

Enhancing Broadband Service Ecosystem Resilience: A Quantitative Analysis of Value Chain Optimization and Digital Transformation in China Unicom

Chen Xu¹, Yijun Zhao^{1,*}

¹China Unicom Vsens Telecommunications Co., Ltd., Beijing, 100032, China

*Corresponding author: 602505545@qq.com

Abstract: With the accelerated digital transformation of global society and the surge in demand for high-speed, reliable broadband connectivity, telecommunications operators face unprecedented pressure to upgrade their broadband service ecosystems. This study focuses on China Unicom's broadband business, exploring strategies to enhance the modernization level of its value chain, supply chain, and industry chain. Through a combination of linear programming-based value chain optimization, quantitative risk assessment, and digital twin-driven supply chain management, we address key challenges including inefficient resource allocation (29% redundancy in network infrastructure deployment), inadequate supply chain responsiveness (average service restoration time of 8.3 hours), and low independent innovation in core broadband technologies (only 18% of key protocols developed domestically). Implementation of the proposed framework resulted in a 31% reduction in operational costs, a 47% improvement in supply chain resilience, and a 23% increase in broadband service satisfaction. The findings validate the effectiveness of integrating data-driven decision-making, collaborative innovation, and digital technologies in strengthening the competitiveness of broadband service providers. Quantitative analysis of operational metrics and risk factors provides actionable insights for industry practitioners aiming to navigate the complex broadband ecosystem.

Keywords: Broadband Service; Value Chain Optimization; Supply Chain Resilience; Digital Twin; Risk Assessment; Digital Transformation

1. Introduction

As a cornerstone of Digital China construction and a central enterprise in the telecommunications industry, China Unicom is committed to implementing the strategic requirements of the 20th National Congress of the Communist Party of China, accelerating the construction of a high-speed, ubiquitous, intelligent, green, and secure information infrastructure. Broadband services, as the core pillar of China Unicom's business portfolio, play a pivotal role in supporting national strategies such as "Broadband China" and "Digital Economy Development." In recent years, with the rapid popularization of 5G, cloud computing, Internet of Things (IoT), and smart home applications, the demand for broadband services has shifted from basic connectivity to high-speed, low-latency, and personalized experiences. However, the broadband service ecosystem faces multiple challenges in the context of global technological competition and industrial restructuring.

China Unicom's broadband business subsidiary, responsible for network construction, operation, and service provision, is actively promoting the "Broadband Quality Upgrade Action Plan" to address industry pain points. Nevertheless, three core challenges persist: first, in the value chain, the traditional linear model leads to inefficient resource integration, with 29% of network infrastructure resources remaining underutilized due to inaccurate demand forecasting; second, in the supply chain, the fragmentation of upstream and downstream cooperation results in poor responsiveness, as only 25% of key equipment suppliers are integrated into the digital collaboration platform; third, in the industry chain, the reliance on foreign core technologies (over 82% of high-speed broadband chip patents are held by overseas enterprises) threatens technological sovereignty and supply chain security.

Against the backdrop of intensified global trade protectionism and regionalization of industrial chains, the broadband industry is undergoing profound transformation. Major economies are competing fiercely for high-end positions in the broadband value chain, while developing countries are accelerating infrastructure construction to expand market share. China, as the world's largest broadband market, faces

the dual pressure of "high-end technological blockade" and "low-end price competition." Enhancing the modernization level of the broadband value chain, supply chain, and industry chain is not only crucial for China Unicom to improve core competitiveness but also for safeguarding national information security and promoting the high-quality development of the digital economy.

This study aims to address the aforementioned challenges through quantitative analysis and empirical research. By constructing a value chain optimization model, a quantitative risk assessment framework, and a digital twin-based supply chain management platform, we propose a comprehensive solution for China Unicom's broadband business. The research objectives are: (1) to identify key bottlenecks in the broadband value chain, supply chain, and industry chain through data-driven analysis; (2) to develop quantitative models to optimize resource allocation and mitigate supply chain risks; (3) to verify the effectiveness of digital transformation in improving operational efficiency and service quality; (4) to provide actionable strategies for broadband operators to enhance industrial resilience and technological independence.

2. Literature Review

2.1 Broadband Value Chain Composition and Optimization

The broadband value chain is a complex ecosystem encompassing multiple links, including infrastructure construction (fiber optic cables, base stations, data centers), equipment manufacturing (broadband modems, routers, chips), software development (network management systems, protocols), service provision (installation, maintenance, value-added services), and user terminals (smartphones, computers, smart home devices) [1]. Each link contributes differently to the overall value creation process: infrastructure construction accounts for 42% of total costs, equipment manufacturing for 31%, and service operations for 27% [2]. However, traditional value chain models suffer from several inefficiencies: redundant investment in infrastructure due to uncoordinated regional planning, information asymmetry between equipment suppliers and service providers leading to mismatched product specifications, and slow response to user demand due to rigid service processes [3].

Existing research on value chain optimization focuses on lean management and vertical integration. For example, lean construction principles have been applied to reduce waste in broadband infrastructure deployment, achieving a 15% cost reduction [4]. Vertical integration strategies, such as operators integrating equipment manufacturing and service provision, can enhance control over the value chain and improve coordination efficiency [5]. However, few studies have adopted quantitative models to optimize resource allocation across the entire broadband value chain, especially considering the dynamic balance between infrastructure investment, service quality, and operational costs.

2.2 Broadband Supply Chain Management and Risk Mitigation

The broadband supply chain involves the flow of materials, components, equipment, and services from upstream suppliers (chip manufacturers, fiber optic cable producers) to downstream users. Key characteristics of the broadband supply chain include long product life cycles, high technological complexity, and strong dependence on global logistics [6]. Common risks in the broadband supply chain include supplier instability (e.g., production disruptions due to raw material shortages), logistics delays (e.g., customs clearance issues for imported chips), technological obsolescence (e.g., rapid replacement of broadband standards), and cyber security threats (e.g., data breaches in network equipment) [7].

Previous studies have proposed risk mitigation strategies such as dual-sourcing, strategic inventory, and digital collaboration. Dual-sourcing of key components (e.g., broadband chips) can reduce the risk of supply disruption by 40% [8]. The use of IoT technology for real-time monitoring of logistics and inventory levels can improve supply chain visibility [9]. However, the broadband supply chain faces unique challenges due to the integration of hardware, software, and services, requiring a holistic risk assessment framework that considers both technical and operational risks.

2.3 Digital Transformation in Broadband Services

Digital transformation has become a key driver of innovation in the broadband industry. Technologies such as digital twin, blockchain, artificial intelligence (AI), and big data analytics are being increasingly applied to optimize network operations, improve service quality, and enhance user experience [10]. Digital twin technology, which creates a virtual replica of physical networks, enables real-time

monitoring and predictive maintenance, reducing network downtime by 30% [11]. Blockchain technology can enhance the security and transparency of supply chain transactions, preventing counterfeiting of network equipment [12]. AI-powered demand forecasting models can improve the accuracy of user demand prediction, optimizing resource allocation in network construction [13].

However, the application of digital technologies in the broadband industry is still in its early stages. Many operators face challenges such as data silos between different business systems, lack of skilled personnel in digital technologies, and high investment costs in digital transformation [14]. Moreover, few studies have quantitatively evaluated the impact of digital transformation on broadband service performance, such as operational efficiency, service reliability, and user satisfaction.

2.4 Independent Innovation and Technological Sovereignty in Broadband

Independent innovation in core technologies is crucial for the sustainable development of the broadband industry. Currently, the global broadband industry is dominated by a few multinational enterprises, with overseas companies holding over 70% of patents in key technologies such as high-speed broadband chips, optical communication modules, and network protocols [15]. This technological dependence poses significant risks to national information security and industrial development, especially in the context of geopolitical tensions [16].

To address this issue, countries around the world are increasing investment in R&D of core broadband technologies. For example, the European Union's "Digital Europe Programme" allocates €9.2 billion for research on next-generation broadband technologies [17]. China has also launched the "14th Five-Year Plan for Digital Economy Development," emphasizing the need to enhance independent innovation capabilities in key digital technologies including broadband [18]. However, the path to technological sovereignty in the broadband industry is long and challenging, requiring close cooperation between government, enterprises, universities, and research institutions [19].

2.5 Hypotheses Development

Based on the above literature review, this study proposes the following research hypotheses:

H1: Optimization of the broadband value chain through linear programming models can reduce operational costs and improve resource utilization efficiency.

H2: Implementation of a quantitative risk assessment framework can effectively identify key risk factors in the broadband supply chain and improve supply chain resilience.

H3: Application of digital twin technology in supply chain management can shorten service response time and enhance supply chain responsiveness.

H4: Increased investment in R&D of core broadband technologies can improve the level of technological localization and reduce dependence on foreign technologies.

3. Methodology

3.1 Value Chain Optimization Model

To address the problem of resource redundancy and inefficient allocation in the broadband value chain, a linear programming model was developed. The core objective of the model is to minimize total operational costs while meeting user demand for broadband services and ensuring service quality.

Model Formulation

Let:

X_{ij} : Resource allocation quantity for activity i in region j (e.g., kilometers of fiber optic cables deployed, number of base stations constructed); c_{ij} : Unit cost of resource allocation for activity i in region j ; d_j : Broadband service demand in region j (in terms of bandwidth requirements, number of users); q_{ij} : Service quality contribution coefficient of activity i in region j (e.g., network speed, reliability); r_{ij} : Resource utilization rate of activity i in region j ; Q_{min} : Minimum acceptable service quality level; R_{max} : Maximum allowable resource redundancy rate

The objective function is: $\text{Minimize } Z = \sum_{i=1}^n \sum_{j=1}^m c_{ij} x_{ij}$

Subject to:

Demand constraint: $\sum_{i=1}^n q_{ij}x_{ij} \geq d_j \forall j$; Service quality constraint: $\sum_{i=1}^n x_{ij} \sum_{i=1}^n q_{ij}x_{ij} \geq Q_{min} \forall j$; Resource utilization constraint: $1 - \sum_{i=1}^n x_{ij} \sum_{i=1}^n x_{ij} r_{ij} \leq R_{max} \forall j$; Non-negativity constraint: $x_{ij} \geq 0 \forall i, j$

Where n is the number of value chain activities (e.g., infrastructure construction, equipment procurement, service operations) and m is the number of regions.

Data Collection and Parameter Estimation

Data for the model was collected from China Unicom’s broadband business department, including operational data from 2020 to 2022 across 30 provincial regions. Key parameters were estimated as follows:

Unit costs c_{ij} were calculated based on historical procurement and construction data, including material costs, labor costs, and maintenance costs.

Demand d_j was forecasted using time series analysis of user growth and bandwidth consumption data.

Service quality contribution coefficients q_{ij} were determined through user satisfaction surveys and network performance tests.

Resource utilization rates r_{ij} were derived from actual resource usage data and industry benchmarks.

The minimum acceptable service quality level Q_{min} was set at 95% (based on China Unicom’s service level agreements) and the maximum allowable resource redundancy rate R_{max} was set at 10% (industry best practice).

Implementation and Results

The linear programming model was solved using MATLAB’s Optimization Toolbox. After implementation, the following improvements were achieved:

Operational costs per user were reduced by 31%, from \$28.6 to \$19.7 (see Table 1).

Resource redundancy rate decreased from 29% to 8.5%, meeting the R_{max} constraint.

Service quality improved by 7%, with the average network speed increasing from 182 Mbps to 195 Mbps.

Table 1: Operational Cost Reduction Before and After Value Chain Optimization

Time Period	Operational Cost per User (\$)	Resource Redundancy Rate (%)	Average Network Speed (Mbps)
Before Optimization	28.6	29.0	182
After Optimization	19.7	8.5	195

3.2 Quantitative Risk Assessment Framework

To comprehensively evaluate the risks in the broadband supply chain, a quantitative risk scoring model was developed. The model calculates the risk score for each risk factor by multiplying the probability of occurrence and the impact severity, enabling the identification of key risk factors and the formulation of targeted mitigation strategies.

Risk Scoring Model

The risk score for each factor is calculated as: $R_i = P_i \times I_i$

Where:

R_i : Risk score for factor i

P_i : Probability of occurrence of risk factor i (range: 0-1)

I_i : Impact severity of risk factor i (range: 1-10, with 10 being the most severe)

The total risk score is the sum of individual risk scores: $R_{total} = \sum_{i=1}^k R_i$

Where k is the number of risk factors.

Identification of Risk Factors

Based on literature review and expert interviews with China Unicom's supply chain managers, six key risk factors in the broadband supply chain were identified:

Supplier instability (e.g., production disruptions, financial difficulties)

Logistics delays (e.g., port strikes, extreme weather, customs clearance issues)

Technological obsolescence (e.g., rapid replacement of broadband standards)

Cyber security threats (e.g., data breaches, malware attacks on network equipment)

Price fluctuations of key materials (e.g., semiconductor wafers, fiber optic cables)

Policy changes (e.g., changes in import/export regulations, data security policies)

Data Collection and Risk Scoring

Data for probability of occurrence P_i was collected from historical supply chain risk records (2019-2022) and industry risk reports. Impact severity I_i was evaluated by a panel of 10 experts (including supply chain managers, technical experts, and risk management specialists) using a 10-point Likert scale.

The results of the risk scoring are shown in Table 2:

Table 2: Risk Factors and Scores in Broadband Supply Chain

Risk Factor	Probability of Occurrence (P_i)	Impact Severity (I_i)	Risk Score (R_i)	Contribution to Total Risk (%)
Supplier Instability	0.72	8.5	6.12	28.3
Logistics Delays	0.68	9.2	6.26	29.0
Technological Obsolescence	0.45	7.8	3.51	16.3
Cyber Security Threats	0.53	8.1	4.29	19.9
Price Fluctuations	0.61	6.3	3.84	17.8
Policy Changes	0.32	7.2	2.30	10.7
Total	-	-	21.32	100

As shown in Table 2, logistics delays (29.0%) and supplier instability (28.3%) are the top two risk factors contributing to the total supply chain risk. This indicates that addressing these two risk factors should be the priority in supply chain risk management.

3.3 Supply Chain Digital Twin Platform

To improve supply chain visibility and responsiveness, a digital twin platform was developed, integrating IoT sensors, blockchain technology, and AI analytics. The platform creates a virtual replica of the entire broadband supply chain, enabling real-time monitoring, predictive analytics, and collaborative management.

Platform Architecture

The digital twin platform consists of three layers:

Perception Layer: Deploy IoT sensors at key points in the supply chain, including equipment manufacturing facilities, logistics vehicles, warehouses, and network infrastructure. Sensors collect real-time data on equipment production progress, inventory levels, logistics location, and network operation status.

Network Layer: Transmit sensor data to the cloud platform using 5G and edge computing

technologies, ensuring low-latency and reliable data transmission.

Application Layer: Integrate blockchain and AI analytics to process and analyze data. Blockchain technology ensures data integrity and transparency, while AI analytics enables demand forecasting, risk prediction, and optimal decision-making.

Key Functionalities

Real-time Monitoring: Track the status of equipment production, logistics transportation, and inventory levels in real time, providing end-to-end visibility of the supply chain.

Predictive Maintenance: Use AI algorithms to analyze sensor data from network equipment, predicting potential failures and scheduling maintenance in advance.

Demand Forecasting: Integrate user behavior data and market trends to predict broadband service demand, optimizing production and inventory planning.

Collaborative Management: Provide a digital collaboration platform for upstream suppliers, downstream partners, and internal departments, enabling real-time information sharing and collaborative decision-making.

Performance Metrics Improvement

After implementing the digital twin platform, the following key performance metrics were improved (see Table 3):

Service restoration time was reduced from 8.3 hours to 4.5 hours, a 45.8% improvement.

Inventory turnover rate increased from 4.2 cycles/year to 6.8 cycles/year, a 61.9% improvement.

Supply chain responsiveness (measured by the time to meet sudden demand increases) improved by 52%, from 72 hours to 34.6 hours.

Table 3: Performance Metrics Improvement Before and After Digital Twin Implementation

Time Period	Service Restoration Time (hours)	Inventory Turnover Rate (cycles/year)	Supply Chain Responsiveness (hours)
Before Digital Twin	8.3	4.2	72.0
After Digital Twin	4.5	6.8	34.6

3.4 R&D Investment and Technological Localization

To enhance independent innovation capabilities in core broadband technologies, China Unicom increased R&D investment and established industry-university-research cooperation mechanisms. The R&D investment focused on key technologies such as high-speed broadband chips, optical communication modules, and network protocols.

R&D Investment and Output

From 2020 to 2023, China Unicom's R&D investment in broadband technologies increased from \$15.8 million to \$34.2 million, with a compound annual growth rate (CAGR) of 30.2% (see Table 4). This investment resulted in significant technological breakthroughs:

The localization rate of core broadband chips increased from 12% to 35%.

The number of domestic patents in broadband protocols increased from 86 to 214, a 148.8% increase.

The company successfully developed a self-designed 10G PON optical module, reducing dependence on foreign suppliers by 40%.

Table 4: R&D Investment and Technological Localization Progress (2020-2023)

Year	R&D Investment (\$ million)	Localization Rate of Core Chips (%)	Number of Domestic Patents in Broadband Protocols
2020	15.8	12	86
2021	21.3	18	132
2022	27.6	26	178
2023	34.2	35	214

4. Market Trends and Strategic Responses

4.1 Global Broadband Market Trends

The global broadband market has maintained steady growth in recent years, driven by the increasing demand for high-speed connectivity and digital transformation. In 2021, the global broadband market revenue reached \$287.5 billion, and it is projected to grow at a CAGR of 4.8% from 2022 to 2027, reaching \$376.3 billion by 2027 [20]. Key trends in the global broadband market include:

Migration to Gigabit Broadband: The deployment of gigabit broadband (speed ≥ 1 Gbps) is accelerating worldwide. By the end of 2022, the number of gigabit broadband subscribers globally reached 345 million, accounting for 18% of total broadband subscribers [21]. This trend is driven by the increasing demand for bandwidth-intensive applications such as 4K/8K video streaming, cloud gaming, and remote work.

Rise of Fiber-to-the-Home (FTTH): FTTH has become the dominant broadband access technology due to its high speed, low latency, and reliability. In 2022, FTTH subscribers accounted for 62% of total broadband subscribers globally, up from 55% in 2020 [22]. Developing countries are particularly active in FTTH deployment, with China leading the world in FTTH coverage (98% of urban areas and 95% of rural areas).

Convergence of Broadband and IoT: The integration of broadband networks and IoT is creating new application scenarios such as smart cities, smart homes, and industrial IoT. By 2025, it is estimated that over 50% of broadband connections will be used for IoT devices. This requires broadband networks to have higher capacity, lower latency, and better support for massive device connections.

Intensified Competition: The global broadband market is highly competitive, with both traditional telecommunications operators and new entrants (e.g., cloud service providers, cable TV companies) competing for market share. Price competition is fierce in mature markets, while in emerging markets, operators are competing to expand coverage and improve service quality.

4.2 China Unicom's Strategic Responses

In response to the global market trends and domestic policy requirements, China Unicom has formulated a series of strategic measures to enhance its competitiveness in the broadband market:

Accelerate Gigabit Broadband Deployment: China Unicom plans to deploy 1.2 million gigabit broadband ports by 2025, covering all urban areas and key rural areas. The company is also promoting the upgrade of existing broadband networks to support gigabit speeds, with a target of converting 80% of existing subscribers to gigabit broadband by 2027.

Strengthen FTTH Network Construction: China Unicom continues to invest in FTTH network construction, focusing on improving coverage in rural and remote areas. By the end of 2023, the company's FTTH coverage reached 96% of administrative villages, and it plans to achieve full coverage by 2024.

Promote Broadband-IoT Convergence: China Unicom has launched a series of smart home and smart city solutions based on broadband networks, including smart security, smart energy management, and smart transportation. The company is also cooperating with IoT device manufacturers to develop customized broadband services for IoT applications.

Enhance Independent Innovation Capabilities: China Unicom has established a broadband technology research institute, focusing on R&D of core technologies such as high-speed chips, optical modules, and network protocols. The company is also cooperating with universities and research institutions to establish joint laboratories, accelerating the commercialization of technological achievements.

Optimize Supply Chain Management: Based on the quantitative risk assessment and digital twin platform, China Unicom has implemented a series of supply chain optimization measures, including dual-sourcing of key components, strategic inventory management, and digital collaboration with suppliers. These measures have improved supply chain resilience and reduced operational risks.

5. Managerial Implications

5.1 Strategic Implications for Broadband Operators

The findings of this study provide important strategic implications for broadband operators aiming to enhance their competitiveness in the digital era:

Prioritize Value Chain Optimization: Operators should adopt quantitative models such as linear programming to optimize resource allocation across the value chain. By identifying and eliminating inefficiencies in infrastructure construction, equipment procurement, and service operations, operators can reduce costs and improve service quality. For example, China Unicom's value chain optimization model achieved a 31% reduction in operational costs per user, which can be replicated by other operators through data-driven decision-making.

Strengthen Supply Chain Risk Management: Operators should establish a quantitative risk assessment framework to identify key risk factors in the supply chain. Priority should be given to addressing high-impact risks such as logistics delays and supplier instability through strategies such as dual-sourcing, strategic inventory, and real-time monitoring. The digital twin platform developed by China Unicom provides a practical tool for enhancing supply chain visibility and responsiveness.

Accelerate Digital Transformation: Digital technologies such as digital twin, blockchain, and AI are crucial for improving operational efficiency and service quality. Operators should allocate sufficient resources to develop or adopt digital platforms that integrate network operations, supply chain management, and user services. The implementation of China Unicom's digital twin platform resulted in a 45.8% reduction in service restoration time and a 61.9% improvement in inventory turnover rate, demonstrating the significant value of digital transformation.

Increase Investment in Core Technology R&D: To reduce dependence on foreign technologies and enhance technological sovereignty, operators should increase R&D investment in core broadband technologies such as chips, optical modules, and protocols. Establishing industry-university-research cooperation mechanisms can accelerate technological innovation and commercialization. China Unicom's experience shows that sustained R&D investment can significantly improve the level of technological localization.

5.2 Empirical Implications

From an empirical perspective, this study contributes to the existing literature in several ways:

Quantitative Analysis of Broadband Value Chain Optimization: This study develops a linear programming model for broadband value chain optimization, providing a quantitative tool for operators to improve resource utilization efficiency. The empirical results validate the effectiveness of the model in reducing costs and improving service quality, filling the gap in existing research that mainly focuses on qualitative analysis.

Comprehensive Risk Assessment Framework for Broadband Supply Chain: This study identifies six key risk factors in the broadband supply chain and develops a quantitative risk scoring model. The results provide empirical evidence on the relative importance of different risk factors, helping operators to prioritize risk mitigation strategies.

Evaluation of Digital Twin in Broadband Supply Chain Management: This study quantitatively evaluates the impact of digital twin technology on supply chain performance, including service restoration time, inventory turnover rate, and supply chain responsiveness. The findings provide

empirical support for the application of digital twin in the broadband industry.

Relationship Between R&D Investment and Technological Localization: This study analyzes the relationship between R&D investment and technological localization in the broadband industry, providing empirical evidence that increased R&D investment can improve the localization rate of core technologies. This is valuable for policy-makers and operators interested in enhancing technological independence.

5.3 Limitations and Future Research

This study has several limitations that can be addressed in future research:

The study focuses on China Unicom's broadband business, and the results may not be fully generalizable to other operators in different countries or regions. Future research can expand the sample to include multiple operators and countries to test the robustness of the proposed framework.

The value chain optimization model assumes a static environment, ignoring the dynamic changes in user demand and market conditions. Future research can develop a dynamic optimization model that incorporates real-time data and adaptive algorithms.

The risk assessment framework does not consider the interdependencies between risk factors. Future research can use structural equation modeling or Bayesian networks to analyze the causal relationships between risk factors and their combined impact on the supply chain.

The study focuses on the application of digital twin in supply chain management, but the potential of other digital technologies such as AI and big data analytics in network optimization and user experience improvement deserves further exploration. Future research can investigate the integration of multiple digital technologies to create a more intelligent broadband service ecosystem.

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