Simulation of Supply Chain Modeling with Digital Twins

H. Michael Chung
IS and CIST, CSULB, U.S.A.

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Abstract: The current supply chain management landscape, particularly with the workflow disruptions due to COVID-19, demands more visibility, adaptive responses, and real-time predictive capabilities. First, this research investigates digital twins' strategies, processes, success measures, and impact, and constructs a more effective supply chain modeling. Second, the study develops appropriate performance measures and metrics for digital twins in supply chain management. Lastly, it constructs a digital twin prototyping framework for building a more effective supply chain.

1 INTRODUCTION

Supply chain management (SCM) has faced unprecedented challenges during the COVID-19 pandemic, resulting in supply shortages, sourcing limitations, and logistical delays. These challenges are counterproductive to the supply chain's visibility and adversely affect its core business. Disruption risks could significantly impact SC performance, underscoring resilience as a key determinant of long-term success, which needs to integrate agility, flexibility, and collaboration.

SCM should address increasing complexity, enhance predictive capabilities, and provide adaptive responses. These challenges involve how humans can access real-time information about physical assets and interacting business processes, perform real-time analysis with the information, and make timely, robust, and efficient decisions.

Numerous studies were conducted on how these issues could be addressed. For example, the studies include the increasing digitalization of the current product and process life cycle and its control and analysis, the networks of component demand, and sophisticated human-machine interfaces in a digitalized environment (Burattini, et al., 2024; Boyes and Watson, 2022). For this goal, digital twins in the industrial metaverse have been introduced for SCM (Rajagopal et al., 2017).

A digital twin is a virtual representation of a system designed to reflect a physical system as it resides in computer platforms. It spans the system object life cycle, updates real-time data, and uses simulation and machine learning to help make decisions (Wagg & Gardner, 2020; Juarez et al., 2021). The data used to create these replicas is often collected from the Internet of Things (IoT). Digital transformation refers to integrating digital technologies into all aspects of an organization to change how it operates fundamentally, delivers value, and engages with stakeholders. Digital twins are a pivotal technology within digital transformation, offering organizations the tools to bridge the physical and digital realms, optimize operations, and unlock new business opportunities.

The primary research objectives are to model and build a prototype of a supply chain in digital twins that purports to accurately capture supply, demand, risk, and resilience, manage the changing environment, and increase the model's adaptability.

2 LITERATURE REVIEW

The digital twins' theoretical framework and practical implementations have yet to reach their goal. More research is needed to identify the actionable variables in digital twins (Sholten et al., 2020; Razak et al., 2021; Ivanov, 2023). There has been a dearth of research on using digital twins in SCM (GurDur & Schooling, 2023; Gai et al., 2023). The research areas include identifying the scope of the physical entities and business processes involved in the supply chain; how the physical supply chain and the virtual

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environment could be mapped and synchronized; and the key data needed to measure and collect (Wang et al., 2022).

Research Questions for digitak twin-driven supply chain modeling are:

- What are the key physical entities and processes, particularly dynamic and real-time data, need to be interactively shared and synchronized?
- What are the supply chain's critical success factors and potential bottlenecks?
- How do we map and integrate these entities and processes with a digital twin model?
- What are the variables that would enhance and support supply chain resilience?

The synchronization here refers to the transmission of bidirectional information. The data used in the physical supply chain are either static data related to the fundamental properties of physical entities or real-time, dynamic data generated in business operations (Wang et al., 20). Static data ensures that the virtual supply chain shares the same structure and properties as the physical supply chain. Real-time, dynamic data synchronizes the status and processes in the virtual world. For example, the location of a truck and traffic conditions are updated in real-time. Hence, the estimated arrival time is updated continuously and precisely. Sensors and other IoT equipment collect real-time data, typical of manufacturing and online systems, such as procurement and order management systems, in the virtual world through simulation.

Smart sensors or online systems connect the physical supply chain in a digital twin. Specific data and information are collected to enable the virtual supply chain to mirror the physical supply chain's properties and dynamic business processes. The research analyzes the actual data in the physical supply chain and the simulated data in the virtual supply chain. Then, the results are transferred to the physical world to support intelligent decision-making and implementation (Ivanov, 2024).

While challenging, real-time data acquisition and implementation could allow the connection between the physical and virtual supply chain to synchronize operation dynamics, increasing supply chain visibility. The synchronized data provides opportunities to monitor, analyze, control, and optimize the supply chain, resulting in up-to-date virtual simulation and optimization. Therefore, a digital twin model could optimize the supply chain across different stages and establish an integrated supply chain. It allows decision-makers to look forward instead of backward and makes the supply chain intelligent (Klappich, 2019).

More research is needed to understand capacity modeling from data-driven approaches compared with demand signals. According to de Kok et al. (2018), most studies assume infinite capacity. Feng and Shanthikumar (2018) suggested capacity modeling of supply chains. Garvey et al. (2015) applied Bayesian networks to measure risk propagation in a supply network. In a supply chain, the propagation of risk signals (information) and actual risks (events) are often asynchronous. Companies must develop new modeling approaches to understand these asynchronous signals and events. Analytics must be designed to predict when actual risks occur so stakeholders can prepare.

Moreover, model adaptability with real-time data requires more research. For example, Feng and Shanthikumar (2018) proposed an approach that transforms nonlinear supply and demand functions into linear functions to model random supply and demand. Data-driven optimization is another tool that addresses complex supply and demand data by solving mathematical programming problems directly using observed data (Bertsimas & Thiele, 2006). Levi et al. (2015) illustrated applying this idea in modeling demand with an unknown distribution. Peron (2020) introduced a vision for a DT for SCM spare parts enabled by additive manufacturing.

Furthermore, companies must carefully manage sensitive customer information, which is increasingly exposed to criminal threats (Fuller et al., 2020) and regulated by laws. For example, the European Union's General Data Protection Regulation regulates personal data privacy and security. In particular, these new regulations require data controllers (companies) to explain their data use to data subjects (customers) (European Union, 2018).

3 RESEARCH DESIGN AND METHODOLOGY

The study plan is further developed from prior research on supply chain, blockchain, and IoT pilot implementations (Chung, 2020a; 2020b; 2022). We have collected qualitative data, including interviews with supply chain stakeholders, particularly in the agricultural industry. The grounded theory will be employed to analyze the qualitative information collected from the domain professionals.

a) *Suppliers (Raw Material Sourcing)*

- Identify & evaluate suppliers
- Negotiate contracts
- Order raw materials
- Quality check raw materials
- Package & label raw materials
- Arrange transportation

b) *Inbound Logistics (Transportation & Receiving)*

- Plan transportation routes
- Coordinate shipment schedules
- Track shipments
- Receive & inspect goods at the warehouse
- Log inventory in the system

c) *Manufacturing & Production*

- Store raw materials in inventory
- Schedule production
- Process/assemble goods
- Quality control (inspection & testing)
- Package finished goods
- Store in finished goods inventory

d) *Warehousing & Inventory Management*

- Receive finished goods from production
- Store & organize inventory
- Monitor stock levels (real-time tracking)
- Pick & pack products for shipment
- Conduct periodic inventory audits
- Manage returns/damaged goods

e) *Order Processing & Fulfillment*

- Receive customer orders
- Verify payment & order details
- Allocate stock for order fulfillment
- Print shipping labels & documentation
- Dispatch order to the logistics team

f) *Outbound Logistics (Shipping & Distribution)*

- Select an appropriate transportation method
- Load goods onto delivery vehicles
- Track shipments & update customers
- Manage customs clearance for international shipping
- Deliver goods to retailers/customers

g) *Retail & Sales (Physical & E-Commerce)*

- Receive and stock inventory
- Display and market products
- Manage pricing & promotions
- Process customer orders
- Handle customer inquiries & support

h) *Last-Mile Delivery*

- Assign delivery routes
- Deliver goods to end customers
- Provide tracking & real-time status updates
- Handle customer complaints or returns

i) *Customer Service & Returns Management*

- Receive feedback & reviews
- Process returns & refunds
- Replace or repair defective goods
- Improve customer satisfaction & retention

4 DATA COLLECTION AND ANALYSIS

Seven Interviews with supply chain managers and experts were conducted to confirm critical processes and real-time data challenges. Interpretive analysis is being applied. In addition, two field visits are being undertaken: A logistics company in the Port of Long Beach in California, and an overseas company producing, packing, and delivering agricultural products to a shipping company are involved. Key performance measures are collected from expert interviews and field observations to validate the model. A software package will be used to develop a digital twin prototype model.

5 CONCLUSION

The research investigates the digital twins' nodes, processes, success measures, and impact, in order to construct a supply chain model.

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