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ARTIFICIAL INTELLIGENCE ASSISTED DESIGN AND INNOVATION FOR INDUSTRY 5.0

Stelian BRAD

Abstract: This paper proposes a reconceptualization of artificial intelligence in design, aligned with the philosophical foundations of Industry 5.0—where innovation is guided by ethics, purpose, and human values. It introduces Unified Design Intelligence (UDI), a framework that integrates four AI roles - explorative, generative, cognitive, and discoverative - to support co-evolutionary design processes. Unlike the use of AI for predefined, task-bound operations, UDI enables AI to contribute to value-driven ideation, contradiction resolution, and context-aware innovation. The framework is validated through case studies in manufacturing, robotics, mobility, and product authentication. Results confirm UDI's capacity to align technological capabilities with societal relevance and ethical foresight, showing that the real shift in Industry 5.0 lies not in what AI can build - but in why and for whom we choose to build.

Key words: Industry 5.0; AI-assisted design; Unified Design Intelligence; Explorative AI; Generative AI; Cognitive AI; Discoverative AI; Ethical innovation.

1. INTRODUCTION

The fourth industrial revolution promised to transform manufacturing and value chains through unprecedented levels of automation, connectivity, and data-driven intelligence. With its roots in cyber-physical systems, IoT, and cloud-integrated infrastructures, Industry 4.0 sought to maximize efficiency, flexibility, and productivity across the board [1]. Yet over a decade later, many initiatives have stalled in pilot phases, failing to deliver measurable returns at scale or to address deeper societal and ecological needs [2]. It became increasingly clear that technology alone is not enough, especially when it lacks alignment with human purpose and systemic meaning.

In response, the vision of Industry 5.0 began to take shape - not as a replacement for Industry 4.0, but as its necessary evolution. This new paradigm places human-centricity, sustainability, and resilience at the core of industrial innovation [3]. It invites us to move from optimizing systems to rethinking the very goals we pursue. In this light, the role of artificial intelligence also changes fundamentally. No

longer confined to executing predefined tasks, AI is now called to participate in design, reason in context, and amplify ethical foresight.

But this shift requires new models of thinking. We must architect intelligent systems that explore, generate, reason, and reveal. This paper introduces the concept of Unified Design Intelligence (UDI) - an integrative framework that connects four complementary roles of AI in inventive design:

- *Explorative AI*, which broadens the design space by navigating uncharted possibilities.
- *Generative AI*, which creates novel alternatives under constraints.
- *Cognitive AI*, which aligns results with purpose, ethics, and feasibility.
- *Discoverative AI*, which uncovers latent contradictions, unmet needs, and emergent insights.

Each of these roles supports a different cognitive layer of human-AI collaboration, not to replace human ingenuity, but to enrich it. Through real-world case studies in the electrical industry, urban mobility, anti-counterfeiting in engineered wood products, and a multi-role robotic platform for agile factories, we illustrate

how UDI enables co-evolution between design logic and societal need. The result is not limited to more intelligent systems, but more responsible ones.

Ultimately, this paper argues that the real frontier of Industry 5.0 is not technological. It is philosophical. It asks not just *what can we build?* but *what should we build - and why?*

2. FROM INDUSTRY 4.0 TO INDUSTRY 5.0 AS A NECESSARY EVOLUTION

Industry 4.0 emerged with the ambition to digitize manufacturing through the integration of intelligent automation, real-time data, and interconnected systems [4]. Enabled by technologies such as the Industrial Internet of Things (IIoT), big data analytics, robotics, and cyber-physical systems, this revolution aimed to elevate industrial performance by orders of magnitude. In many ways, it succeeded - at least technically.

However, beneath the surface of smart factories and digital twins, cracks began to show. Despite massive investments, many initiatives yielded limited return on investment and struggled to scale beyond prototype stages [5]. In what has come to be called "pilot purgatory," organizations found themselves showcasing advanced technologies without integrating them into their core operations. The reasons were manifold: legacy infrastructures incompatible with modern platforms, unclear value propositions, prohibitive integration costs, and - most critically - a disconnection from human and organizational context [6].

What Industry 4.0 lacked was not intelligence, but intent. It optimized processes for performance but overlooked meaning. It automated tasks but failed to elevate human roles. As systems grew more complex, the gap between technological capability and societal relevance widened. The lesson was clear: progress without purpose leads to stagnation, not evolution.

Industry 5.0 responds to this systemic shortfall. It does not discard the digital backbone of Industry 4.0, but repositions it within a higher-order framework - one where technological advancement is guided by ethical foresight, ecological balance, and human dignity

[7]. It is a civilizational correction: a recognition that we cannot design resilient futures if we exclude people from the center of the process.

The core values of Industry 5.0 are not just slogans - they are design imperatives:

- *Human-centricity* means designing systems that empower, not displace, human beings. It values cooperation over replacement, dignity over speed, and meaning over metrics.
- *Sustainability* demands that we align innovation with the limits of planetary resources and the needs of future generations.
- *Resilience* acknowledges that efficiency is no longer enough. In a world shaped by volatility, systems must adapt, self-correct, and evolve in real-time.

This shift opens a new space for Artificial Intelligence - one where its role is no longer that of a silent executor, but of an active co-designer. It is in this context that Unified Design Intelligence (UDI) becomes a foundational concept. By weaving together multiple forms of AI reasoning, UDI enables innovation processes to become both more creative and more responsible, grounded in real human needs, and open to the futures we have yet to imagine.

3. INNOVATION WITH INTENTION

Innovation is never a neutral act. Every technological choice is implicitly a value statement - a declaration of what we consider meaningful, for whom, and at what cost. The discourse surrounding Industry 5.0 calls for a deeper reflection on this premise: that not every idea that can be engineered necessarily deserves to be realized. The guiding principle must shift from feasibility to intentionality.

This transition reflects a growing awareness that efficiency and novelty, while essential in previous industrial revolutions, are insufficient as sole drivers of design in a world shaped by social fragmentation, ecological strain, and ethical uncertainty [8], [9]. Industry 5.0 introduces a corrective logic that places human dignity, societal inclusion, and long-term planetary well-being at the center of innovation processes [10].

We propose that *intentional design* - the conscious alignment of design outputs with desired futures - becomes a central philosophy

in engineering and innovation. This orientation demands the integration of ethical foresight from the earliest phases of idea generation and problem framing. In this context, intelligence - whether human or artificial - must be steered by purpose, not just performance.

3.1 Principles of moral innovation

The movement toward purposeful design requires a new moral framework. In contrast to the value-neutral ethos of optimization, *moral innovation* insists that design must be accountable, inclusive, and sustainable by default [11], [12]. We articulate this framework through four interdependent principles:

- *Accountability over Brilliance*: Technological sophistication is not an ethical substitute for responsibility. If no agent or institution is accountable for the impact of an innovation, its intelligence is irrelevant to its legitimacy [13].
- *Long-Term Impact over Short-Term Gain*: Innovation must be assessed not only in terms of immediate returns but also in terms of its structural and intergenerational consequences. Resilience, not volatility, should define success [14].
- *Inclusion over Optimization*: Design must recognize the plurality of human experience. Optimization for efficiency often marginalizes edge cases, which represent real people. Systems that exclude are not efficient; they are incomplete [15].
- *Purpose over Possibility*: The availability of technology does not justify its deployment. Ethical justification must precede technical implementation. Innovation must serve articulated, justifiable goals rooted in social and ecological well-being [16].

This framework does not argue for less innovation. It argues for more relevant, resilient, and responsible innovation.

3.2 Reframing intelligence

A fundamental limitation of the Industry 4.0 paradigm lies in its implicit assumption that technological sophistication is inherently valuable. In reality, innovation devoid of ethical grounding risks reinforcing systemic blind spots. As we move toward Industry 5.0, the question is

no longer how much we can automate, but *why* we automate - and what kind of futures we enable in the process.

3.3 Reframing the scope of Industry 5.0

Industry 5.0 retains production as a key domain but reframes its purpose. It promotes *human-machine collaboration* through technologies such as collaborative robots and wearable augmentations, not as a means to replace human labor, but to support human capacity [17]. Flexible production, informed by AI and real-time data, allows for *mass customization*, where systems adapt to contextual requirements, rather than enforcing standardization. Moreover, *decentralized and resilient supply chains* are emphasized over centralized optimization. Localized adaptability is viewed as critical to coping with disruptions, whether environmental, geopolitical, or epidemiological [18]. Circular manufacturing models further embed environmental sustainability directly into system architecture, reinforcing the shift toward *energy-aware and regenerative industry* [19].

In the Industry 5.0 framework, *product design is elevated from functional optimization to moral responsibility*. Products are no longer designed merely for performance or market share, but for human and ecological well-being. For example, emotionally adaptive vehicles, health-integrated devices, and ergonomic tools reflect a growing commitment to user-centered and culturally aware design [20].

Sustainability is no longer treated as a post-design consideration. Instead, it becomes integral to the design process itself, encompassing materials, energy use, disassembly, and lifecycle strategy. Furthermore, inclusive design practices ensure that diversity across ability, age, and culture is embedded from the outset. This approach reflects the recognition that design must serve all, not the statistically average user [21].

A significant departure from previous models lies in the reframing of *business models and innovation ecosystems*. Industry 5.0 promotes *distributed value creation*, where co-design occurs across networks of stakeholders, rather than within isolated firms. Servitization models

- particularly *product-as-a-service* offerings - redefine ownership, shifting the emphasis from material acquisition to usage, performance, and lifecycle responsibility [22].

In this context, *AI-supported co-design and real-time decision-making* become essential. Intelligent systems assist not just in operational tasks, but in dynamic ecosystem navigation. Furthermore, evaluation metrics are being restructured to include *societal and ecological impact indicators*, moving beyond conventional key performance indicators (KPIs) centered solely on profit [23], [24].

This shift requires us to embed Artificial Intelligence not only in production systems, but within the creative and reflective stages of design itself. When AI becomes a partner in shaping questions, framing possibilities, and surfacing unintended consequences, it transcends its traditional role. It no longer merely executes - it participates. It helps navigate complexity, illuminate contradictions, and reveal design directions that are ethically, socially, and ecologically aligned.

Thus, the focus of research must also evolve. We can no longer afford to evaluate AI solely through metrics of performance. We must investigate how AI can support meaningful, value-sensitive, and adaptive innovation processes, particularly in environments where complexity, uncertainty, and responsibility intersect. This leads us to the central research question of this paper: *How can Artificial Intelligence meaningfully assist human-led design and innovation processes to meet the ethical, sustainable, and adaptive requirements of Industry 5.0?*

4. RETHINKING THE ROLE OF ARTIFICIAL INTELLIGENCE FROM IMITATION TO INVENTIVE DESIGN

The prevailing narrative surrounding Artificial Intelligence in design tends to oscillate between exaggerated optimism and dystopian caution. Too often, AI is framed as a substitute for creativity - a tool that will independently generate novel designs, bypassing the need for human insight. This view is misleading and strategically counterproductive. AI is not the future of design in itself - it is a *mirror of our*

thinking. Its contributions are fundamentally shaped by the quality of the assumptions, intentions, and knowledge we encode into its learning process.

4.1 The echo chamber effect of conventional artificial intelligence use

Modern AI systems operate through probabilistic modeling, trained on large datasets that reflect existing preferences, behaviors, and biases. As a result, generative outputs tend to represent *compressed probability spaces*, offering what is most statistically likely rather than what is truly novel [25], [26].

If AI is trained on mediocre inputs, it amplifies mediocrity. If it is trained on bias, it institutionalizes that bias. And if design intent is vague or undefined, AI will return results that mimic existing solutions, not because it lacks intelligence, but because it *lacks direction*. In this context, AI becomes an echo chamber of historical patterns rather than a portal to future possibilities.

This recognition reframes the role of AI: it does not *create better design* on its own. Instead, it *exposes the limitations of our thinking*. As such, AI must not replace human foresight and purpose - it must *amplify it*, provided we intervene with clarity and intent.

4.2 AI as an inventive partner

True innovation is born from *contradiction, curiosity, and constraint*, not from precedent. This is where *AI-assisted inventive design* begins. Not in CAD tools, nor in optimization loops, but in the articulation of new value systems, contradictions to be resolved, and futures to be made thinkable.

To serve this function, AI must be trained not only on data but on *values, purpose, and possibility*. This shift calls for a methodological realignment. AI should assist designers in:

- Identifying latent needs and contradictions through pattern mining.
- Generating a wide range of valid design alternatives under structured constraints.
- Simulating trade-offs in real time to support reflective iteration.
- Supporting strategic foresight by mapping innovation trajectories [27], [28].

4.3 A four-stage model for AI-assisted design

We propose a four-stage framework where AI meaningfully supports the design process from ideation to strategic validation. Unlike conventional workflows, this model integrates machine reasoning with human purpose at each step, as it is shown in Fig. 1.

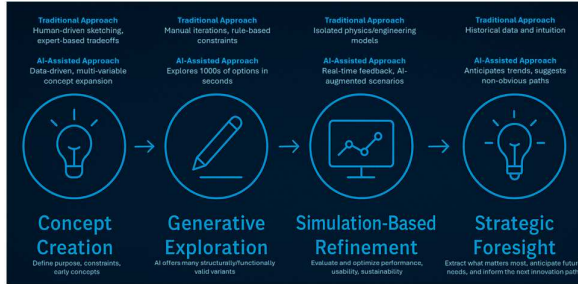


Fig. 1. A four-stage model for AI-assisted design.

- *Concept Creation*: Define human-centered constraints and intent. AI assists in surfacing needs, contradictions, and contextual signals (e.g., behavioral data, environmental triggers).
- *Generative Exploration*: AI explores wide-ranging solution spaces, producing numerous structurally and functionally diverse variants, expanding what human imagination alone might overlook.
- *Simulation-Based Refinement*: AI enables rapid scenario testing and feedback integration, optimizing for sustainability, usability, and resilience, without physical prototyping.
- *Strategic Foresight*: AI identifies systemic risks and opportunities, aligns outcomes with long-term societal trends, and recommends design pathways with future relevance [29].

This model transforms the role of AI from an automation tool to a *cognitive augmentation system*, where its strength lies not in replacing design but in helping discover it. To operationalize the proposed four-stage model for AI-assisted inventive design, we present two illustrative case studies. Each example demonstrates how AI, when aligned with purpose and human-led exploration, can transcend automation and function as a co-creator of meaningful and contextually relevant innovation.

4.4 Case study: Designing a smart, sustainable urban bike

Urban mobility remains a persistent challenge in many cities, where dense traffic, limited infrastructure, and environmental concerns converge. In this case, the AI system was tasked with identifying emerging needs in sustainable urban transport through large-scale analysis of mobility data, commuter frustration indicators, and sustainability regulations (e.g., CO₂ targets).

- *Concept Creation*: The AI identified the need for a lightweight, foldable, electric-assisted bike tailored for short, multi-modal urban commutes. The initial insight emerged from patterns in urban flow data and social sentiment analytics.
- *Generative Exploration*: Hundreds of frame geometries were generated, each balancing weight, strength, and foldability. Many configurations challenged conventional engineering intuition, enabling novel combinations of modular integration and ergonomic structure.
- *Simulation-Based Refinement*: Each concept was tested in AI-augmented simulation environments, assessing crash resilience, vibration dampening, and folding/unfolding durability. Iterative feedback loops allowed structural components to evolve in real time.
- *Strategic Foresight*: The system proposed biodegradable materials for non-load-bearing parts and modular electronics for long-term reparability, aligning the product with circular economy principles and future regulatory landscapes.

See the proposed concept in Fig. 2.



Fig. 2. Urban electric bike concept.

The result is more than a better bike. It is a *reframed product archetype* designed for

sustainability, adaptability, and modularity from the ground up.

Unlike traditional foldable bikes that use obvious hinges and brackets, this concept features a *vertical (z-axis) folding mechanism*. The folding hinge is *eccentrically placed and beautifully integrated* into the frame line, allowing the bike to fold *laterally* while standing *vertically*. There is no visual clutter - clean, monocoque-inspired surfaces. The frame is *designed for modular integration* (e.g., sensors, smart locks, lightweight batteries). Technology *serves the user invisibly* - there is *no overload of visible tech elements*. It is prepared for *future upgrades* without needing to redesign the body. It supports *upright riding posture* for better comfort in urban environments. Its *soft geometry* minimizes impact points on the body. Materials are selected for *vibration damping*, improving daily usability. It includes *repairable and recyclable* components (biodegradable plastics for non-structural parts, modular electronic bays). It promotes a *longer life-cycle* and easy upgrades - no planned obsolescence. Also, it fits Industry 5.0's philosophy of *resilient and sustainable products*. The visual design expresses *calm, balance, and trust*. It doesn't scream "performance" or "speed" - it speaks of *purposeful urban living*. And it fosters *emotional attachment*, encouraging long-term use rather than replacement.

4.5 Case study: Discovering “Responsive Rest Pods” for cognitive recovery at home

The second example explores a novel product category discovered through an AI-driven exploration of behavioral and emotional needs in post-pandemic home living. NLP models analyzed millions of digital content sources, from product reviews to social media discussions, to identify patterns in psychological discomfort, environmental stress, and hybrid work routines.

- *Concept Creation*: The AI surfaced an unmet need for *dynamic environmental experiences* in home spaces, particularly among users in static or overstimulating indoor settings. It revealed latent emotional fatigue linked to poor lighting, low movement, and confined sensory environments.

- *Generative Exploration*: Using cross-domain constraints, the AI proposed combinations such as biofeedback lighting, modular kinetic walls, and multi-sensory pods. These were not incremental improvements - they were *entirely new product typologies*.
- *Simulation-Based Refinement*: AI simulated interactions with these ambient environments, evaluating airflow, acoustic diffusion, visual modulation, and physiological effects on mood. With VR, human response data (e.g., heart rate, voice tone) refined usability features iteratively.
- *Strategic Foresight*: Long-term trend scanning linked the design to neurotech integration, elderly care, and overstimulated professionals. It recommended material sustainability choices and platform-based modularity to ensure longevity.

The resulting solution - *Responsive Rest Pods* - represented an original innovation class, emerging at the intersection of well-being, AI, and spatial design (Fig. 3). Importantly, AI did not optimize existing products. It helped us *discover a new one*.



Fig. 3. Responsive rest pods.

The pod dynamically *adapts lighting, sound, and kinetic wall movements* based on the user's biofeedback (heart rate, breathing, emotional states). *Real-time sensing* transforms the environment into an *extension of the user's inner state*, creating personalized relaxation or stimulation. Unlike static pods, this uses a *dynamic modular wall* that *moves softly* to simulate calming natural rhythms (like breathing waves, ocean ripples). It creates *immersive, evolving spatial textures* - a new dimension of spatial experience. *Visuals, sound, touch, and possibly even smell* are integrated harmoniously.

No single dominant stimulus - the system creates a *holistic, subtle atmosphere* that supports emotional regeneration. The pod *does not interfere* with wearables or wires. It *passively collects bio-data* through seat pressure sensors, microclimate monitoring, or infrared (IR) analysis, respecting user comfort. No mechanical complexity is visible. The pod is shaped like a *soft organic form* (egg/seed/cocoon) that naturally blends into home or work environments without looking clinical or technical. The AI system *learns* from user patterns and *gradually tunes* the environment to optimize each user's long-term resilience, circadian balance, and mental recovery. It's a *personal emotional twin* - growing with you. Material selection and construction logic support *easy disassembly, recycling, and bio-sourced materials* for non-structural parts. This makes the pod *aligned with Industry 5.0*: resilience, human-centered design, and sustainability.

5. FROM TOOL-AI TO PARTNER-AI

As Artificial Intelligence continues to evolve, its application in design has progressed from mere automation to a *collaborative partner* in creative and inventive processes. Traditionally, AI has been perceived as a tool designed to follow instructions, automate workflows, and classify data. This *Tool-AI* model, although effective in specific task-bound roles, is limited when applied to the creative demands of design and innovation. To fully unlock AI's potential, especially in human-centered design, we must shift towards a *Partner-AI* model, where AI is not just an instrument but a *thinking collaborator*.

5.1 Fundamental differences between Tool-AI and Partner-AI

The primary distinction between *Tool-AI* and *Partner-AI* lies in the *intelligence* they embody and the *role* they play in the creative process.

- *Tool-AI* is narrow, task-specific, and operates within predefined rules. It excels at automating repetitive tasks, optimizing processes, and improving efficiency. However, it *lacks* the ability to generate novel

ideas, challenge assumptions, or reason about complex, uncertain scenarios. It is reactive rather than proactive, and its role in design is to *accelerate existing processes* rather than create new possibilities.

- *Partner-AI*, in contrast, possesses *exploratory, generative, cognitive, and discovery-oriented* capabilities. It assists designers by *co-creating, expanding possibilities, and challenging conventional thinking*. Unlike *Tool-AI*, *Partner-AI* does not simply follow instructions; it *learns, adapts, and thinks* alongside human designers, contributing to the design process with *creativity and strategic foresight*. *Partner-AI* helps to push the boundaries of what is possible by exploring new design spaces, generating novel solutions, and discovering emergent patterns that humans might not foresee (see Table 1).

Table 1

Key differences between Tool-AI and Partner-AI

Aspect	Tool-AI	Partner-AI
Purpose	Executes predefined tasks	Co-creates and explores possibilities
Logic	Follows rules and inputs	Learns, adapts, reasons
Role in Innovation	Accelerates what is already defined	Challenges assumptions, opens new paths
Scope	Narrow, task-specific	Explorative, generative, and contextual
Human Interaction	Used as an instrument	Engaged as a thinking partner

In practical terms, *Tool-AI* and *Partner-AI* can be seen as working together in a complementary manner, where *Tool-AI* handles well-defined, rule-based tasks while *Partner-AI* fosters creativity, innovation, and systemic thinking.

5.2 The Four Dimensions of Partner-AI

For innovation to flourish, *Partner-AI* must operate across four distinct dimensions: *Explorative, Generative, Cognitive, and Discovers* (see Fig. 4).

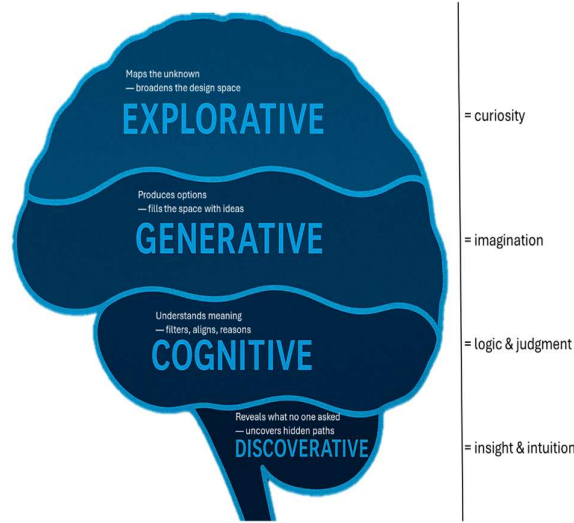


Fig. 4. Partner-AI dimensions of exploration.

Each of these roles empowers AI to engage with the design process in a unique and transformative way.

Explorative AI: This AI navigates the unknown by exploring diverse design spaces, testing unconventional paths, and revealing options that humans may overlook. It is curiosity-driven, focusing on *possibility* rather than goal-oriented outcomes. The *explorative* nature of AI broadens the design space, uncovering *unseen patterns* and contradictions that lead to novel insights. Fig. 5 highlights the main aspects of Explorative AI.

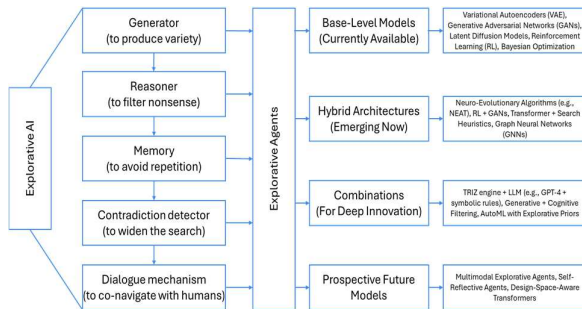


Fig. 5. Explorative AI architecture, models, and tools.

Generative AI: AI in this capacity creates new content or structures by learning patterns and reassembling elements in innovative ways. It is *creative under constraints*, ideal for generating design variants or entirely new concepts. Generative AI fills the space with diverse ideas, enriching the design process by proposing solutions that may not have been initially considered (see Fig. 6).

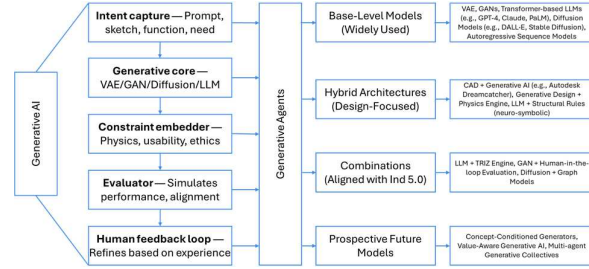


Fig. 6. Generative AI architecture, models, and tools.

Cognitive AI: This type of AI understands context, logic, and purpose. It reasons, adapts, and aligns its outputs with human intent, not just generating but *making sense* of the design space. Cognitive AI enables deeper collaboration with humans, allowing for the *co-creation of conceptual solutions* that reflect both *human values and design objectives*. The framework of Cognitive AI is shown in Fig. 7.

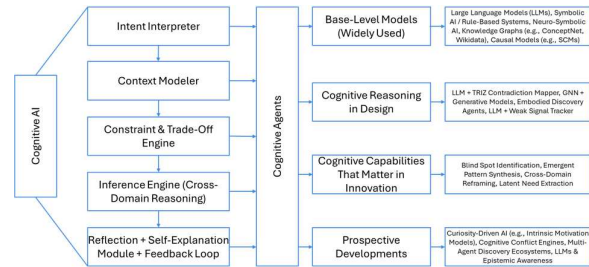


Fig. 7. Cognitive AI architecture, models, and tools.

Discoverative AI: This role goes beyond generative tasks, focusing on uncovering hidden contradictions, emerging needs, and insights from complex systems. Discoverative AI *anticipates* opportunities by revealing what was previously unasked, allowing for *breakthrough innovations* that emerge from the *unknown*. The framework of Discoverative AI is shown in Fig. 8. *Discoverative* is not yet a widely established term in AI discourse; therefore, its usage requires careful definition to ensure conceptual rigor and avoid ambiguity.

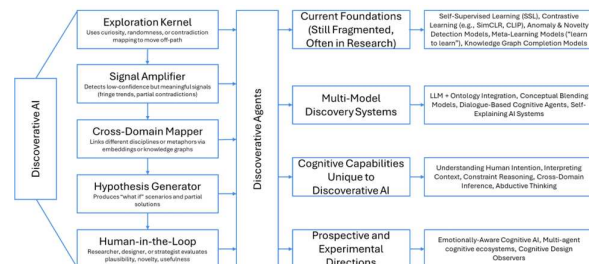


Fig. 8. Discoverative AI architecture, models, and tools.

5.3 Design as evolutionary intelligence

When combined, these four roles create a *closed-loop system* that mimics *evolutionary intelligence* (see Fig. 9).

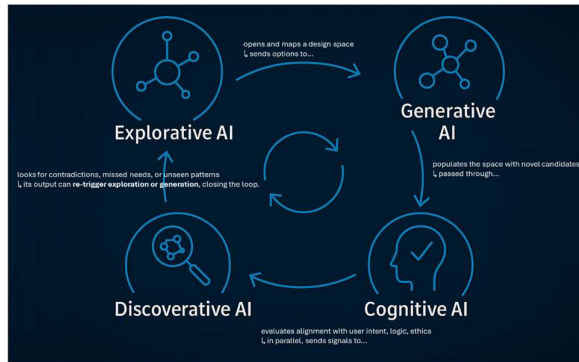


Fig. 9. Design as an evolutionary intelligence cycle.

The cycle starts with *Explorative AI*, which opens the design space by seeking new opportunities. These insights feed into *Generative AI*, which fills the space with diverse solutions.

As the system iterates, *Cognitive AI* evaluates the viability of these solutions, ensuring that human goals and constraints are met.

Finally, *Discoverative AI* uncovers unforeseen possibilities or contradictions, prompting further exploration or refinement of the design space.

This cycle continuously evolves the design, facilitating innovation that is *adaptive*, *resilient*, and *human-centered*.

6. UNIFIED DESIGN INTELLIGENCE AND THE HUMAN-AI CO-EVOLUTION IN INNOVATION

In the context of Industry 5.0, innovation is no longer a linear or mechanistic process. Instead, it is an emergent phenomenon, shaped by the dynamic interplay between human cognition and artificial intelligence. The Unified Design Intelligence (UDI) architecture proposed here reflects this shift - from automation to co-evolution.

It integrates four distinct yet interdependent AI roles: explorative, generative, cognitive, and discoverative. These are not merely modules, but cognitive extensions of human capabilities.

6.1 Architecture and functional integration

UDI is not a static pipeline. It is a fluid, reconfigurable architecture tailored to each design context. The *explorative* component probes the design space, revealing unconventional paths, contradictions, and missed needs. It triggers the generation of novel variants through *generative* models such as GANs, diffusion systems, and transformers, guided by cognitive filters that ensure alignment with human values and technical feasibility.

The *cognitive* module, powered by neuro-symbolic engines and knowledge graphs, serves as the logic core. It filters outputs, checks ethical alignment, and helps maintain systemic coherence. Finally, the *discoverative* module acts as an epistemic scout, revealing what was not being asked - latent tensions, blind spots, or untapped intersections. Together, these modules are coordinated by an *orchestration* and *memory* unit that adapts in real-time, avoids design loops, and incorporates user feedback preferences over time (Fig. 10).

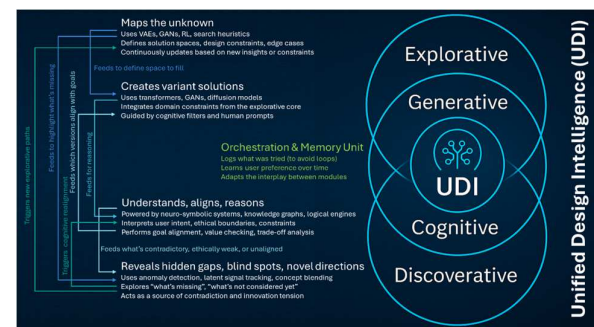


Fig. 10. Unified Design Intelligence framework.

6.2 Human-AI symbiosis

What differentiates UDI from traditional design-support systems is its human-centricity. Industry 5.0 calls not for AI supremacy, but for AI-human synergy. UDI reflects this by enabling an ethical symbiosis: humans contribute empathy, intuition, ethics, and narrative reasoning; AI contributes speed, memory, and combinatorial power. This dual-helix dynamic aligns with a deeper shift in design philosophy - from solving problems to evolving intentions.

A fundamental tenet of the UDI approach is flexibility. Unlike rigid design pipelines, UDI supports the reconfiguration of workflows and

AI module sequences based on context-specific needs. Human agents define the problem, tune the AI's boundaries, and govern its evolution through iterative feedback.

This marks a departure from "AI-as-tool" to "AI-as-partner," making the system not only responsive but also reflexive.

7. CASE STUDIES IN UNIFIED DESIGN INTELLIGENCE (UDI)

The theoretical framework of Unified Design Intelligence (UDI) presented in the previous section provides a structured, modular, and co-evolutionary architecture for enabling advanced design and innovation with artificial intelligence.

However, the relevance of this architecture must be substantiated through real-world applications to highlight both its conceptual validity and its transformative potential in practice.

In what follows, we present a series of four case studies that demonstrate the application of the UDI framework across diverse design challenges.

7.1 Case study: Designing a wire assembly gripper for electric modules

In modern electronics manufacturing, wire assembly remains a critical bottleneck due to its high sensitivity to positioning tolerances, cable variability, and the need for adaptive manipulation. To address this challenge, the Unified Design Intelligence (UDI) architecture was instantiated using a hybrid of pre-trained foundation models, symbolic logic engines, evolutionary algorithms, and multi-agent cognitive modules. Each module in the UDI architecture played a distinct role:

- *Data Enhancement*: Initial input came in the form of a CSV file detailing physical constraints—material properties, geometric bounds, and motion parameters. This data was structured and semantically enhanced using a GPT model prompted via Python scripting to translate engineering terms into promptable formats.
- *Explorative AI Layer*: A heuristic combinatorial search algorithm (Python-based) was employed to define the solution space.

Constraint-based filtering reduced the candidate space using application-specific logic.

- *Neuro-Symbolic Reasoning Layer*: A TRIZ-driven symbolic logic system filtered potential configurations based on contradiction matrices and complexity trade-offs. A custom rule-based multi-agent model coordinated evaluations across multiple design axes (e.g., stiffness vs. grip precision).
- *Generative AI Layer*: Leveraging GPT-4 and diffusion models, conceptual variants were generated as sketches and parametric CAD model proposals. Design prompts were fine-tuned based on human feedback and functional goals.
- *Discoverative Layer*: Novel combinations were proposed using anomaly detectors, failure-spotting modules, and contradiction overlays. This layer also included exploratory hypothesis generation using conditional GANs and reinforcement-driven LSTM modules tuned to seek outlier configurations.
- *Cognitive AI Layer*: The semantic and functional validity of proposed designs was assessed via GPT-based explainers and CSP models. Ontological filters applied ethical, ergonomic, and usability rules, refining the solution space through feasibility reasoning.
- *Human Feedback Loop*: Expert designers interacted with the system through GPT-guided dialog. Rationales were explained, trade-offs evaluated, and scores were manually assigned for criteria like manufacturability, adaptability, and safety.

The resulting solution, visualized in Fig. 11, featured a modular robotic gripper with dynamic actuation and wire-guiding architecture.

Designed for high precision and adaptability, it included a dual-mode grip mechanism, modular geometry optimized for additive manufacturing, and compatibility with sensor-based error detection.

The final concept was not selected from a list of pre-programmed options but was sculpted iteratively, through a dialog between algorithmic suggestion and human judgment.

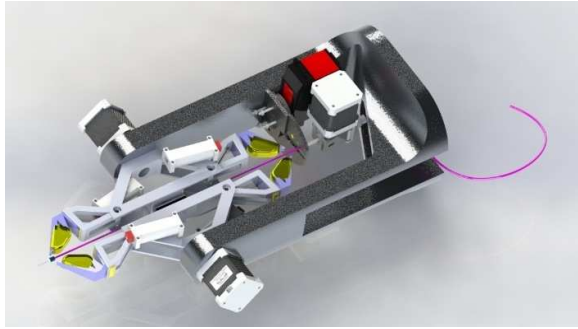


Fig. 11. CAD rendering of the AI-generated wire assembly gripper.

7.2 Case study: Designing an adaptive micro-mobility vehicle

The second case study demonstrates the application of the Unified Design Intelligence (UDI) framework to conceptualize and develop an adaptive micro-mobility vehicle that addresses the pressing demands for safe, sustainable, and inclusive urban transportation. This effort targets environments such as hospitals, airports, senior living campuses, and smart cities, where conventional mobility solutions often fall short in adaptability and user dignity.

The project was initiated in response to multiple user- and context-driven requirements: (1) the need for silent and zero-emission operation in indoor and outdoor environments; (2) inclusive usability across diverse user groups such as the elderly, mobility-impaired individuals, and urban workers; (3) design simplicity for low-cost mass production; and (4) reconfigurable architecture for modular attachments, such as trays, sensor modules, or seats. These specifications called for an intelligent mobility system that could dynamically respond to contextual and ergonomic constraints.

The UDI process began with *Opportunity Discovery*, using large language models (LLMs) - GPT-4 and Claude to extract user needs, mine trend data, and identify latent opportunities. Diffusion models simulated future product forms based on semantic prompts, generating early hypotheses grounded in user-centric trends. Next, *Explorative Mapping* used Variational Autoencoders (VAEs) and TRIZ-guided rule overlays to identify unconventional

configurations and simulate their impact through reinforcement learning agents.

In the *Generative Expansion* phase, GPT-4 scripted diverse CAD geometries while GANs and diffusion models generated functionally varied prototypes. These were evaluated in the *Cognitive Reasoning* layer using CSP solvers and semantic ontologies to validate compliance with usability, ethics, and safety. The *Discoverative Layer* further introduced creative challenges, mapping TRIZ contradictions (e.g., low cost vs. adaptability, compactness vs. comfort) and proposing designs that had not been previously considered. Validation used GAN-driven anomaly detection and hypothesis stress-testing.

The *Human Alignment Loop* ensured stakeholder input throughout the design evolution. Human experts contributed through dialog interfaces, UX simulations, and trade-off justification modules, improving the semantic fit between technical feasibility and human values.

The resulting adaptive micro-mobility vehicle (Fig. 12) offers a *high-back ergonomic seat and upright posture*, significantly improving comfort and dignity compared to traditional scooters or wheelchairs.



Fig. 12. CAD concept of the micro-mobility vehicle.

AI-embedded controls enable *context-aware adaptability*, allowing the vehicle to dynamically adjust to users' speed, terrain, and behavior. The *minimalist body design* simplifies manufacturing and lowers failure risk, while the *modular architecture* facilitates easy upgrades or customization. This results in a robust solution aligned with circular economy principles and capable of evolving alongside user needs.

The adaptive micro-mobility vehicle is designed for deployment across a wide spectrum of public and private environments. In *hospitals and medical facilities*, its silent, zero-emission operation and ergonomic design enhance patient mobility and safety. Within *smart cities*, its AI-driven adaptability enables personalized routing and context-aware interaction, supporting urban inclusivity. In *airports and malls*, the vehicle offers user-assisted navigation for individuals with varying levels of mobility. For *senior living facilities*, the design prioritizes dignity and ease of use, fostering acceptance and independence. Lastly, in *industrial campuses and parks*, its modular architecture allows it to transport workers between various locations, as well as tools, and materials, making it a flexible platform for operational efficiency.

7.3 Case study: Designing an anti-counterfeiting solution for engineered wood panels

A Romanian manufacturer of engineered wood panels - such as PAL, MDF, and OSB - was facing a serious threat of intellectual property theft. Counterfeiters, particularly from Asia, were producing visually identical panels and distributing them under false branding in international markets. This illicit practice was not only undermining the company's economic viability but also endangering consumer trust and the broader supply chain of legitimate retailers. Compounding the challenge was the fact that the company's production line could not be modified to accommodate embedded anti-counterfeit elements like metal tags, chips, or QR labels. The rigid nature of the equipment and the homogeneous composition of the panels ruled out any traditional intervention. What was needed was an invisible, system-level protection architecture - something verifiable by authorized users but entirely undetectable to fraudsters.

To address this complex challenge, the design team applied the Unified Design Intelligence (UDI) methodology to construct a non-intrusive, AI-assisted authenticity solution. The process began with *Advanced Cognitive Reasoning*, where a GPT-4-based symbolic logic engine was used to frame the problem and map contradictions using TRIZ principles. These contradictions highlighted the core barriers:

high-speed industrial flow, low margin tolerance for hardware additions, and visually simple material textures. From there, *Explorative AI* modules were activated to search for solutions beyond the immediate domain. Latent diffusion models and graph neural networks were deployed to explore symbolic and visual identity mechanisms in fields as diverse as cryptography, biometrics, and cybersecurity. Semantic search techniques using vector embedding (e.g., FAISS, Pinecone) suggested analogies from unrelated industries that could inspire cross-domain solutions.

Generative AI modules were employed next, producing concept variants and texture encodings using GPT-4 prompts, GANs, and stable diffusion models. These systems created unique micro-textures, dynamic graphical labels, and symbolic identifiers embedded at a logic level to enable invisible authentication. A hybrid symbolic-generative layer ensured that even aesthetic features carried verification logic. Meanwhile, *Discoverative AI* agents simulated attacker-defender dynamics using multi-agent LSTM-GAN systems. These simulations were critical for stress-testing the solution under adversarial conditions. If a generated configuration failed under simulated fraudulent behavior, it was automatically discarded or redesigned. TRIZ-based agents and GPT-based reflective models were used to detect weaknesses and propose revised architectures.

The system also included a *Cognitive Filtering and Human-in-the-Loop* mechanism. Constraint satisfaction solvers validated feasibility in terms of cost, manufacturability, and ethical considerations. Simultaneously, explainability modules such as GPT-4 chain-of-thought agents ensured that human reviewers could understand why certain configurations were approved or rejected. This dialogic loop fostered transparency and built trust in the AI system. Finally, a *Feedback and Learning* mechanism was introduced to capture real-world validation data from retail scanning systems, logistics networks, and fraud reports. These were fed into federated learning networks to continuously adapt and optimize the AI models.

The resulting solution, named GenuineMark (Fig. 13), was a multi-layered authenticity framework combining five core elements.



Fig. 13. Visual concept of GenuineMark.

First, it introduced a physical texture signature - an AI-generated micro-pattern encoded onto the panel surface using non-intrusive rollers. This acted like a fingerprint, visually imperceptible but mathematically unique. Second, an invisible optical layer was integrated via a chemical treatment that activated only under polarized light and was readable with a simple smartphone lens. Third, every panel included a digital twin code, a generative ID stored on a blockchain ledger, verifying authenticity without revealing the code itself - akin to a *zero-knowledge proof*. Fourth, before any product reached the market, it was tested through counter-AI simulation. Only configurations that resisted more than 95% of adversarial attacks were deemed valid. Lastly, a human-AI consumer app was developed to enable visual scanning, encrypted matching, and intuitive feedback, explained by cognitive AI in plain language, making it accessible to non-experts.

This innovation fully embodies the principles of Industry 5.0, with four strategic pillars. First, it is *human-centric*: the system protects not just a product, but the brand's reputation, the consumer's trust, and the jobs and value chain of a legitimate manufacturer. Second, it adheres to *sustainability and ethics* by minimizing waste, preventing exposure to toxic or low-quality imitations, and ensuring fair competition in the marketplace. Third, it is a *paradigm of advanced AI-assisted design*, orchestrating explorative, generative, cognitive, and adversarial intelligences within a robust protection architecture - guided by a human-in-the-loop model that enables judgment, adaptation, and explainability. And fourth, it delivers *industrial*

value through its complex design process, even though the final output may appear as just a label or texture. The real innovation lies in orchestrating multiple intelligent agents, navigating logic and creativity, and integrating seamlessly with logistics and retail environments. GenuineMark proves that design for protection can be just as strategic, sophisticated, and impactful as design for performance.

7.4 Case study: Designing a multi-purpose robotic solution for Industry 5.0

This case study illustrates how Unified Design Intelligence (UDI) enables the creation of a multi-purpose robotic platform that is not just adaptive but capable of evolving continuously in response to changing environments, tasks, and operator feedback. The initial challenge addressed was the need for a versatile robotic solution that could operate in both structured and unstructured environments, supporting various tasks such as rescue, logistics, and manufacturing. The solution needed to handle modular configurations, support AI-in-the-loop adjustments, and co-evolve with its users - ideal for an Industry 5.0 context focused on human-machine collaboration and system resilience.

The design process began with *Mission Framing and Constraint Mapping* using GPT-4 and ontology-driven reasoning systems. This step decomposed complex tasks into machine-executable roles, aligned with functional expectations, ethical limits, and safety boundaries. Next, the *Explorative AI* layer - driven by VAEs, GNNs, and Bayesian optimization - mapped design variants under different operational constraints, while large language models extracted functional logic and reusable modules from engineering documentation. Based on this, the *Generative AI* component proposed full CAD layouts for various configurations and UI modes, combining Python API scripting with diffusion and reinforcement models to explore modular logic paths.

Crucial to this project was the *Discoverative AI* system, which simulated edge cases and uncovered critical stress points using multi-

agent interaction models. These included human-robot-system dynamics, failure loop detection, and contextual TRIZ-based contradiction overlays. Creative anomaly detection mechanisms enabled the system to recognize emergent vulnerabilities in configuration logic. In parallel, neuro-symbolic reasoning tools - including symbolic TRIZ logic engines and Complex System Design Technique (CSDT) interpreters - enabled function-behavior-structure mapping and multi-function alignment within modular robot architecture. *Cognitive Filtering* modules then verified feasibility, ethics, and usability using GPT-based explanation tools and CSP solvers, before entering a human-guided validation phase. Conceptual results are shown in Fig. 14.



Fig. 14. Concept sketches of the robot.

The most innovative element of this robotic solution lies in its evolutionary architecture. Instead of treating design as a fixed launch activity, the robot is embedded with evolutionary resources - unused ports, digital twin synchronization, firmware-level hooks, and adaptive memory - all enabling real-time learning and reconfiguration. If a robot unit fails under a new terrain condition, such as snow, it logs the behavior, sends data to the cloud, and triggers the generation of a new forearm design or locomotion pattern. A recommendation file is produced, complete with part codes, firmware updates, and installation sequences. The operator installs the update, validates performance, and feeds confirmation back into the system.

This solution embodies the strategic principles of Industry 5.0 by prioritizing dynamic human-AI co-evolution. The robot is

not a fixed-function machine but a partner that adapts task flow, voice tone, and interaction logic according to user feedback. It is designed to operate across industrial, public safety, and personalized service domains - reconfigurable for roles ranging from first-responder deployment to tool-assisted co-working in factories. Its evolutionary logic not only enhances operational resilience but also creates a fluid bridge between product use and ongoing design. This is not predictive maintenance; it is *design-in-operation*. Through UDI, the boundary between the lab and the field dissolves, enabling the robot to think, adapt, and co-design the future in partnership with humans.

8. THE ETHICS OF AI AS A CREATIVE PARTNER

Unified Design Intelligence (UDI) does more than optimize innovation - it redefines its moral landscape. As the case studies illustrate, once artificial intelligence becomes a co-designer, the neutrality of technology dissolves. Designers are no longer just problem-solvers; they become moral agents accountable for the consequences of both visible outputs and hidden logic chains. In Industry 5.0, where human-machine collaboration reaches unprece-dented depth, the ethics of innovation is no longer a peripheral discussion - it is a design parameter.

This shift requires moving beyond black-box acceptance of AI outputs. Trust in AI-generated solutions emerges not from blind reliance but from explainability, consistency, and the ability to trace reasoning chains. When AI proposes a configuration, designers must validate not only its function but also its rationale.

This introduces a new balance: not full transparency of every layer, but justified outcomes that preserve interpretability and prevent over-trust. Over-reliance leads to blind spots; under-trust blocks adoption. UDI requires a new mindset: one that transitions from understanding every component to auditing the AI's reasoning and aligning it with intent.

The problem deepens when we consider bias. AI systems inherit human shadows - amplifying the datasets and logic we feed them. Without conscious correction mechanisms, they may reinforce stereotypes, marginalize edge users, or

codify design patterns that serve only the majority.

That's why explainability (XAI) isn't an optional feature - it is essential in domains where safety, dignity, and accessibility matter. UDI-based systems must not only detect bias but explain it and allow human agents to course-correct before models become products. In doing so, designers shift from model users to curators of ethical systems.

This reconfiguration of roles also demands a radical rethinking of intellectual property. When AI contributes to design, who owns the thought? Industry 5.0 reframes this as a question of *collaborative authorship*. If AI is used as a creative instrument - not a creator - then it remains an extension of the human team. It accelerates ideation, but it is still the human who frames the problem, builds or selects models, curates the training data, interprets outputs, and defines what is meaningful. Thus, the ownership of innovation remains with the human entity, so long as AI is used to enhance judgment, not replace it.

In this light, originality does not vanish in a world of generative models - it transforms. The new originality lies in human curation, interpretation, and intent.

Even when trained on collective data, the application of AI in a specific industrial, medical, social, or aesthetic context carries distinct intellectual merit. Therefore, in UDI ecosystems, authorship must be reclaimed through a new framework: one that recognizes shared creativity but ensures final accountability lies with those who shape, justify, and approve the design.

This is the ethical architecture of UDI in Industry 5.0 - where co-creation demands co-responsibility, and where the right to innovate carries the duty to explain.

9. CONCLUSION

This work has introduced a set of novel, interrelated concepts situated within the emerging paradigm of Industry 5.0, where the fusion of human values and machine intelligence redefines both the nature and purpose of technological innovation. At its core, this

research proposes not a singular model, but an integrated epistemological and methodological framework that bridges AI-powered design, systemic reasoning, and ethical co-creation. Among the novel contributions are the Unified Design Intelligence (UDI) architecture, the Discoverative AI Layer, the EvoDesign concept of embedded evolutionary resources, and the AI contradiction engines for ideation under constraint. These are complemented by human-centric mechanisms such as value-sensitive design filtering, explainable reinforcement learning, and feedback loops that recalibrate decision-making not just based on performance, but on social legitimacy.

A central contribution of this paper is the reconceptualization of design intelligence from a predictive, static act toward an adaptive, layered, and continuous negotiation between generative potential and real-world constraints. The Discoverative Layer, in particular, introduces a new cognitive function in AI design frameworks: the ability to simulate divergent futures, test them via multi-agent contradiction logic, and propose novel resolutions beyond optimization. The paper also critically advances the notion of co-authorship between human and AI agents, offering a framework for intellectual responsibility that reclaims human agency in the era of black-box creativity.

The four case studies collectively confirm that the Unified Design Intelligence (UDI) framework enables more than design automation - it supports context-aware, value-sensitive, and evolutionary design reasoning. In the *gripper case*, a key finding was that combining GPT-driven semantic enhancement with neuro-symbolic contradiction resolution led to a marked improvement in identifying viable yet unconventional configurations under tight spatial and functional constraints. Moreover, the ability of generative AI to translate constraint-filtered logic into viable CAD variants demonstrated how language models can serve as creative actuators in tightly engineered systems. In the *micro-mobility project*, the most significant outcome was the realization that UDI's explorative and discoverative layers enabled the design process to engage with users' latent needs and aesthetic dignity, rather than

optimizing for function alone. Generative models expanded morphological space, but it was the neuro-symbolic and human-alignment loops that ensured coherence with societal contexts, proving critical in domains where design affects inclusivity and perception.

In the *anti-counterfeiting solution*, UDI enabled the emergence of a new design genre - invisible, layered protection architectures. Here, the key insight was that discoverative AI, simulating adversarial behavior and ethical failure modes, could proactively generate robustness that traditional linear design cannot foresee. The case also underscored that trust in AI-generated security requires explainability chains, not just encryption. The *robotics case* introduced EvoDesign and demonstrated the value of embedding not only hardware modularity but latent architectural affordances that support post-deployment reconfiguration. The primary finding was that real-time feedback loops - both human and environmental - could be structurally integrated as design resources, turning operational break-downs into learning inputs. This fundamentally shifts the notion of deployment from terminal delivery to continuous design-in-use.

Together, these cases highlight that UDI is not a unifying toolchain but a reasoning architecture that elevates the role of contradiction, human feedback, and AI explainability in inventive design. The framework enables not only intelligent outputs, but the creation of systems capable of *learning*, *justifying*, and *aligning* with human purpose across time and context. This is not simply a new method - it is a new ontology for responsible innovation.

Despite these advances, the research presented here remains bound by several limitations. First, the proposed architectures, though well-structured and theoretically grounded, are demonstrated at a conceptual-prototype level. Comprehensive benchmarking and industrial deployment would be needed to validate generalizability, particularly under the constraints of commercial-scale implementation. Second, the symbolic layers of contradiction analysis, while innovative, require formal integration with legal, regulatory, and organizational ontologies to ensure applicability

in tightly governed domains such as health, defense, or infrastructure. Third, while the human-in-the-loop strategy has been employed throughout, more work is needed to define robust socio-technical metrics that measure alignment with user values, cultural constraints, and evolving ethical standards.

Future research should further explore the cognitive and organizational dimensions of co-design with AI. This includes building longitudinal studies to evaluate how these architectures evolve over time; developing mixed-reality simulation environments for real-time testing of explainability and trust; and refining the theoretical underpinnings of distributed authorship, responsibility, and value co-creation. Furthermore, interdisciplinary inquiry is urgently needed to anchor these technical advances within broader philosophical, legal, and cultural discourses around the future of innovation.

In conclusion, this paper has demonstrated that the real revolution is not AI itself, but the redefinition of design as a collaborative, value-oriented act that is co-shaped by machine capabilities and human purpose. It calls for a new generation of designers: sense-makers who interpret contradictions, bridge-builders who reconcile logic and imagination, and meaning architects who design not only systems, but significance. The future, we argue, will not be built by AI alone - it will be co-authored by deeper minds, wiser systems, and shared intentions.

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Proiectare și Inovație Asistate de Inteligența Artificială pentru Industria 5.0

Lucrarea propune o reconceptualizare a rolului inteligenței artificiale în proiectare, în acord cu fundamentele filozofice ale Industriei 5.0—unde inovația este ghidată de etică, scop și valori umane. Este introdus cadrul Inteligenței Unificate în Proiectare (UDI), care integrează patru roluri ale IA—explorativ, generativ, cognitiv și descoperitor—pentru a susține procese de proiectare co-evolutive. Spre deosebire de utilizarea IA ca instrument de execuție în sarcini prestabilite, UDI permite implicarea acestora în generarea de idei orientate pe valori, în rezolvarea de contradicții și în inovare contextuală. Cadrul este validat prin studii de caz în producție, robotică, mobilitate și protecția produselor. Rezultatele confirmă potențialul UDI de a alinia capacitățile tehnologice la relevanța societală și previziunea etică.

Cuvinte cheie: Industria 5.0; proiectare asistată de inteligență artificială; Inteligență de proiectare unificată; IA exploratorie; IA generativă; IA cognitivă; AI descoperitor; Inovație etică.

Stelian BRAD, PhD, Full Professor, Technical University of Cluj-Napoca, Department of Design Engineering and Robotics, stelian.brad@staff.utcluj.ro, +40 730 017 126, B-dul Muncii 103-105, Cluj-Napoca, Romania.