Article

Reshaping Electronics Supply Chain Dynamic Capabilities and Resilience through AI-driven Generative Design: A Theoretical Framework Integrating Design-as-a-Service (DaaS) and Flexible Response

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Abstract: Amidst the dual challenges of vulnerability and customization facing the global electronics supply chain, where traditional PCB design has emerged as a critical bottleneck constraining corporate agility, this study investigates how AI-driven generative design reconfigures supply chain dynamic capabilities and resilience. Employing a mixed-methods approach that combines multiple case study analysis with system dynamics simulation, the findings reveal that AI-driven generative design fosters a novel corporate dynamic capability centered on 'Design-as-a-Service' (DaaS). By decoupling the design and manufacturing stages, this capability significantly enhances the supply chain's flexibility in responding to market volatility and its resilience against external disruptions. Consequently, this paper proposes a theoretical framework that integrates DaaS with flexible response, elucidating the core mechanisms through which AI empowers supply chains and offering strategic guidance for firms navigating digital transformation to build sustainable competitive advantage.Do not regard AI as a mere tool, but rather as a strategy to reshape core corporate capabilities and supply chain ecosystems.

Keywords: Generative Design 1; Dynamic Capabilities 2; Flexible Supply Chain 3

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0. Introduction

The global electronics industry is experiencing unprecedented "new normal" challenges, including escalating geopolitical risks, persistent component shortages (particularly chips), and highly personalized and rapidly iterating consumer demands [1]. The traditional linear design-procurement-production model, with its lengthy processes, has shown evident fatigue under unexpected shocks, leading to significant "bullwhip effects" and insufficient response capabilities. PCB design and manufacturing, as the "mother of electronic products," has become a critical bottleneck for rapid product market entry due to its long cycles, high costs, and poor flexibility.

The emergence of AI (Artificial Intelligence) generative design brings hope for breaking through this bottleneck. It can autonomously generate and optimize thousands of design solutions based on preset constraints such as performance, cost, materials, and manufacturability, transforming the traditionally human experience-dependent "creation" process into "human-machine collaborative exploration" [2]. However, existing research primarily focuses on the application of AI algorithms in engineering fields, with insufficient exploration of their business and strategic value. While management research has addressed supply chain flexibility, it rarely delves into the implementation mechanisms from the core link of "design origin." The internal mechanisms of how AI design technology empowers enterprise core capabilities and drives supply chain model transformation have not been adequately revealed in current literature.

This study aims to fill this gap by deeply exploring how AI-driven generative design reshapes the dynamic capabilities and resilience of the electronics industry supply chain, and by integrating "Design as a Service" (DaaS) and flexible response mechanisms, constructs a comprehensive theoretical framework.

Part I: Research Background and Problem Statement

1.1 Macro Context: The "New Normal" of Electronics Industry Supply Chain

The electronics industry supply chain, due to its inherent complexity and globalization characteristics, appears particularly vulnerable when facing external shocks. Currently, from the ongoing impact of the COVID-19 pandemic to geopolitical conflicts (such as the Russia-Ukraine conflict and US-China trade friction) and frequent natural disasters, the multiple uncertainties in the global economy are continuously amplifying this vulnerability [3]. The recent semiconductor chip shortage serves as compelling evidence, severely impacting key industries such as automotive and consumer electronics, highlighting the risk of core component supply disruption. Simultaneously, consumer market demand for personalized and rapidly iterating products continues to rise, posing severe challenges to traditional mass production models and exacerbating the "bullwhip effect" in supply chains due to distorted supply and demand signals.

1.2 Industry Bottleneck: PCB Design and Manufacturing

PCB is a core component of all electronic products, and its design and manufacturing cycle directly determines the speed of new product market entry. Traditional PCB design processes heavily rely on engineers' experience and skills, often requiring multiple iterations and manual adjustments to meet requirements. Moreover, information asymmetry between the design process and manufacturing side makes it difficult for design solutions to achieve optimal manufacturability, ultimately resulting in high design costs, long development cycles, and difficulty in rapidly responding to market changes, becoming a critical bottleneck in electronic product innovation [4].

1.3 Technological Breakthrough and Research Gap: AI Generative Design

AI generative design technology provides a breakthrough for addressing the aforementioned bottlenecks. Through machine learning, optimization algorithms, and other techniques, AI can rapidly generate numerous design variants that satisfy specific constraints (such as dimensions, performance, cost, materials, manufacturing processes, etc.) and conduct rapid evaluation and optimization. This transforms the design process from traditional serial, iterative mode to parallel, exploratory mode, greatly improving design efficiency and the breadth of design space exploration [5]. For example, in PCB design, AI can automatically route and place components based on electrical performance, thermal requirements, space limitations, and manufacturability rules, and even recommend optimal component selection and material combinations.

Existing research exhibits significant limitations and disconnection when exploring the intersection of artificial intelligence (AI) and supply chain management. On one hand, literature in the engineering and technology fields primarily focuses on the mathematical principles and technical implementation of AI algorithms, while generally lacking in-depth exploration of their potential value and impact at more macro business and strategic levels such as supply chain management. On the other hand, although the management academia has conducted extensive research on supply chain flexibility, resilience, and digital transformation, these discussions rarely trace back to the "source" link of product design, failing to adequately elucidate how AI fundamentally enhances overall supply chain performance by restructuring design processes [6]. Consequently, current literature lacks a clear and complete logical chain that effectively reveals the intrinsic connections between "AI design technology application," "enterprise core capability enhancement," and "supply chain model transformation," making it difficult to systematically understand and comprehensively present AI's deeper strategic value in supply chains.

1.4 Core Research Questions

Based on the aforementioned background and research gaps, this study will focus on the following core questions:

RQ1: How does AI generative design fundamentally change the PCB design process and give rise to new enterprise capabilities?

RQ2: Through what mechanisms do these AI-enabled new capabilities transform into supply chain flexibility and resilience?

RQ3: How should enterprises construct strategic frameworks to maximize the supply chain advantages brought by AI generative design and form sustainable competitive barriers?

Part II: Theoretical Architecture

This study will construct an integrative theoretical framework with supply chain management theory, dynamic capabilities view, and digital transformation and platform ecosystem theory as core pillars.

2.1 Supply Chain Management Theory: Flexibility and Resilience

Supply chain flexibility and resilience are critical capabilities for enterprises to respond to market environment changes and external shocks. Among these, flexibility primarily refers to the supply chain's ability to rapidly adapt and adjust to foreseeable or anticipated changes (such as product customization, demand fluctuations, etc.), aiming to enhance operational efficiency and meet diversified market demands. Resilience, on the other hand, focuses on the supply chain's ability to resist, adapt to, and recover from sudden, unforeseen events (such as natural disasters, supplier disruptions, etc.), to ensure the continuous and stable operation of the supply chain [7].

This study posits that AI-driven generative design can synergistically enhance both supply chain flexibility and resilience: on one hand, through rapid iteration and multi-solution generation, it promotes product and service customization, enhancing supply chain flexibility; on the other hand, by accelerating the validation of alternative solutions and dynamic reconfiguration of manufacturing resources, it improves the supply chain's response and recovery capabilities to sudden events, thereby strengthening its resilience.

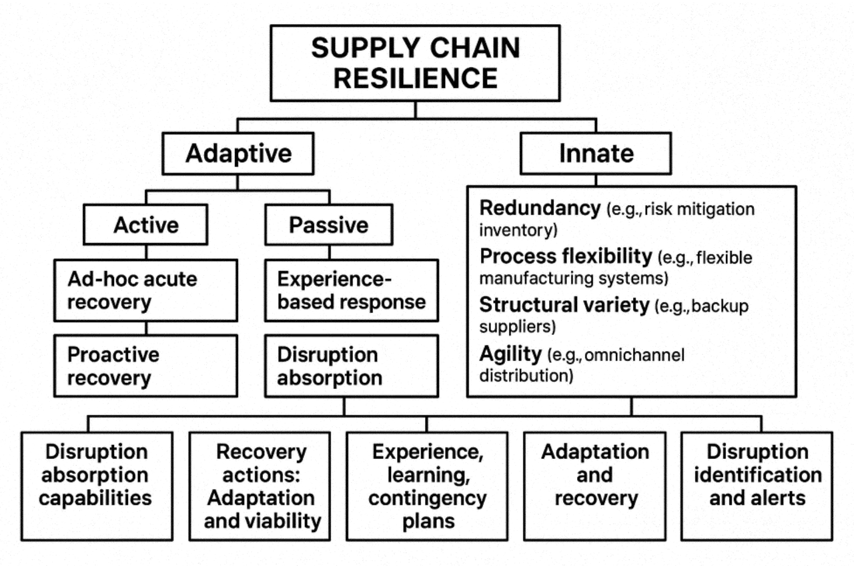

Figure 1. This is the supply chain resilience classification diagram.

Supply chain resilience can be further subdivided into innate resilience and adaptive resilience. Innate resilience is primarily reflected in the inherent redundancy in supply chain design (such as safety stock and backup suppliers), process flexibility (such as rapid production line switching), and structural diversity (such as multi-channel distribution). These factors provide fundamental protection for supply chains in dealing with risks. Adaptive resilience refers to the supply chain's ability to achieve immediate response and proactive recovery to emergencies through continuous learning, experience accumulation, and contingency planning when encountering disruptions, thereby enhancing its overall recovery capability and dynamic

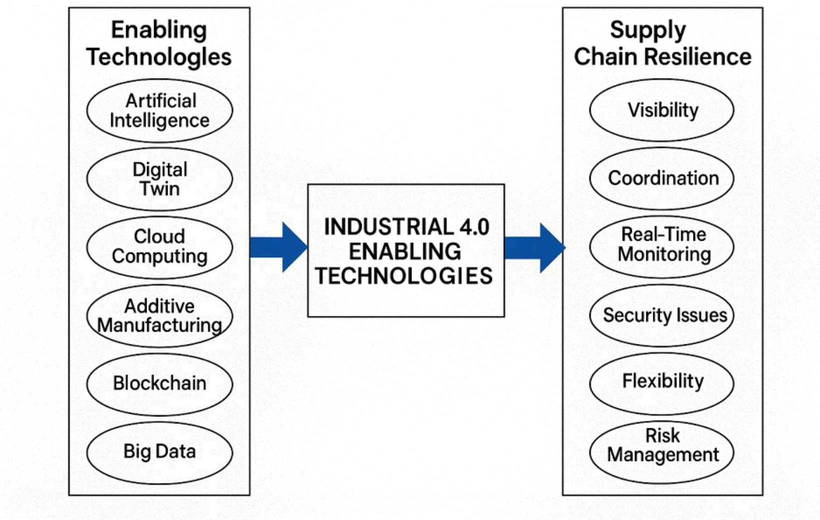

Figure 2. This is the supply chain resilience classification diagram.

2.2 *Dynamic Capabilities View: AI-Driven Design as a Core Tool*

The Dynamic Capabilities View emphasizes that in rapidly changing environments, enterprises should possess the ability to sense, seize, and reconfigure internal and external resources and capabilities, thereby continuously maintaining and strengthening competitive advantages [8]. This study views AI-driven generative design as a core tool for building dynamic capabilities in the digital age, specifically manifested in the following three aspects:

Sensing: AI enables enterprises to more rapidly and accurately sense new market demands, technological trends, and potential supply chain risks. Through deep analysis of massive data (such as customer feedback, market trends, component supply information, and geopolitical dynamics), AI can identify potential patterns, predict demand changes, and even provide early warnings for possible supply chain disruption risks. For example, AI can quickly evaluate the feasibility of different component substitution options, helping enterprises identify and avoid risks at early stages.

Seizing: AI's efficient design and simulation capabilities enable enterprises to quickly grasp fleeting market opportunities [9]. Once new market demands are sensed, AI-driven generative design tools can generate and optimize design solutions within seconds, dramatically shortening new product development cycles. Enterprises can therefore launch products targeting specific needs more quickly and respond to market changes in a timely manner. Additionally, AI can rapidly assess the feasibility of alternative components or materials, helping enterprises effectively seize opportunities to mitigate risks.

Reconfiguring: The platformization of AI-driven design promotes the decoupling of design and manufacturing processes, providing strong support for dynamic supply chain reconfiguration. Enterprises can allocate the same design solution to different production bases globally almost in real-time based on multiple factors such as cost, capacity, and geopolitical risks, achieving flexible configuration of manufacturing resources. For example, in PCB design, AI can automatically adjust and optimize design solutions according to the process capabilities and cost structures of various manufacturing facilities, thereby facilitating dynamic reconfiguration of supply chain assets [10].

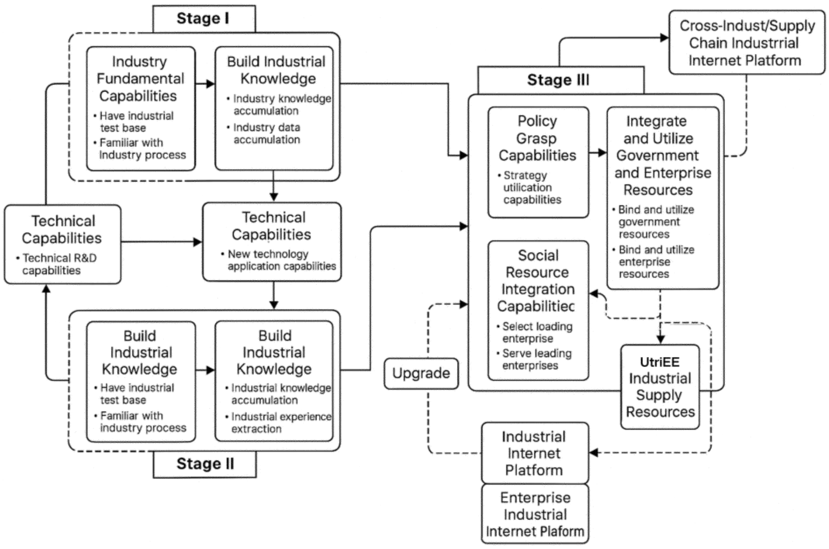

Figure 3. This is the development of key capabilities for industrial internet platforms

This diagram illustrates how industrial internet platforms, in their evolution from enterprise-level to industry-level to cross-industry chain, continuously enhance their capabilities by leveraging technical capabilities (such as new technology applications), industry foundational capabilities (such as in-depth understanding of industry processes), and policy comprehension capabilities, thereby driving resource reconfiguration and value creation [11]. In the third stage of "cross-industry chain," the diagram particularly emphasizes the deep utilization of cross-industry data and the reuse of industrial modules, which highly aligns with the core concepts of AI-driven design platformization and supply chain reconfiguration, providing strong support for promoting efficient collaboration and innovative development of supply chains.

2.3 Digital Transformation and Platform Ecosystem: "Design as a Service"

Digital transformation is not merely the application at the technical level, but signifies a profound shift in mindset—from "product thinking" to "platform thinking." In the context of AI empowerment, PCB design is no longer an isolated project-based activity, but can evolve into a platformized model of "Design as a Service" (DaaS). This platform can efficiently connect customers, designers, component suppliers, and manufacturers, building a collaborative win-win ecosystem. Customers can directly submit design requirements on the platform, with the AI system automatically generating design solutions accordingly and intelligently matching optimal components and manufacturing resources. This model significantly enhances supply chain visibility and integration, reduces transaction costs, and simultaneously promotes multi-party value co-creation.

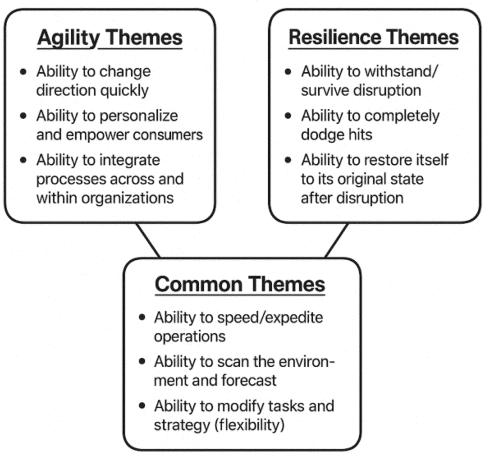

Figure 4. This is the development of key capabilities for industrial internet platforms

This diagram illustrates how digital transformation enhances the overall capabilities of supply chains by improving agility (such as rapid directional changes and customization capabilities) and resilience (such as disruption resistance and rapid recovery capabilities). Meanwhile, environmental scanning and operational adjustment capabilities are identified as common themes supporting both agility and resilience. AI-driven generative design is precisely the key technological means to achieve these agility and resilience characteristics, providing strong support for efficient adaptation and continuous optimization of supply chains.

Part III: Research Design and Methods

Digital transformation is not merely the application at the technical level, but signifies a profound shift in mindset—from "product thinking" to "platform thinking." In the context of AI empowerment, PCB design is no longer an isolated project-based activity, but can evolve into a platformized model of "Design as a Service" (DaaS). This platform can efficiently connect customers, designers, component suppliers, and manufacturers, building a collaborative win-win ecosystem. Customers can directly submit design requirements on the platform, with the AI system automatically generating design solutions accordingly and intelligently matching optimal components and manufacturing resources. This model significantly enhances supply chain visibility and integration, reduces transaction costs, and simultaneously promotes multi-party value co-creation.

This study will adopt a mixed research methodology, combining exploratory multi-case study with theoretical framework construction and quantitative simulation analysis, striving to conduct a comprehensive and in-depth exploration of the research questions from both qualitative and quantitative perspectives.

3.1 Phase One: Exploratory Multi-Case Study

This study will systematically understand the application methods of AI generative design in PCB design processes, the challenges faced, the new capabilities generated, and how these capabilities drive supply chain practice transformation through in-depth interviews and case analyses of different types of enterprises. This phase focuses on answering "how" and "why" questions, and provides empirical evidence and practical insights for subsequent theoretical model construction.

To obtain diverse perspectives, this study selects three types of typical enterprises for case studies:

(1) Large multinational technology companies (e.g., NVIDIA): These enterprises possess strong R&D capabilities and complex global supply chains. Case analysis of NVIDIA helps reveal how AI design is applied in high-end, complex product development and explores its impact on the entire value chain (from chip design to end products). The focus is on how they utilize AI for large-scale design space exploration and collaborate with supply chain partners for innovation.

(2) Leading PCB design software/AI companies (e.g., Cadence): As suppliers of AI design tools, these companies have deep understanding of AI technology's potential and application boundaries. By studying these companies, we can analyze the development and promotion process of AI generative design from the technology supply-side perspective, as well as its transformation of design service models, particularly the implementation of the "Design as a Service" concept.

(3) Agile small and medium-sized hardware startups (e.g., Oculus): Although these enterprises have limited resources, they can respond rapidly to market changes. The study examines their application of AI tools to facilitate rapid innovation, shorten product development cycles, and gain advantages in competitive environments, with particular attention to how they utilize AI to compensate for design capability shortcomings and enhance supply chain flexibility under resource constraints.

3.2 Theoretical Framework Diagram

Part IV: Expected Contributions

The theoretical and practical contributions of this study will be multifaceted.

4.1 Theoretical Contributions

Extending Dynamic Capabilities Theory: This study defines "generative AI design" as a new type of enterprise dynamic capability in the digital age for the first time. By systematically elucidating the specific implementation paths of AI in the three aspects of sensing, seizing, and reconfiguring, it enriches and extends the connotation of dynamic capabilities theory in the digital context. Particularly in the "sensing" dimension, AI's data-driven analysis enables enterprises to identify market demands and potential risks earlier and more accurately; in the "seizing" dimension, AI's rapid iteration and multi-solution generation capabilities in the design phase enable enterprises to efficiently transform captured opportunities into specific products, significantly shortening time-to-market; in the "reconfiguring" dimension, AI-driven design platformization and deep integration with manufacturing enable enterprises to flexibly reconfigure their global manufacturing and procurement networks, achieving dynamic optimization of resource allocation.

Building Theoretical Bridges Between Engineering Design, Artificial Intelligence, and Strategic Management: This study elevates AI generative design from the engineering technology level to strategic management height, revealing how technological innovation directly shapes enterprise core capabilities and supply chain strategies, providing a new theoretical paradigm for interdisciplinary research. This research helps integrate knowledge bases from different fields, such as effectively connecting AI's technical advantages in PCB design (such as batch generation of layout solutions and optimization of signal integrity) with flexibility and resilience objectives in supply chain management (such as shortening delivery cycles and responding to chip shortages).

Deepening Supply Chain Flexibility and Resilience Research: Traditional supply chain research on flexibility and resilience mostly focuses on procurement, production, and distribution links, while this study shifts the perspective upstream to the "design source," revealing how AI generative design, as an upstream capability, fundamentally enhances supply chain flexibility (responding to customization demands) and resilience (resisting design-inherent risks and external shocks) by influencing product architecture, bill of materials, and manufacturability. For example, AI can generate more design solutions that use common or easily substitutable components, thereby effectively reducing the risk of supply chain disruptions.

Part V: Conclusion

Facing the high uncertainty and complex challenges under the "new normal" of the global electronics industry supply chain, traditional human-dominated PCB design and manufacturing models can no longer support enterprises' needs for agile innovation and supply chain risk management. AI-driven generative design technology, with its capabilities of rapid iteration, multi-solution optimization, and deep manufacturing integration, provides a new pathway for breakthrough innovation in the electronics industry. It not only reshapes PCB design processes and generates new enterprise capabilities such as rapid prototyping, multi-dimensional optimization, and cross-domain collaboration, but also significantly enhances supply chain flexibility and resilience through "Design as a Service" platform innovation.

Based on supply chain management theory, dynamic capabilities view, and digital transformation theory, this study systematically examines the core role of AI generative design in sensing, seizing, and reconfiguring enterprise resources and capabilities, and empirically demonstrates its profound impact on supply chain performance through multi-case studies and simulation modeling. The research finds that AI generative design not only significantly shortens product development and time-to-market cycles and optimizes supply chain cost structures, but also effectively enhances enterprises' ability to respond to sudden risks and market changes through data-driven agile response and multi-solution alternative capabilities.

Overall, AI generative design has become a key tool for electronics industry enterprises to build dynamic capabilities in the digital age and achieve intelligent supply chain transformation and sustainable competitive advantages. In the future, with the continued deepening of platform-based business models such as "Design as a Service," AI is expected to drive the electronics industry supply chain to accelerate its evolution toward greater intelligence, efficiency, flexibility, and resilience, providing solid support for global industrial innovation and value chain upgrading.

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