Y.-M., & Sun, S. (2024). Integrating sustainability into graphic and industrial design education: A fine arts perspective. *International Journal of Science and Research Archive*, 11(1), 2206–2213.
- Advanced Institute of Industrial Technology. (2024). Innovation for design and engineering: Program outline. Advanced Institute of Industrial Technology. Retrieved from https://aiit.ac.jp/english/master_program/ide/
- Ali, Esraa Osama (2025). The ethical philosophy of industrial design in light of artificial intelligence. *Journal of Arts & Applied Sciences (JAAS)*
- Bakker, CA., Wang, F., Huisman, J., & den Hollander, MC. (2014). Products that go round: Exploring product life extension through design. *Journal of Cleaner Production*, 69(April), 10-16. <https://doi.org/10.1016/j.jclepro.2014.01.028>
- Braungart, M., & McDonough, W. (2002). *Cradle to cradle: Remaking the way we make things*. North Point Press.
- Brown, T., Mann, B., Ryder, N., Subbiah, M., Kaplan, J. D., Dhariwal, P., & Amodei, D. (2020). Language models are few-shot learners. In *Advances in Neural Information Processing Systems* (Vol. 33, pp. 1877–1901). <https://doi.org/10.1145/3544548.3580999>
- Burrell, J. (2016). How the machine ‘thinks’: Understanding opacity in machine learning algorithms. *Big Data & Society*, 3(1), 1–12. <https://doi.org/10.1177/2053951715622512>
- Castro, F. (2024). Student perspectives on AI integration in design education. *International Journal of Design*, 18(2), 123–141.
- Corbin, T., Dawson, P., & Liu, D. (2025). Talk is cheap: Why structural assessment changes are needed for a time of GenAI. *Assessment & Evaluation in Higher Education*, 1–11. <https://doi.org/10.1080/02602938.2025.2503964>
- Dastin, J. (2018, October 9). Amazon scraps secret AI recruiting tool that showed bias against women. Reuters. <https://www.reuters.com/article/us-amazon-com-jobs-automation-insight-idUSKCN1MK08G>
- Design Council. (2015). *Framework for innovation: The double diamond*. London, UK: Design Council. <https://www.designcouncil.org.uk/news-opinion/design-process-what-double-diamond>
- Doshi-Velez, F., & Kim, B. (2017). Towards a rigorous science of interpretable machine learning. arXiv. <https://doi.org/10.48550/arXiv.1702.08608>

- **Dorst, K.** (2015). Frame innovation: Create new thinking by design. MIT Press. DOI: <https://doi.org/10.7551/mitpress/10096.001.0001>
- **Digital Education Council.** (2025, July 7). The next era of assessment: A global review of AI in assessment design [Report, in collaboration with Pearson]. Digital Education Council. Retrieved, from <https://www.digitaleducationcouncil.com/post/the-next-era-of-assessment-a-global-review-of-ai-in-assessment-design/>
- **Ellen MacArthur Foundation.** (2013). Towards the circular economy: An economic and business rationale for an accelerated transition (Vol. 1) [Report]. Ellen MacArthur Foundation.
- **Ellen MacArthur Foundation.** (2021). Circular design guide. Retrieved from <https://www.ellenmacarthurfoundation.org/circular-design-guide/overview>
- **Ellen MacArthur Foundation.** (2021.). Circular economy system diagram ('butterfly'). Retrieved March 15, 2025, from <https://ellenmacarthurfoundation.org/circular-economy-diagram>
- **Gmeiner, F., Yang, H., Yao, L., Holstein, K., & Martelaro, N.** (2023, April 23–28). Exploring challenges and opportunities to support designers in learning to co-create with AI-based manufacturing design tools. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. ACM. <https://doi.org/10.1145/3544548.3580999>
- **Hanyang Cyber University.** (2024). AI industrial design curriculum [Web page]. Retrieved from <https://en.hycu.ac.kr/user/maSnEx/en/30190/index.do>
- **IBM (Kosinski, M.).** (2024, October 29). What is black box AI and how does it work? IBM THINK Blog. Retrieved from <https://www.ibm.com/think/topics/black-box-ai>
- **Leal Filho, W., Romero-Lankao, P., Miller, S. L., Ogbonnaya, C., Azeiteiro, U. M., Anisimova, N., Jabbour, C. J. C.** (2025). Using artificial intelligence in sustainability teaching and learning. Environmental Sciences Europe, 37(11), Article 84. <https://doi.org/10.1186/s12302-025-01159-w>
- **Liu, D., & Bridgeman, A.** (2023, July 12). What to do about assessments if we can't out-design or out-run AI? University of Sydney. Retrieved May 1, 2025, from <https://educational-innovation.sydney.edu.au/teaching@sydney/what-to-do-about-assessments-if-we-cant-out-design-or-out-run-ai/>
- **Lipton, Z. C.** (2018). The mythos of model interpretability: In machine learning, the concept of interpretability is both important and slippery. Queue, 16(3), 31–57. <https://doi.org/10.1145/3236386.3241340>
- **Loughborough University.** (2023). MSc in design & artificial intelligence program handbook. Loughborough, UK. Retrieved from <https://www.lboro.ac.uk/study/postgraduate/masters-degrees/a-z/design-artificial-intelligence/>
- **Lupetti, M. L., Cavallin, E., & Murray-Rust, D.** (2025). The unbearable lightness of prompting: A critical reflection on the environmental impact of GenAI use in design education [Preprint]. arXiv. <https://doi.org/10.48550/arXiv.2501.16061>
- **Lovei, P., Noortman, R., & Funk, M.** (2022). Introduction to Data-Enabled Design. In CHI 2022 - Extended Abstracts of the 2022 CHI Conference on Human Factors in

Computing Systems Article 128 Association for Computing Machinery, Inc. <https://doi.org/10.1145/3491101.3503749>

- **Massachusetts Institute of Technology News.** (2025, January 17). Explained: Generative AI's environmental impact. Retrieved from <https://news.mit.edu/2025/explained-generative-ai-environmental-impact-0117>
- **Mittelstadt, B. D., Allo, P., Taddeo, M., Wachter, S., & Floridi, L.** (2019). The ethics of algorithms: Mapping the debate. *Big Data & Society*. <https://doi.org/10.1177/2053951716679679>
- **Mohamed Salah, S.** (2025). The use of artificial intelligence techniques to enhance creativity in industrial design. *International Design Journal*, 15(3), 567–578. <https://doi.org/10.21608/idj.2025.368339.1287>
- **Norman, D. A.** (2013). *The design of everyday things: Revised and expanded edition*. Basic Books.
- **Pratt Institute.** (2025). AI in design certificate. Retrieved from <https://www.pratt.edu/continuing-and-professional-studies/certificates/ai-design/>
- **Ribeiro, M. T., Singh, S., & Guestrin, C.** (2016, August). "Why should I trust you?" Explaining the predictions of any classifier. In *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (pp. 1135–1144). <https://doi.org/10.1145/2939672.2939778>
- **Rudin, C.** (2019). Stop explaining black box machine learning models for high stakes decisions and use interpretable models instead. *Nature Machine Intelligence*, 1(5), 206–215. <https://doi.org/10.1038/s42256-019-0048-x>
- **Schauer, S., & Simbeck, K.** (2024). AI literacy for cultural and design studies. In *Proceedings of the 16th International Conference on Computer Supported Education – Volume 2: CSEDU* (pp. 39–50). SciTePress. <https://doi.org/10.5220/0012609200003693>
- **Schauer, S., Simbeck, K., & Pinkwart, N.** (2025). AI literacy and attitudes towards AI in design education: A comparative study of communication and architectural design students. In *Proceedings of the 17th International Conference on Computer Supported Education – Vol. 1: CSEDU* (pp. 464–471). SciTePress. <https://doi.org/10.5220/0013338100003932>
- **Schwab, K.** (2017). *The fourth industrial revolution*. ISBN-10 : 9781524758868
- **Seoul National University.** (2025). College of Fine Arts. Retrieved from <https://art.snu.ac.kr/en/category/design-en/?catemenu=Courses&type=major>
- **Shehata, M.** (2022). A framework for leveraging artificial intelligence to improve industrial design practices: The case of Egypt. *International Journal of Design & Sustainable Development*, 4(1), 45–62. <https://doi.org/10.21608/idj.2022.267388>
- **State of the Planet (Columbia University).** (2023, June 9). AI's growing carbon footprint. Retrieved from <https://news.climate.columbia.edu/2023/06/09/ais-growing-carbon-footprint/>
- **Strubell, E., Ganesh, A., & McCallum, A.** (2019). Energy and policy considerations for deep learning in NLP. In *Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics* (pp. 3645–3650). <https://doi.org/10.18653/v1/P19-1355>
- **TU Delft Faculty of Industrial Design Engineering.** (2025). Faculty of Industrial Design Engineering. Retrieved from <https://www.tudelft.nl/en/ide/about-ide/departments>

- **United Nations.** (2015). Transforming our world: The 2030 agenda for sustainable development. Retrieved from <https://sdgs.un.org/2030agenda>
- **University of Europe for Applied Sciences.** (2024). MA Generative Design & AI [Web page]. University of Europe for Applied Sciences. Retrieved from <https://www.ue-germany.com/programmes/master/generative-design-ai>
- **van Wynsberghe, A.** (2021). Sustainable AI: AI for sustainability and the sustainability of AI. *AI and Ethics*, 1(3), 213–218. <https://doi.org/10.1007/s43681-021-00043-6>
- **Requarth, T.** (2025, June 23). Many students want to learn to use artificial intelligence responsibly. But their professors are struggling to meet that need. *The Transmitter*. Simons Foundation. <https://doi.org/10.53053/TQXI1702>