Advancing Smart Supply Chain Security Through Digital Twin Technology

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ABSTRACT In the global context of combating COVID-19, the complexity and demands associated with supply chain security have significantly intensified. Moving forward, the innovation and advancement of supply chain security will increasingly reflect the evolving requirements of global economic activities. The integration of digital twin technology promises to usher in a new era of intelligent supply chain security. This technology facilitates the complete digital representation of supply chain security by leveraging advancements in technology, centralized information management, and standardized rule formulation. Unlike the physical world, the virtual realm created by digital twins operates without the constraints of spatial distance, where distance serves merely as a reference rather than a barrier influenced by time zones. The virtual environment, being a folded space, allows for real-time observation and control interventions regardless of the physical separation between points A and B, provided digital twin technology is employed. Consequently, future smart supply chain security should be represented and validated through digital simulation models grounded in digital twin technology.

Keywords smart supply chain, security, digital twin, Internet of Things, digital simulation model.

I. INTRODUCTION

In the era of global economic integration and the ongoing battle against the novel coronavirus pandemic, the digital economy is poised to drive a new wave of scientific and technological advancements. The rise of digital assets—including digital currencies, digital artworks, and Non-Fungible Tokens (NFTs)—is expected to disrupt existing industrial paradigms and reshape the global economic landscape. As a pivotal technology within the realm of information technology development, digital twin technology is set to integrate with various industry sectors, emerging as a strategic focus of the technological revolution. The expanding applications of digital twin technology underscore the potential for its synergy with smart supply chain security, facilitating the transition from traditional to intelligent supply chain security systems.

The development of an innovative digital twin coupling mechanism will represent a critical technical advancement in smart supply chain security. Currently, digital twin technology is instrumental in transforming and upgrading smart supply chain security, transitioning from a "linear paradigm" to a "network paradigm." This shift will be driven by domestic demand and digital interaction transformation. Nonetheless, the integration of digital twin technology with smart supply chain security systems faces challenges related to technical barriers and system compatibility. To advance smart supply chain security, it is essential to establish a trust-based, mutually beneficial data-sharing network. Additionally, developing a government-guided, institutionally supported, and market-driven standardization system for digital twin technology is crucial to ensuring both the security and ecological integrity of smart supply chains.

II. Overview of digital twin technology

(1) Origins of Digital Twin Technology

The concept of "digital twins" was first introduced in 2003 by Professor Michelle Greaves from the University of Michigan. The core principle involves leveraging physical models, sensor data, operational histories, and other relevant information to create a comprehensive virtual representation of a physical product. This digital twin serves as a virtual space for managing the product's lifecycle through multi-disciplinary and multi-scale simulations.

Building upon Greaves' foundational concept, scholars have proposed two primary perspectives on digital twins. The first perspective posits that a digital twin represents a model from which various simulation models can be derived, characterizing the digital twin as an integration of models, data, and information. The second perspective views the digital twin primarily as a type of simulation. The prevailing view among researchers supports the first perspective, asserting that digital twins are combinations of multiple models, extensive data, and business information.

In China, research on digital twins has advanced significantly within the context of intelligent manufacturing and production. Notable contributions include Zhang Hao's development of personalized product design methods driven by digital twins, and Professor Tao Fei's formulation of application criteria and exploration of the digital twin's role throughout the product lifecycle, highlighting critical issues and technological challenges.

(2) Characteristics of Digital Twin Technology

The integration of digital twin technology with various industrial sectors has significantly advanced the digitalization, networking, and intelligence of these industries, becoming a crucial driver of economic and social development. In the foreseeable future, organizations are expected to transition into digital entities. This shift will necessitate not only the development of digitally enhanced products but also the transformation of entire product design, development, manufacturing, and service processes through digital means, linking both internal and external organizational environments.

Digital twin technology is a key enabler of organizational digital transformation, establishing a universally applicable theoretical and technical framework. Its application spans product design, manufacturing, engineering construction, and other analytical domains. At present, as industries focus on technological autonomy and digital security, the inherent characteristics of digital twin technology—such as efficient decision-making and in-depth analysis—are poised to accelerate the digital evolution of organizations and support the achievement of strategic development goals.

The characteristics of digital twins can be outlined as follows:

(a) Interoperability: Digital twins exhibit bidirectional mapping, dynamic interaction, and real-time connectivity between the physical object and its digital counterpart. This capability allows for the integration of diverse digital models, enabling transformations, mergers, and the establishment of coherent "representations" across different digital models.

(b) Scalability: Digital twin technology is inherently scalable, supporting the integration, addition, and replacement of digital models. It facilitates extension across various scales, physical dimensions, and levels of abstraction, accommodating a broad range of model content.

(c) Real-time Operation: Digital twin technology necessitates the digitization of data to enable computer recognition and processing, thereby accurately representing physical entities that evolve over time. This representation encompasses the entity's appearance, state, attributes, and internal mechanisms, resulting in a real-time digital virtual mapping of the physical entity.

(d) Fidelity: Fidelity in digital twins refers to the degree of accuracy with which the digital model replicates the physical entity. High fidelity is required not only in geometric structure but also in the entity's state, phase, and temporal dynamics. It is important to note that the level of simulation fidelity can vary across different digital twin scenarios.

(e) Visibility: Digital twins provide visibility by offering a visual representation and detailed description of the physical entity's model and internal mechanisms. This functionality enables monitoring, analysis, and reasoning of the physical entity’s state data, optimizing process and operation parameters, and facilitating decision-making processes, thereby endowing the digital twin with a "cognitive" capability akin to a brain.

(3) Application of Digital Twin Technology

With the increasing adoption of the Internet of Things (IoT), numerous organizations across various sectors are actively planning the implementation of digital twins. The Industrial Internet represents an extension and practical application of digital twin technology, enhancing its potential within the industrial domain.

In comparison to the United States and Germany, research and development of digital twins in China have progressed more recently. Nevertheless, digital twin technology has begun to demonstrate its value across multiple industries, particularly in smart manufacturing (refer to Figure 1). The digital twin system framework in the realm of intelligent manufacturing is typically structured into six levels:

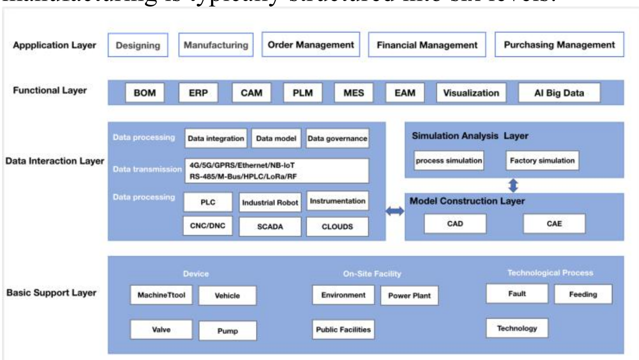


Figure 1: Framework of digital twin system in intelligent manufacturing field

(a) Basic Support: This foundational level involves the establishment of digital twins through the collection of extensive data. It necessitates the deployment of numerous sensors to monitor physical processes and devices, capturing essential data from both the processes and their surrounding environments.

(b) Data Interaction: Industrial data is primarily gathered through distributed control systems (DCS), programmable logic controllers (PLC), and advanced sensing instruments. This data collection forms the basis for subsequent analysis and application.

(c) Model Building and Simulation Analysis: This stage encompasses the creation of digital twins through modeling and simulation. Modeling involves constructing a 3D virtual representation of physical entities, accurately depicting attributes such as appearance, geometry, and motion. Simulation models, built upon these 3D representations, integrate physical laws and mechanisms—such as structural, thermal, electromagnetic, and fluid dynamics—to compute, analyze, and forecast the physical object's future states.

(d) Functional Layer and Application: This level utilizes the data-driven models and analytical results to perform specific functions. It represents the core functional value of the digital twin system by providing real-time insights into the physical system, aiding decision-making processes, and enhancing performance and user experience throughout the system's lifecycle.

An illustrative case of digital twin technology is Musk's ejection separation experiment. In this experiment, the rocket's booster, which is jettisoned after launch, is initially connected to the main rocket via explosive bolts. These bolts are detonated after reaching a specific altitude to release the satellite; however, the explosive bolts and the metal structure they eject are typically not recoverable. Musk's innovative approach involved using a mechanical spring mechanism for ejection, aimed at both separating and recovering the rocket components. This approach utilized extensive publicly available NASA data for computer-based modeling and simulation to analyze the performance of the spring mechanism and ejection bolts, foregoing physical experimentation. The successful separation of the ejection bolts and recovery of the rocket shell not only enhanced the efficiency of the process but also significantly reduced launch costs. Digital twin technology played a crucial role in shortening the product design cycle, improving the feasibility and success rates of product development, mitigating risks, and substantially lowering trial production and testing costs.

III. Importance of Supply Chain Management for China's Economy

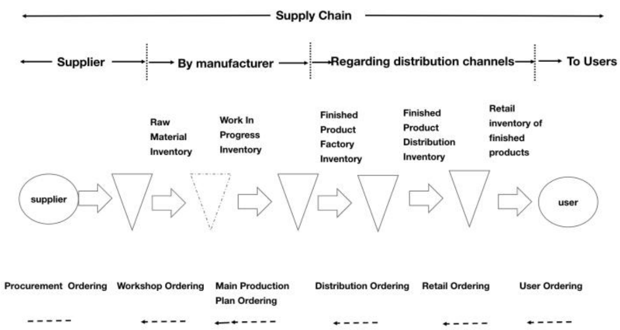
The supply chain is an important guarantee for the smooth operation of China's economy.

(1) Background

The rise of anti-globalization forces, the increasingly complex international environment, and the accelerated restructuring of global industrial chains due to the COVID-19 pandemic have markedly heightened the instability and uncertainty within the global supply chain. China's industrial supply chain is confronted with critical challenges related to autonomy, controllability, security, and stability. The Central Government has emphasized in the "14th Five-Year Plan" and the "Proposal for 2035 Vision Goals" the need to enhance the modernization of the industrial and supply chains. The Central Economic Work Conference (2021) further underscored the importance of "enhancing the autonomous and controllable capabilities of the industrial and supply chains" as foundational for establishing a new development paradigm. Additionally, the Government Work Report (2021) identifies "optimizing and stabilizing the industrial supply chain" and "enhancing its autonomous and controllable capabilities" as key priorities.

(2) Concept and Significance of Supply Chain Management

The supply chain encompasses the entire process from procurement of raw materials and parts, through transportation, processing, and manufacturing, to final distribution and delivery to the end user. Internally, the supply chain involves procurement, manufacturing, distribution, and other enterprise departments. Externally, it includes raw material suppliers, manufacturers, distributors, and end users. The fundamental goal of supply chain management is to ensure that the right product is produced at the right time, in the right quantity, and with the right quality, and is delivered to the right place—often referred to as the "6R"—while minimizing overall costs.



In the era of economic globalization, the manufacturing sector's labor division has become increasingly intricate, with the complete supply chain's reliability playing a crucial role throughout the product lifecycle. Huang Qifan, former mayor of Chongqing and deputy chairman of the Financial and Economic Committee of the 12th National People's Congress, highlighted at the Third High-end Forum of Chinese Economists in 2019 that "40 years ago, finished products constituted over 70% of global trade volume." In contrast, contemporary global trade comprises 70% components, raw materials, and intermediate goods, with only 30% consisting of finished products. This inversion in the ratio of trade between finished goods and intermediate goods underscores China's central role in the global supply chain network. According to the WITS database, nearly 200 economies import an average of 21.7% of their intermediate goods from China. The economic impact and growth rate of China surpass the global average, signifying China's pivotal position and significant contribution to the international economic cycle. The stability of the supply chain is crucial to the new development pattern where domestic and international circulations mutually reinforce each other.

Conversely, effective supply chain management is essential for enhancing production efficiency and distinguishing products in a competitive market. Research indicates that the supply chain costs throughout the product lifecycle increasingly contribute to the total cost. As the proportion of intermediate goods and materials rises, so do inventory costs. The globalization of labor division often results in production and delivery occurring in disparate locations, leading to higher transportation and tariff costs. Additionally, variances in product standards across countries and regions contribute to increased adaptation and compliance expenses. As supply chain costs escalate, managing a large number of upstream suppliers for production, transportation, and delivery becomes a significant challenge. The level of supply chain management is not only a critical factor for enterprises to gain a competitive edge in the market but also a key indicator of national competitiveness.

(3) Principal Objectives of Supply Chain Management

(a) Strategic Planning, Enhanced Management, and Cost Reduction

As previously discussed, the core objective of supply chain management is to achieve the "6R" criteria. Consequently, the primary aim of supply chain management is to develop a comprehensive strategy for the production process, addressing aspects such as timing, location, output, quality, and format to minimize costs and maximize benefits. For instance, Apple Inc., exemplifying an asset-light business model, has eliminated all its manufacturing facilities since 1998, opting instead to outsource production globally while concentrating on research, development, and marketing. The company has also streamlined its logistics by closing numerous warehouses and domestic distribution centers, strategically positioning parts suppliers near outsourced manufacturing sites to reduce delivery distances. By limiting the number of suppliers, Apple enhances management efficiency and mitigates supply risks, maintaining minimal inventory reserves and short inventory cycles to prevent simultaneous stockouts of high-demand products and overstocking of others. Such exemplary supply chain management practices have solidified Apple's position as a global leader.

(b) Responsive Adaptation to Market Volatility

The intricate nature of supply chain networks, coupled with evolving consumer preferences and increased market volatility, often results in significant distortions in upstream order demand that cascade down to production and manufacturing stages. This phenomenon, known as the "Bullwhip Effect," can lead to severe operational challenges such as excessive inventory, diminished service levels, elevated product costs, and compromised quality. An essential function of supply chain management is to devise effective strategies and coordinate both internal and external resources to adeptly manage and mitigate market fluctuations.

(c) Mitigating Supply Chain Risks

The growing complexity of supply chain networks exposes enterprises to a range of risks and threats. These include: (i) the impact of hegemonism, unilateralism, trade conflicts, technological disputes, and economic sanctions, which disrupt global supply chain labor divisions; (ii) fluctuations in the prices and costs of raw materials and intermediate goods, affecting production plans; (iii) potential disruptions from upstream suppliers, such as defaults, breaches of contract, delays, and bankruptcies; and (iv) the effects of natural disasters and global events, such as the COVID-19 pandemic, which can severely disrupt production, manufacturing, warehousing, and transportation processes, leading to dramatic reductions in production capacity and supply that are exacerbated throughout the supply chain.

(4) Challenges in Addressing Supply Chain Issues

At present, two primary challenges impede the resolution of supply chain issues. Firstly, insufficient trust among supply chain participants leads to ineffective cooperation. Enterprises within the supply chain network often engage in simultaneous competition, collaboration, and strategic maneuvering. In the absence of trust, firms frequently opt to maximize their own profits while offloading risks—such as market volatility, delivery delays, and order changes—onto their partners. This behavior undermines the sustainability of cooperative operations within the supply chain network. Secondly, outdated technological capabilities result in inadequate information communication. Domestic enterprises often lack the technological infrastructure necessary to gather and analyze customer demand and preferences effectively. Furthermore, the absence of a robust communication platform hampers the integration of suppliers, distributors, and retailers, resulting in low levels of network coupling and ineffective coordination.

IV. Advancements in Digital Twin Technology for Enhanced Supply Chain Security

In the context of the global battle against the COVID-19 pandemic, the complexity of supply chain security has intensified, alongside a heightened demand for robust security measures. The future of supply chain security innovation will increasingly rely on advancements in digital twin technology, ushering in a new era of smart supply chain protection. Digital twin technology will enable comprehensive digital mapping of supply chain security through technological advancements, centralized information management, and standardized protocols. Unlike the physical world, the virtual digital realm is characterized by the absence of spatial constraints; distances within this realm are merely markers, not barriers requiring traversal. The digital domain is effectively a folded space, where physical distance becomes irrelevant due to real-time observation and control facilitated by technologies such as sensors and the Internet of Things (IoT). Thus, ensuring the security of future smart supply chains will increasingly depend on the integration of digital simulation models based on digital twin technology.

(1) Simulation of Smart Supply Chains through Digital Twin Technology

Supply chain security incidents pose significant risks to international trade and economic growth, necessitating robust protection for personnel, goods, infrastructure, and transportation methods against potential threats and their adverse impacts. Such protective measures are crucial for the stability of both economic and societal systems. Given the dynamic nature of international supply chains, which encompass numerous entities and business partners, it is essential to examine how individual organizations can leverage digital twin technology to align with their specific value models and roles within the global supply chain.

Traditional supply chain security models often suffer from delayed information, leading to decision-making errors, inefficient processes, slow responses, and unforeseen risks. The complexity of managing vast data streams, such as logistics, capital flows, and information exchanges, renders conventional methods inadequate for addressing current challenges. In the digital era, simulation technology has emerged as a valuable tool for supply chain security management. While simulation has been utilized to address localized issues within supply chain security, comprehensive simulation modeling of the entire complex and dynamic supply chain ecosystem remains challenging. Digital twin technology extends the capabilities of simulation beyond product design and physical testing reduction, offering applications in remote diagnostics, intelligent maintenance, shared services, dynamic process optimization, risk analysis, and emergency response. This evolution reflects a shift towards more integrated and effective solutions for managing supply chain security in the face of extensive data and interconnected organizational networks.

(2) Applications of Digital Twin Technology in Enhancing Smart Supply Chain Security

The security of smart supply chains encompasses the entire lifecycle of product production and distribution. This lifecycle involves a comprehensive process centered around a core organization, incorporating the secure management of logistics, information flow, and capital flow. Starting with raw material procurement, progressing through the production of intermediate and final products, and culminating in the delivery to end-users via a marketing network, the supply chain consists of interconnected entities including suppliers, manufacturers, distributors, retailers, and consumers. Ensuring the safety and control of each link within this network is essential for effective emergency response and overall operational integrity.

Digital twin technology plays a pivotal role in modernizing supply chain security by offering a digital representation of the supply chain ecosystem. This approach integrates predictive technologies (such as time series analysis and machine learning), decision support tools (including artificial intelligence and operational research optimization), and business continuity strategies (such as emergency management and risk analysis). The digital twin supply chain model enhances traditional systems by overcoming limitations in response speed and cost, enabling more refined management and data-driven intelligent decision-making. This technology improves the safety, reliability, and efficiency of the supply chain while significantly reducing operational costs.

Specifically, digital twin technology involves creating simulation models for each node within the supply chain—such as warehousing, hubs, transportation, and distribution—along with their respective business links (e.g., inventory management in warehousing). This granular approach to digital twin supply chain security management allows for real-time online functionality and detailed operational analysis. By leveraging digital twin modules for individual structural components and their corresponding processes, front-line operators can perform critical tasks such as capacity assessment, equipment simulation, risk prediction, and strategy validation.

The synergy of smart supply chain security through digital twin technology relies on effective planning and execution. This includes developing a smart supply chain network security plan and a safety production guarantee plan, which cover all operational aspects from warehousing to distribution. The integration of digital twin technology across different supply chain links fosters enhanced security efficiency and collaborative optimization. By facilitating data collection, intelligence sharing, and upstream-downstream linkage, digital twin technology addresses key challenges in supply chain management, promotes strategic advancements in supply chain security, and accelerates industry and commercial transformation.

(3) Mitigating the Risk of Misuse of Digital Twin Technology in Supply Chain Security

The advent of digital twin technology has revolutionized the digitalization of organizational operations by integrating information with physical systems. However, this advancement also introduces potential vulnerabilities to malicious attacks that could severely disrupt both economic and social stability. The National Institute of Standards and Technology (NIST) has developed a set of guidelines to address security risks associated with traditional ICT systems. Nonetheless, the unique characteristics of digital twin systems—particularly their mapping relationship with physical entities and the pervasive connectivity enabled by the IoT—pose distinct challenges. Unlike traditional ICT security, which often benefits from physical and data isolation to mitigate threats, digital twin environments lack these isolating factors, complicating the security landscape across economic, social, legal, and technical domains.

To address these challenges, it is imperative to focus on the security of digital twin technology within the supply chain. This involves a comprehensive analysis of various risk sources, constructing targeted security processes, and developing technical solutions tailored to the specific vulnerabilities of digital twin systems. The construction of protective measures for digital twin open-source supply chain systems involves identifying and analyzing threat vectors, listing potential risk sources, and evaluating their likelihood and potential impact. By systematically cataloging these threats and their corresponding risk factors, optimal security strategies can be devised to safeguard digital twin implementations.

V. Conclusion

Although digital twin technology has been conceptualized for over 17 years, its application across diverse fields remains relatively novel. The development of technical standards, safety protocols, and production practices is ongoing, and a comprehensive, secure, and effective framework for managing digital twin supply chain security has yet to be fully established. Therefore, further theoretical research is necessary to address emerging security risks and challenges. Digital twin systems involve not only first-order interactions between physical entities and data models but also higher-order cooperative mechanisms such as incentives, feedback, and control, making them complex systems. The introduction of new technologies fosters new demands and innovations. Digital twin technology has the potential to offer novel approaches and solutions for enhancing smart supply chain security.

Future advancements will likely integrate digital twin technology with emerging fields such as 5G, IoT, big data, and artificial intelligence. This multidimensional integration will enable the mapping of various components—such as warehousing, transportation, personnel, infrastructure, and environmental factors—from physical space to cyberspace. Establishing digital twin simulation models will enhance the safety, efficiency, and continuity of smart supply chain security, demonstrating the practical value and transformative potential of digital twins.

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