Journal of Research and Innovation for Sustainable Society (JRISS)
Volume 7, Issue 2, 2025
ISSN: 2668-0416
Thoth Publishing House

DOI: 10.33727/JRISS.2025.2.2:14-19

Integrating TRIZ Methodology with Digital Innovation in Product Design: From Classical Principles to Industry 4.0 Applications

Stefan Ghimisi[1]

[1]Constantin Brancusi University of Targu Jiu, Romania, ORCID:0000-0002-0881-1137

E-mail: ssghimisi@gmail.com

Abstract. This paper revisits the fundamental principles of product design in the context of digital transformation and Industry 4.0. [1]. Building on the conceptual framework of classical methodologies and the Theory of Inventive Problem Solving (TRIZ), it proposes an updated model that integrates artificial intelligence (AI), data-driven processes, and collaborative digital platforms into the design workflow. The study highlights how digital tools enhance creativity, reduce psychological inertia in concept generation, and accelerate innovation cycles. The paper also discusses methodological shifts from analytical and systemic approaches toward hybrid, AI-supported frameworks that connect idea generation, simulation, and prototyping in real time. This integrative perspective provides a foundation for sustainable and intelligent product design capable of addressing the challenges of the modern industrial ecosystem.

Keywords: *Product Design; TRIZ; Digital Innovation; Industry 4.0; Artificial Intelligence; Design Methodology; Smart Manufacturing*

Introduction

Creative activity, informed by articulated needs and existing knowledge, seeks to delineate a material or immaterial item, termed an artifact, that fulfills these criteria and can be classified as an industrial design product (engineering design). The concept is essential for the advancement of a new product design activity, representing the transformation of an invention into innovation. To define design, we must first contemplate the concepts of creation, innovation, and scientific discovery. Innovation is characterized as: - a novelty stemming from an invention, manufactured on a large scale and introduced to the market (Freeman, 1983); - the development of new product concepts through innovative operational procedures or actions related to service provision (Fracasti, 1994); - alignment with actual needs or the attainment of potential market solutions (INSA, 1998).

The invention constitutes a novel technological concept and/or a new technical means that executes a certain function (Freeman, 1983; Kline and Rosenberg, 1986). [2]. To discover signifies to reveal, indicating that a thing already exists and may be sought and located. Inventing, conversely, entails creating something that has yet to exist. Scientific discovery arises from investigation, whereas invention stems from design. idea is impossible without conception, as design facilitates the conversion of an idea into an innovation. The concept of a product encompasses all activities and processes that facilitate the transition from the conception of a new product to its release, enabling production, usage, and maintenance. The development of a product encompasses all actions involved in the creation and dissemination of information that converts market data into actionable insights and technical possibilities for manufacturing, including models, specifications, prototypes, designs, and programs.

The evolution of product design reflects the ongoing tension between creativity and technological advancement. Traditional methodologies, rooted in systematic engineering design, have gradually merged with data-driven approaches that leverage computational intelligence. In the age of Industry 4.0, digital innovation has transformed how products are conceived, designed, tested, and delivered.

This study seeks to integrate the TRIZ inventive problem-solving methodology within a digital framework, proposing an applied pathway for modern engineering design

A product design methodology encompasses the examination of the principles, techniques, and procedures associated with design. It encompasses:
- The cognitive approaches of product developers;
- The establishment of suitable design frameworks;
- The creation and execution of innovative methodologies, strategies, and procedures;
- An analysis of the knowledge base in design and its application to resolving design challenges.

A design methodology can be organized according to three principles of action (Asimov,1962). [3]:
- Divergence - an activity intended to enhance the design of borders to expand research space solutions;
- Processing - the process of constructing a model solution framework based on the logic derived from divergence; it represents a phase of discovery and creativity; Convergence refers to the progressive reduction of uncertainty resulting from numerous potential solutions, aimed at identifying the most satisfactory option. Divergence pertains to analysis, whereas transformation and convergence engage the specific capacities of synthesis.

Design patterns can be categorized into three distinct classifications:
- Prescriptive models that seek to offer a design methodology;
- Descriptive models that try to elucidate the design activities;
- Computational models that focus on the integration of numerical and qualitative artificial intelligence approaches.

A different classification of design patterns is founded on five concepts (Perrin, 2001) [4]:
- Design as a hierarchical succession of distinct phases;
- Iteration of design as a fundamental cyclical process;
- Design as an emergent phenomenon of self-organization based on interaction within a design group;
- Design as a cognitive process;
- Concept as a mode of discourse.

1.Theoretical Background

Classical product design methodologies, as articulated by Pahl and Beitz (1996)[5] and Asimov (1982), emphasize a structured and sequential process that begins with problem identification, followed by concept generation, embodiment design, and finally, detailed prototyping. It is based on the concept of hierarchical sequence of phases , the dominant logic of action being convergence.

These approaches are grounded in engineering logic, where each design stage delivers specific outputs—requirements, functions, and geometries—that feed into subsequent stages. The purpose of such structured methodologies was to reduce uncertainty, standardize design procedures, and enhance reproducibility in engineering outcomes.

Within this traditional framework, creativity was often guided by systematic reasoning rather than spontaneous ideation. The designer's role was to transform functional requirements into physical solutions through careful analysis, decomposition, and synthesis. Pahl and Beitz introduced the concept of a hierarchical design process, in which the product evolves from abstract functions to concrete structures, emphasizing traceability and technical rigor. Similarly, Asimov's design cycle advocated for logical iteration between analysis and synthesis, where divergence and convergence phases alternate until an optimal solution is reached.

The TRIZ theory, developed by Genrich Altshuller in the mid-20th century, revolutionized this understanding by introducing a science of innovation rooted in the systematic study of patents and inventive principles. TRIZ (Teoriya Resheniya Izobretatelskikh Zadatch) provided a toolkit to overcome technical contradictions—situations where improving one aspect of a system degrades another. By identifying recurring patterns of innovation, Altshuller proposed 40 inventive principles and the Contradiction Matrix, which allowed engineers to approach creativity analytically rather than intuitively.

While classical methodologies tend to progress linearly—from problem to artifact—modern design paradigms embrace a non-linear, iterative, and knowledge-intensive perspective. With the advent of digital tools, computer simulation, and virtual prototyping, the design process has evolved into a continuous feedback loop that integrates experimentation, data analytics, and interdisciplinary collaboration. Designers now operate within cyber-physical environments, using real-time information and AI-driven insights to refine and optimize product performance before physical realization.

Therefore, the contemporary view of product design is not merely about structured progression but about adaptive integration—a balance between systematic logic and computational creativity. In this context, TRIZ serves as a conceptual bridge between classical engineering discipline and digital innovation, offering a framework that remains both methodical and flexible enough to support intelligent, data-driven design workflows.

2.Digital Innovation in Product Design

Digital transformation has fundamentally reshaped the landscape of product design, enabling designers to leverage advanced computational tools that integrate intelligence, automation, and connectivity throughout the entire design lifecycle. Modern engineering teams now rely on **computer-aided design (CAD)**, **computer-aided engineering (CAE)**, and **computer-aided manufacturing (CAM)** environments that are seamlessly connected through **digital twins**—virtual replicas of physical systems that simulate real-world performance under variable conditions. These digital twins allow continuous validation of product behavior, enabling early detection of design flaws and optimization of functionality, cost, and sustainability before any physical prototype is produced. [6]

Artificial intelligence (AI) has emerged as a powerful enabler of this digital shift. Through **machine learning (ML)** and **deep learning** algorithms, AI systems analyze vast design repositories, performance data, and user feedback to uncover patterns and correlations that inform design decisions. These algorithms can automatically generate design variants, predict material performance, and even suggest optimal configurations based on multiple, sometimes conflicting, criteria. The role of the designer is thus evolving—from manually exploring possible solutions to **curating and interpreting AI-generated insights** within a strategic design context.

Moreover, **cloud-based collaboration platforms** have transformed how interdisciplinary teams operate. Designers, engineers, and stakeholders can work concurrently on shared digital models, accessing real-time updates, simulation results, and project documentation from any location. This **distributed design ecosystem** supports concurrent engineering, shortens iteration cycles, and reduces time-to-market while maintaining design coherence and traceability.

Beyond efficiency, digital transformation also fosters **greater adaptability and responsiveness** in product development. Through **data-driven feedback loops** and **IoT-enabled product monitoring**, real-world usage data can be continuously fed back into the design process, promoting dynamic product evolution and lifecycle optimization. This convergence of data analytics, AI, and virtual modeling is driving a paradigm shift from reactive design to **proactive, predictive, and adaptive design systems**—a cornerstone of Industry 4.0 and an emerging foundation for the next generation of intelligent product design.

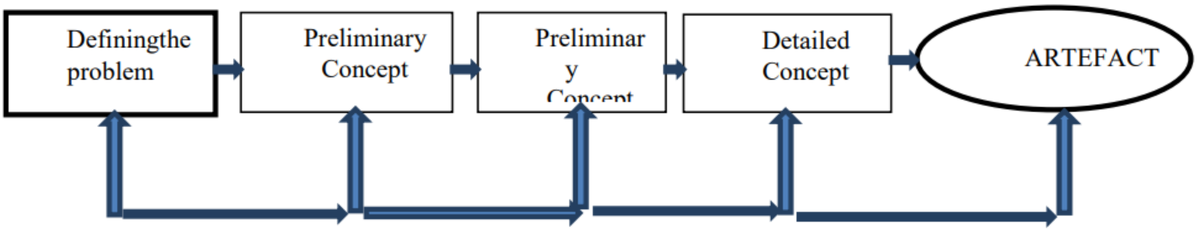

Figura 1. Design phases

3.TRIZ and Digital Transformation

The TRIZ methodology remains highly relevant in the digital era as a structured and systematic approach for overcoming **psychological inertia** and stimulating **creative problem-solving** in engineering design. Originally conceived as a tool for inventive reasoning, TRIZ now serves as a conceptual backbone for digital innovation, helping designers move beyond conventional thinking patterns and explore alternative design paths grounded in scientific and technological principles. Its value lies in its capacity to transform ill-defined problems into solvable contradictions, providing designers with a logical framework to generate inventive solutions systematically rather than through trial and error.

In the context of digital transformation, TRIZ gains new potential when integrated with **artificial intelligence (AI)**, **data analytics**, and **simulation-driven design environments**. AI-powered tools can analyze extensive design data to identify recurring contradictions, inefficiencies, or performance bottlenecks, which can then be directly mapped to TRIZ's inventive principles and contradiction matrix. By linking these contradictions to **digital performance metrics**—such as stress distributions, material consumption, energy efficiency, or lifecycle impact—engineers can prioritize solutions that are not only technically inventive but also sustainable and economically viable.

Hybrid TRIZ–AI frameworks represent a transformative step toward augmenting human creativity with algorithmic reasoning. In such models, machine learning systems can automatically suggest inventive strategies, evaluate the impact of alternative design moves, and rank solutions based on multi-objective optimization criteria. The designer's role evolves into that of a **creative orchestrator**, guiding AI-generated proposals through contextual judgment, intuition, and domain expertise. This synergy between human cognition and computational intelligence fosters a continuous, iterative cycle of innovation, in which data-driven insights refine creative exploration, and inventive logic informs algorithmic refinement.

Furthermore, integrating TRIZ into digital ecosystems aligns with the broader objectives of **Industry 4.0**, where smart systems, interconnected devices, and real-time analytics redefine how design knowledge is created and applied. By embedding TRIZ logic into digital design platforms, organizations can institutionalize innovation—making creativity more predictable, measurable, and repeatable. Thus, TRIZ is not merely preserved in the digital age; it is **amplified** by it, evolving from a human-centered heuristic method into a **cyber-physical innovation framework** capable of supporting the complexity and velocity of modern product development.

Various means developed in TRIZ can cover the entire preconception cycle of a product or system (Table 1). Figure 2 shows the design methods used

4.Illustrative Application: Generic Case Study

To demonstrate the practical integration of TRIZ within the framework of digital product design, a **generic engineering application** is presented. The example focuses on the optimization of a **lightweight mechanical bracket**, a structural component commonly used in machinery and aerospace systems. The design challenge embodies a classical contradiction: the need for **high structural strength** while simultaneously **minimizing material usage** to reduce cost and weight. This type of conflict—between opposing design requirements—represents a typical case where TRIZ can provide a systematic path toward innovation [7], [8].

Using TRIZ principles, the problem is reframed not as a trade-off between strength and material efficiency, but as an opportunity to **eliminate the contradiction** through inventive strategies. Specifically, the **Principle of Segmentation** suggests dividing the structure into optimized sub-elements or introducing lattice or ribbed geometries to distribute stress more efficiently. Complementarily, the **Principle of Dynamization** supports the use of adaptive or gradient materials that adjust stiffness based on local loading conditions. By translating these conceptual directions into a digital modeling environment, the designer moves from abstract reasoning to quantitative validation.

Table 1. TRIZ tools and design cycle[9].

Stages	TRIZ Means
Identifyingthe problem	Questionnaire Laws of evolution
Statingthe problem	Clarification of technicalcontradiction, Model field-substanceconstruction Clarificationphysicalcontradiction
Development of concepts	Matrixsolvingcontradictions, Standard solutions, principles of separation PhysicalEffects, Brainstorming
Evaluation	Ideal final result
Implementation	

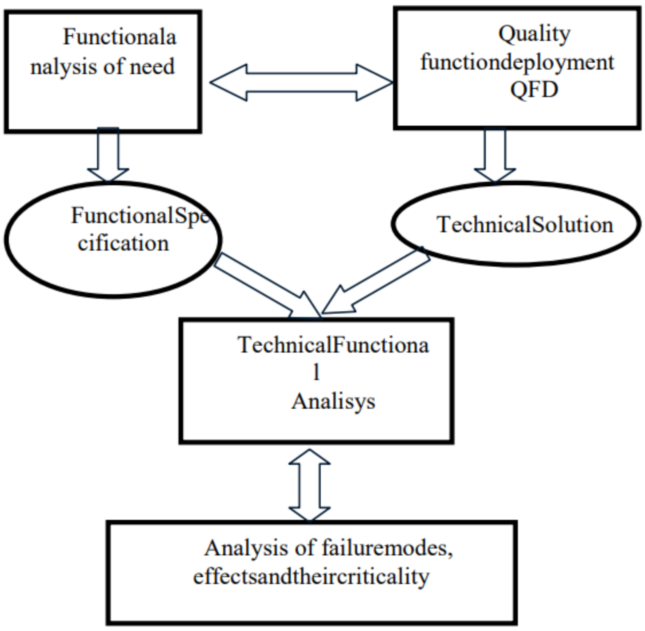

Figura 2 Design methods used

Within an **AI-assisted CAD/CAE environment**, the design space is parameterized and linked to a **finite element analysis (FEA)** engine that evaluates the stress, deformation, and mass distribution across design iterations. AI algorithms—employing optimization heuristics or machine learning models—automatically generate multiple geometry variants using **topology optimization** techniques. Each iteration aims to maximize structural performance while minimizing weight, cost, and environmental impact. The system continuously learns from prior iterations, refining the geometry to converge toward an optimal configuration.

The **integration of TRIZ logic with AI-driven simulation tools** allows the digital workflow to emulate the inventive process traditionally carried out by human designers. Instead of manually testing solutions, the system applies TRIZ principles algorithmically, accelerating the innovation cycle and expanding the exploration space beyond human intuition. The outcome is not a single design solution but a **family of optimized configurations**, each balancing performance and sustainability metrics according to predefined objectives [10].

This generic application demonstrates how **digital product design ecosystems operationalize TRIZ principles** in practice. It exemplifies a shift from reactive to proactive engineering—where design contradictions are identified, modeled, and resolved through iterative computation rather than post-failure correction. The case underscores the transformative potential of combining **systematic inventive reasoning** with **data-driven intelligence**, producing designs that are both functionally superior and environmentally responsible. Ultimately, this integration embodies the essence of **Industry 4.0**, where innovation is guided by both cognitive logic and computational power, leading to more intelligent and adaptive product development processes.

Integrating TRIZ with digital innovation bridges the gap between human creativity and computational efficiency. While traditional design methods rely on experience and intuition, digital systems extend the designer's cognitive capacity through simulation and data analysis. However, the transition to AI-driven design introduces new challenges, such as data dependency, model interpretability, and the need for cross-disciplinary education [11].

5.Conclusions

Concept is key to the development of a new product design activity is one that allows the transformation of an invention into innovation. Concept of a product is defined as all the activities and processes that allow transition from the idea of a new product launch information to allow production to ensure its use and maintainability. There are two methods: systematic and analytical though complementary call differs in approach.

The study confirms that TRIZ remains a valuable framework for systematic innovation, particularly when supported by digital tools and AI. By integrating TRIZ into digital product design workflows, engineers can enhance creativity, efficiency, and adaptability. Future research should focus on developing intelligent TRIZ-based systems capable of autonomous reasoning and adaptive learning, supporting the emerging paradigm of Product Design 5.0.

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