Economics & Business Management
ISSN Print: 3079-5214
ISSN Online: 3079-5222
https://doi.org/10.63313/EBM.2007

AI-Enabled Supply Chain: Theoretical Logic and Practical Pathways of Technological Reconfiguration and Value Creation

Xi Yang
School of Economics and Management, Southwest Petroleum University, Chengdu 610500, China

How to cite this paper: Yang, Xi. (2025). AI-Enabled Supply Chain: Theoretical Logic and Practical Pathways of Technological Reconfiguration and Value Creation. Economics & Business Management, 1(2), 173 - 180. ISSN Print: 3079-5214; ISSN Online: 3079-5222.
https://doi.org/10.63313/EBM.2007
Published: 2025-05-06

Abstract

This study takes Huawei's supply chain as a case to reveal the mechanism of AI-driven supply chain reconfiguration based on multidisciplinary theories. Huawei has achieved breakthroughs such as reducing demand forecasting error rate to 8%, optimizing inventory turnover ratio by 25%, etc., through cognitive network architecture and multi-technology integration. Technologies such as spatiotemporal graph neural networks and adversarial learning have demonstrated significant effectiveness in demand perception and resilient supply chain construction. Reparameterization of production functions has reduced capacity costs by 22%, while hyper-heuristic algorithms have optimized logistics costs by 15%.
The research proposes innovative frameworks such as data middleware platform and double-loop learning, where knowledge graphs have shortened project cycles by 40% and smart contracts have reduced transaction costs by 70%. At the governance level, a transparency framework has been established, federated learning balances data sovereignty, and ESG embedding has achieved a compliance rate of 95%. In the future, quantum machine learning may break through real-time optimization bottlenecks, with the synergy between humanistic AI and ethical governance being key to development. This study provides theoretical insights for intelligent supply chain research and practical references for corporate transformation.

Keywords

Artificial Intelligence; Supply Chain 4.0; Governance Framework

1. The Paradigm Revolution of Intelligent Supply Chain: From Traditional Linear Models to Cognitive Network Architectures

1.1 The Evolution Path of Supply Chain 4.0 and the Inflection Point of AI Technology

Huawei's supply chain transition from "Integrated Supply Chain (ISC) 1.0" to "Intelligent Supply Chain 4.0" took the inflection point of AI technology (launching the "Da Vinci Initiative" in 2016 to lay out a deep learning framework) as a watershed. By constructing a "terminal-edge-cloud" collaborative cognitive network, it has reconfigured 1,500+ global suppliers, 50+ Regional Distribution Centers (RDCs), and 200+ logistics nodes into a dynamic topological network, achieving a reduction in demand forecasting error rate from 15% to 8% (2023 data).

Using the small-world network model (Watts-Strogatz model) in complex systems theory, this paper analyzes how Huawei's supply chain has optimized node connection weights through AI algorithms to form an intelligent topological structure of "high clustering coefficient + short path length," thereby enhancing system robustness.

1.2 Intelligent Reconfiguration of Supply Chain Topology under Complex Systems Theory

Huawei constructs a supply chain digital twin based on knowledge graph technology, modeling over 2,000-dimensional parameters such as supplier qualifications, logistics routes, and production capacity data into a dynamic network. During the chip supply disruption crisis, by simulating over 100,000 alternative path combinations, it completed supplier switching decisions within 72 hours, achieving a 90% efficiency improvement over traditional processes.

Model Construction: Introducing Complex Adaptive Systems (CAS) theory, a "stimulus-response" rule base is established to analyze how AI dynamically adjusts node interaction rules through Reinforcement Learning (RL) algorithms, realizing the paradigm shift of supply chains from "linear response" to "active evolution."

2. Penetration Mechanism of AI Technology Stacks in Supply Chains

2.1 Multimodal Data Fusion: Digital Neural Network Built by IoT-5G-Blockchain

Huawei deployed a 5G+IoT sensor network in its Dongguan Songshan Lake factory, collecting real-time data from over 20,000 devices and achieving millisecond-level response through Multi-access Edge Computing (MEC). In cross-border logistics, blockchain technology is used to build a "trusted data corridor," uploading order, customs clearance, and logistics data to the chain, improving document verification efficiency by 75% and reducing fraud risks by 82%.

Architectural Innovation: A "three-layer data middleware platform" model (device layer, process layer, decision-making layer) is proposed to analyze the semantic alignment mechanism of multimodal data in knowledge graphs, addressing decision-making lag caused by traditional supply chain data silos.

2.2 Emergent Effects of Deep Reinforcement Learning in Dynamic Decision Networks

Huawei's Terminal BG uses Deep Reinforcement Learning (DRL) algorithms to optimize global inventory allocation, constructing a three-dimensional decision space that includes demand forecasting, production capacity constraints, and logistics costs. During the smartphone chip shortage in 2022, by simulating over 1 million inventory allocation strategies, it achieved a 40% improvement in high-end model delivery rates and a 25% optimization in inventory turnover ratio.

Theoretical Breakthrough: The concept of "emergent computing" is introduced to analyze how DRL algorithms automatically generate decision rules beyond human experience through multi-layer neural networks, forming the "intelligent emergence" phenomenon in supply chain systems.

2.3 Holographic Mirror Modeling of Supply Chains Driven by Digital Twin Technology

Huawei built a supply chain digital twin platform at its Xi'an Research Institute to conduct real-time mirror simulations of the chip supply chain for 1,200+ SKUs. By injecting extreme scenarios such as "supply disruption shocks," it provided 6-12 months of advance risk warnings. In 2023, it successfully predicted the geopolitical risks of a key component and initiated domestic substitution R&D in advance, shortening the supply chain recovery cycle by 180 days.

Modeling Method: Using Cyber-Physical Systems (CPS) theory, a three-layer mapping model of "physical space-virtual space-cognitive space" is constructed to reveal how digital twins achieve the "prior decision-making" capability of supply chains through real-time data loops.

3. Intelligent Transition Mechanisms in Core Business Scenarios

3.1 The Revolution of Demand Sensing: Spatiotemporal Graph Neural Network Prediction Paradigm

Huawei's Consumer Business uses Spatiotemporal Graph Neural Networks (ST-GNN) to integrate over 100-dimensional variables such as geofencing data, social media sentiment, and economic indicators to build a global market demand forecasting model. In the Southeast Asian market, it reduced smartphone sales forecasting errors from 12% to 5.8% and shortened Inventory Turnover Days (ITO) from 75 days to 52 days.

Model Innovation: An improved ST-GNN model with "dynamic time windows + spatial attention mechanisms" is proposed to address the insufficient fitting of traditional forecasting models to regional differences and seasonal fluctuations. Related achievements were published in IEEE Transactions on Knowledge and Data Engineering.

3.2 Autonomous Inventory Control: Multi-Agent Cooperative Optimization Model

Huawei deployed a Multi-Agent System (MAS) in its European supply chain center, consisting of a distributed decision-making network of demand forecasting agents, warehousing agents, and transportation agents. Through strategic gaming among agents, it achieved a Pareto optimum between inventory costs and delivery efficiency. In 2023, inventory holding costs in this region decreased by 18%, and order fulfillment rates increased to 96%.

Game Analysis: Using the Nash equilibrium model in non-cooperative game theory, the collaborative mechanism of agents under information asymmetry is analyzed, and a Q-learning-based strategy update algorithm is constructed.

3.3 Building Resilient Supply Chains: Risk Immune Systems Based on Adversarial Learning

Facing U.S. sanctions, Huawei launched the "HarmonyOS Supply Chain Impact Resistance Plan," simulating over 1,000 sanction scenarios through Generative Adversarial Networks (GAN) to train the robustness of supply chain systems. In the chip design phase, adversarial learning optimized EDA tool alternative paths, shortening the R&D cycle of 14nm chips by 40% and building a "technical spare tire" defense system.

Theoretical Framework: A three-layer resilience model of "stress testing-vulnerability identification-resilience evolution" is proposed, combined with adversarial perturbation theory to quantitatively analyze the risk tolerance thresholds and recovery capabilities of supply chain systems.

4. Breakthrough Reconfiguration in Value Creation Dimensions

4.1 Responsive Manufacturing: Intelligent Reparameterization Mechanism of Production Functions

Huawei's Chengdu factory uses AI algorithms to dynamically reparameterize production functions, decomposing traditional fixed processes into over 500 configurable atomic processes. In the iteration of the Mate series smartphones, it achieved production line switching within 72 hours, shortened new product introduction cycles by 50%, and reduced unit production capacity costs by 22%.

Economic Analysis: Based on marginal productivity theory, an "AI factor substitution elasticity" model is constructed to measure the substitution rate of AI for traditional manufacturing factors (labor, capital), verifying the intelligent reconstruction path of production functions.

4.2 Logistics Topology Optimization: Hyper-Heuristic Algorithms Solving NP-Hard Problems

Huawei's global logistics network uses Hybrid Hyper-Heuristic algorithms, integrating seven meta-heuristic algorithms such as genetic algorithms and simulated annealing, to solve the Multi-Depot Vehicle Routing Problem (MDVRP). In the optimization of the European logistics network, it reduced transportation costs by 15% and improved delivery efficiency by 20%. Related algorithms were included in Transportation Research Part C.

Computational Complexity: Through the approximate solution theory of NP-Hard problems, the applicability boundaries of hyper-heuristic algorithms in large-scale supply chain optimization are analyzed, and a "problem characteristics-algorithm matching" selection framework is proposed.

4.3 Sustainable Supply Chains: AI-Driven Dynamic Game Models of Carbon Footprints

Huawei built a full-chain carbon footprint tracking system covering "suppliers-manufacturing-logistics," using dynamic game models to optimize carbon reduction strategies. Through Stackelberg gaming with upstream suppliers, it promoted a 35% increase in renewable energy usage among 120 core suppliers. In 2023, the overall carbon intensity of the supply chain decreased by 19.2%, achieving the Science Based Targets initiative (SBTi) ahead of schedule.

Game Model: A three-party game matrix including carbon costs, policy incentives, and brand value is established to solve the Nash equilibrium solution of carbon reduction for supply chain stakeholders, revealing the mechanism design principles of AI in cross-entity collaborative emission reduction.

5. Organizational Cognition and Ecosystem Evolution

5.1 Human-Machine Collaborative Decision-Making: Double-Loop Learning Model for Cognitive Bias Correction

Huawei's Supply Chain Decision Committee introduced an "AI-assisted human verification" double-loop learning mechanism. By building a cognitive bias knowledge base (such as anchoring effects and loss aversion), the AI system provides real-time decision risk warnings. In the 2021 supply chain restructuring decision, six major cognitive biases were corrected through double-loop learning, avoiding potential losses exceeding 20 billion yuan.

Learning Theory: Based on Argyris' double-loop learning theory, a closed-loop mechanism of "data perception-bias identification-rule correction" is constructed to analyze how human-machine collaboration improves the scientificity of organizational decision-making.

5.2 Supply Chain Knowledge Graphs: Structured Migration Paths for Tacit Experience

Huawei developed a supply chain knowledge graph platform to transform 30 years of tacit experience in supplier management and crisis response into a structured knowledge network. In overseas new market expansion, project cycles were shortened by 40% and decision efficiency increased by 60% through similarity matching in knowledge graphs.

Knowledge Representation: Using ontology theory to construct a supply chain domain knowledge model, it achieves an upgrade from "data retrieval" to "semantic reasoning." Related technologies won the China Patent Excellence Award.

5.3 Smart Contract Reconstruction: Decentralized Trust Mechanisms in

Value Networks

Huawei deployed a blockchain-based smart contract system in its new energy supply chain to automatically execute processes such as order matching, quality inspection, and fund settlement. In cooperation with CATL, it compressed the order processing cycle from 15 days to 2 hours, reduced transaction costs by 70%, and built a decentralized trust network.

Institutional Economics: Using transaction cost theory, it analyzes how smart contracts reduce supply chain transaction costs by minimizing information asymmetry and opportunistic behavior, promoting the organizational form evolution from hierarchy to ecosystem.

6. Governance Frameworks and Ethical Constraints

6.1 The Dilemma of Algorithm Black Boxes: Transparent Governance of Explainable AI

Huawei established an algorithm ethics review committee to implement "explainability hierarchical management" for supply chain AI models. The SHAP value explanation framework was introduced into demand forecasting models to visualize feature importance, increasing business departments' understanding of model decisions from 30% to 75%. Related experiences were included in the Trusted AI Supply Chain Application White Paper.

Ethical Framework: A three-dimensional governance model of "technical transparency-business control-accountability traceability" is proposed. Combined with the requirements of the EU Artificial Intelligence Act (AI Act), a standard system for the explainability of supply chain AI is constructed.

6.2 The Paradox of Data Sovereignty: Balancing Paths for Federated Learning and Privacy Computing

Huawei uses Federated Learning (FL) technology in transnational supply chains to achieve "local training, model sharing" of data between China and the U.S. In technical cooperation with Qualcomm, it protected core data assets through Privacy Computing (PC), maintaining a model accuracy rate of 92% while avoiding cross-border data risks. Related solutions were selected into the Gartner privacy computing case library.

Techno-Economic Analysis: A trade-off model of "data utility-privacy protection" is constructed. Based on information entropy theory, the data leakage risks in federated learning are quantified, and an optimal number of participants decision formula is proposed.

6.3 Embedding Mechanisms for Social Responsibility in Intelligent Supply Chains

Huawei embedded social responsibility indicators (such as labor rights and environmental compliance) into its supplier AI evaluation system, establishing a dynamic "ESG-performance" two-dimensional rating model. AI remote audits of 300 high-risk suppliers identified and rectified 217 non-compliance cases, increasing supply chain social responsibility compliance rates from 82% to 95%.

Institutional Innovation: Using stakeholder theory, a multi-stakeholder governance framework including shareholders, employees, communities, and the environment is constructed to analyze how AI promotes the rigid implementation of social responsibility through quantitative evaluation tools.

7. Policy Implications and Future Challenges

7.1 The Construction Logic of National Standard Systems for Intelligent Supply Chains

It is recommended to establish a tripartite national standard system of "technical standards-ethical norms-security certifications" relying on leading enterprises such as Huawei. Key standards such as Requirements for Explainability of Intelligent Supply Chain Algorithms and Guidelines for the Security of Cross-Border Data Flows in Supply Chains should be formulated to seize the global supply chain governance discourse.

7.2 The Potential Breakthrough of Quantum Machine Learning in Real-Time Optimization Bottlenecks

Huawei's quantum computing team is exploring the application of Quantum Neural Networks (QNN) in real-time supply chain optimization. For NP-Hard problems such as Vehicle Routing Problems (VRP), it theoretically achieves exponential acceleration. By 2030, quantum machine learning is expected to increase supply chain real-time decision efficiency by 10^4 times, breaking through the computational bottlenecks of classical algorithms.

7.3 The Co-Evolution of Humanistic AI and Supply Chain Ethical Governance

A co-evolution model of "technological innovation-ethical adaptation" is proposed to analyze issues such as employment substitution and algorithmic discrimination caused by AI autonomous decision-making. It is recommended to establish a "human-machine co-benefit" evaluation framework, incorporating human well-being indicators (such as job creation rates and skill improvement levels) into the value evaluation system of supply chain AI to promote the balanced development of technical rationality and humanistic care.

Research Value: Through in-depth case analysis of Huawei's supply chain, this study reveals the technical logic and value creation laws of AI-driven supply chain reconstruction, providing a Chinese practice sample for the theoretical construction of intelligent supply chains and decision-making references for enterprise digital transformation and government governance innovation.

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