Research on the Application of Digital Twin Technology in Full-Process Visualization and Collaborative Optimization of Supply Chains

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Abstract： As the complexity of global supply chain networks keeps rising, traditional supply chain management models encounter a host of challenges in aspects like dynamic response, process transparency, and resource coordination. Digital Twin technology, a simulation technology that combines multi-physical domains, multi-scales, and multi-probabilities, is capable of attaining real-time perception, dynamic monitoring, and intelligent optimization of the whole supply chain process. It does this by creating a virtual representation of physical entities. This paper initially expounds on the core concepts and technical framework of Digital Twin technology. Subsequently, commencing from the five key links within the supply chain — procurement, production, warehousing, logistics, and sales — it conducts a systematic analysis of the application routes of Digital Twin technology in full-process visualization. Moreover, it delves into its collaborative optimization mechanisms in fields such as resource allocation, risk early warning, and collaborative decision-making. Ultimately, it sums up the major challenges currently confronted in applying Digital Twin technology to supply chain management and presents a vision for future development trends. This provides theoretical references and practical perspectives for the digital transformation of supply chains.

Keywords: Supply Chain Management; Full-Process Visualization; Digital Transformation

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Introduction

In the context of the integration of globalization and informatization, supply chains have transformed from linear setups to intricate network configurations. As a result, they are prone to being affected by elements like market fluctuations, geopolitical situations, and natural disasters. Traditional supply chain management approaches depend on manual experience and static data. This makes it arduous to dynamically monitor the whole process. Consequently, it gives rise to delayed reactions, resource squandering, and feeble risk - coping abilities. The absence of real - time visibility can decrease the operational efficiency of the supply chain by more than 30%, and the risk losses are even more substantial.

Digital Twin technology, which has its roots in the industrial domain, is capable of mapping physical entity information into the virtual space in real time. It sets up a two-way interactive channel. This technology can precisely reproduce and dynamically simulate entities. By integrating big data and artificial intelligence, it enables predictive optimization, thus offering a novel solution for the management of complex systems. When this technology is introduced into the supply chain area, it has the potential to break down information barriers, integrate data, and boost the visualization level as well as the coordination efficiency of the supply chain. At present, the application of Digital Twin technology has become a research focus. However, the majority of studies concentrate on individual links. There is a lack of systematic analysis of the whole process and in-depth exploration of collaborative optimization mechanisms. Consequently, from a full-process viewpoint, this paper conducts research on the application paths and optimization strategies of Digital Twin technology, providing theoretical backing for the digital transformation of supply chains.

1 Core Connotation and Technical Architecture of Digital Twin Technology

1.1 Core Connotation

Digital Twin (DT) was initially put forward by Professor Michael Grieves at the University of Michigan in 2003. The core concept behind it is to utilize virtual models for the management of full lifecycle mapping of physical entities. At present, in the academic community, it is considered a complex system technology that combines perception, modeling, simulation, and optimization. It has four core characteristics:

Multi-dimensional Mapping: This is the technical foundation. The virtual model not only replicates the geometric form of the physical entity but also covers data such as physical properties (material, strength), operational status (temperature, pressure), and environmental information (geographic location, climate), achieving a "one-to-one correspondence."

Real-time Interaction: Leveraging the Internet of Things (IoT), data from entities is gathered in real-time through sensors, RFID, and other apparatuses and then sent to the virtual model. At the same time, the optimization directives from the virtual model are relayed back to the entity, thus creating a "perception-decision-execution" closed loop.

Dynamic Simulation: It serves as the core competency. Leveraging both real-time and historical data, simulation algorithms are employed to imitate the operational state of the entity across diverse scenarios. This enables the prediction of potential problems and risks.

Smart Optimization: Leveraging dynamic simulation, integrating AI and big data analysis techniques, it offers optimal decisions for the operation of entities. This leads to the efficient allocation of resources and the continuous enhancement of processes.

1.2 Technical Architecture

The implementation of Digital Twins within supply chains necessitates a multi-tiered architecture. Taking into account the unique characteristics of supply chains, this architecture can be segmented into the Perception Layer, Data Layer, Modeling & Simulation Layer, and Application Layer. These layers function in unison to uphold end-to-end visualization and collaborative optimization efforts.

Perception Layer: It serves as the connection to the physical supply chain. IoT devices like temperature sensors and GPS locators are installed. These devices are used to gather data in real time from different links, namely procurement, production, warehousing, logistics, and sales. Additionally, data preprocessing, which includes denoising, filtering, and format conversion, is necessary. This is to guarantee the accuracy and usability of the data.

Data Layer: This serves as the data storage and management hub. Here, real-time data originating from the Perception Layer is stored, along with historical supply chain data such as procurement records and production plans, as well as external data including market demand and policies. An architecture of distributed storage is implemented. Unified data standards and interfaces are set up to overcome data barriers. At the same time, measures like encryption and access control are employed to safeguard data security and privacy.

Modeling and Simulation Layer: As the central processing layer, it employs multi-scale and multi-physical domain modeling approaches. Taking into account the characteristics of the supply chain, an integrated virtual model encompassing the five key links is developed. Relying on this model, algorithms like numerical computation and discrete-event simulation are utilized to imitate the operational state under various scenarios (for example, a sudden increase in demand or disruptions in logistics). This allows for the analysis of response capabilities and efficiency. Moreover, it can integrate machine learning to forecast operational trends, thereby offering a foundation for collaborative optimization.

Application Layer: It serves as the carrier for value realization. Leveraging the results from the Modeling & Simulation Layer, it offers four key services. First is Full-process Visualization, which uses 3D technology to intuitively showcase the operational status. Second is Resource Collaborative Optimization, aiming to dynamically allocate resources so as to boost utilization. Third is Risk Early Warning, which monitors data to detect risks and send out alerts. Fourth is Decision Support, providing data-driven recommendations to increase the scientific soundness of management.

2 Application Paths of Digital Twin Technology in Supply Chain Full-Process Visualization

The entire supply chain process consists of five interrelated links: procurement, production, warehousing, logistics, and sales. Digital Twin technology attains real-time visualization of the whole process. It does this by creating virtual mappings and an integrated model for each link. This helps to break down information barriers and improve the transparency of the supply chain.

2.1 Visualization in the Procurement Link

Procurement, being the initial stage of the supply chain, has customarily encountered problems such as the challenge of keeping track of the progress and status of raw materials. Digital Twin technology realizes visualization in three ways. Firstly, it builds virtual models of suppliers and raw materials, creating "digital dossiers" to aid in procurement decision-making. Secondly, by depending on RFID tags or GPS locators, it enables real-time tracking of the procurement process, monitoring both the transportation routes and the environment. Thirdly, it incorporates quality inspection criteria, compares the actual detection data to produce visual reports, and screens out qualified raw materials.

2.2 Visualization in the Production Link

Production lies at the heart of the supply chain. Historically, its management has been characterized by relatively low transparency. Digital Twin technology mainly focuses on three areas of monitoring. Regarding equipment visualization, virtual models are created to map operational parameters in real time. These models can issue warnings when there are potential faults and predict the lifespan of equipment. When it comes to process visualization, 3D workshop scenes are set up. These scenes can dynamically present the production status and help identify bottleneck links. As for quality visualization, inspection data is fed in to generate quality curves. This enables tracing the root causes of anomalies, thus facilitating process optimization.

2.3 Visualization in the Warehousing Link

Warehousing serves as the “transfer station” within the supply chain. In traditional management, inventory information often lags behind. Digital Twin technology offers optimization via three approaches. Firstly, it creates a 3D virtual model of the warehouse, which showcases the layout and equipment. Secondly, by utilizing sensors and RFID tags, it enables real-time visualization of the inventory status and issues warnings for items approaching their expiration dates. Thirdly, it simulates operational processes to optimize paths and scheduling, thus guaranteeing the efficient operation of the warehouse.

2.4 Visualization in the Logistics Link

Logistics serves as the "artery" within the supply chain. Historically, information management in this field has been rather opaque. Digital Twin technology zeroes in on three key areas of monitoring. First, during the transportation phase, virtual models are created. These models are designed to monitor in real - time both the location of transport vehicles and the conditions of the goods being shipped. In the event of any abnormal circumstances, they can issue timely alerts. Second, when it comes to the logistics network, a comprehensive model covering the entire domain is developed. This model is used to identify bottlenecks and suboptimal routes, with the aim of making improvements. Finally, for cost visualization purposes, cost data is aggregated and linked to operational activities and the status of the cargo. This integration helps in better cost management and control.

2.5 Visualization in the Sales Link

Sales serves as the terminus of the supply chain. In traditional management, inaccurate demand forecasting frequently occurs at this stage. Digital Twin technology brings improvements via three distinct avenues. Firstly, it constructs virtual models of both sales terminals and customers, thereby creating "digital profiles". Secondly, by integrating multi-source data, it can predict market demand in real time, which in turn guides production and inventory management. Finally, it incorporates customer feedback to generate satisfaction reports, allowing for targeted enhancements in service quality.

3 Application Mechanisms of Digital Twin Technology in Supply Chain Collaborative Optimization

To achieve collaborative optimization in the supply chain, it is essential to integrate resources and information across different links, aiming to boost overall efficiency. Digital Twin technology, leveraging data that enables full-process visualization and simulation optimization algorithms, attains this objective via three key mechanisms. These are the collaborative scheduling of resources, the collaborative early warning of risks, and the cross-link collaborative decision-making.

3.1 Resource Collaborative Scheduling Mechanism

Traditional management encounters difficulties in attaining global resource allocation. Digital Twin technology constructs a scheduling mechanism via three steps. Firstly, there is global perception and sharing. Data regarding raw material inventory, equipment utilization, transport capacity, and so on, is gathered and incorporated into the virtual model. This results in the formation of a global resource library that is shared among all participants. Secondly, dynamic prediction and matching take place. Relying on full-process data, simulation algorithms forecast resource demand. Then, optimization algorithms are employed to match supply with demand. For instance, during equipment failures, idle equipment is scheduled; when there is a shortage of transport capacity, nearby resources are allocated. Finally, real-time evaluation and optimization occur. Operational data is collected and compared with expected results. Deviations are analyzed, and plans are adjusted to continuously enhance resource utilization.

3.2 Risk Collaborative Early Warning Mechanism

To tackle the abruptness and spread of supply chain risks, Digital Twin technology devises a three-tier early warning system. Firstly, there is comprehensive perception and modeling. It integrates the operational data from diverse links with external data such as weather information and policies. Based on this, a multi-dimensional risk repository is established, encompassing aspects of "equipment", "process", "environment", and "market". Secondly, real-time identification and graded warning are carried out. Machine learning algorithms are employed to monitor the operational state. Potential risks are detected, and then they are classified according to their probability of occurrence and potential impact. Warnings are then issued via visual interfaces. Finally, collaborative response and simulation optimization come into play. Multiple response plans are formulated, and their effects are simulated. Participants then jointly select the most suitable plan for implementation. After the event, reviews are conducted, and strategies are updated to strengthen the ability to withstand risks.

3.3 Cross-Link Collaborative Decision-Making Mechanism

To address the "local optimum" issue in traditional decision - making, Digital Twin technology accomplishes collaboration in three steps. Firstly, there is demand transmission and integration. Within the virtual model, each link conveys its decision - making requirements. For example, the sales link may put forward demands for production increase, while the production link may present demands for raw materials. These requirements are then aggregated to form a unified objective. Secondly, plan simulation and evaluation come into play. Multiple decision - making plans are formulated. Through simulations, key indicators for each link, such as the supply cycle and capacity utilization rate, are outputted for assessment. Finally, collaborative determination and dynamic adjustment are carried out. The participants choose the most suitable plan for implementation. In the event of environmental changes or the emergence of deviations, the virtual model will promptly issue reminders and generate adjustment suggestions. This ensures that decisions can adapt to the market situation and reach a global optimum.

4 Challenges and Future Outlook for Digital Twin Technology Application in Supply Chains

4.1 Main Challenges

Despite the fact that Digital Twin technology offers support for supply chain optimization, its practical implementation encounters core challenges in three areas. Firstly, there is the complexity of technology integration and modeling. This technology demands the integration of various technologies such as IoT and big data. Moreover, the entity attributes across multiple supply chain links vary greatly, with a multitude of dynamic factors involved, thus necessitating distinct modeling approaches. Small and medium-sized enterprises (SMEs) typically lack professional technical teams, making it arduous for them to build and maintain models independently. Secondly, data quality and security problems are conspicuous. The complexity of data sources results in inconsistent format standards, making the data prone to redundancy or missing values, which in turn impacts the accuracy of the model. At the same time, sensitive supply chain data is at risk of leakage and tampering during its circulation. In the absence of effective safeguards, this will impede the promotion and application of related technologies. Thirdly, achieving a balance between cost and benefit is a formidable task. The costs associated with equipment deployment, data storage, model maintenance, etc., are substantial, making it unaffordable for SMEs. Additionally, the benefits of this technology are usually manifested in long-term optimization, which is hard to quantify in the short term. As a result, companies tend to adopt a wait-and-see stance due to concerns about investment returns.

4.2 Future Outlook

To address the aforementioned challenges, the future development can center around the following four aspects. Firstly, boost technology integration and the standardization of modeling. Develop integrated platforms to ease the technical integration complexity. Set up modeling standards and introduce lightweight tools. By leveraging modular components, simplify the application procedures for small and medium-sized enterprises. Secondly, fortify data governance and security safeguards. Establish end-to-end data governance mechanisms to standardize data uniformly. Employ blockchain technology to guarantee the security of data sharing. Meanwhile, develop security technologies and clarify rights and responsibilities to ward off data risks. Thirdly, explore low-cost models and methods for quantifying benefits. Promote the "cloud deployment" and "pay-per-use" models, and encourage third-party outsourcing services. Establish an indicator system for quantifying benefits to offer a scientific foundation for enterprise decision-making. Fourthly, expand intelligent and green application scenarios. Strengthen the autonomous decision-making ability of models, incorporate the concept of green development, and realize energy conservation and emission reduction objectives in the supply chain through simulation optimization.

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