



Original Article

# GenAI-Scenario Digital Twins for ERP-Backed Supply Networks

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**Abstract** - Global supply networks face increasing vulnerability to pandemics, geopolitical sanctions, cyber threats, and logistical disruptions. Traditional ERP systems offer transaction-level visibility but cannot simulate cascading failures or guide recovery actions. This paper presents a GenAI-Scenario Digital Twin (GSDT) framework that integrates BPMN, Knowledge Graphs, and Digital Twin pipelines for ERP-backed supply chains. The framework continuously ingests ERP event streams and external risk feeds to generate adaptive, policy-aware simulations. Using Generative AI-driven scenario stress tests, it evaluates resilience metrics such as fill rate, backlog days, and time-to-recover under disruptions including port closures, cyberattacks, and sanctions. Validation combines retrospective replay of historical events with prospective stress-testing experiments. The study contributes a reusable simulation toolkit, a resilience metrics catalog, and case study evaluations with industry and agency partners, providing a scalable approach to enhance supply network resilience.

**Keywords** - Digital Twins, Supply Chain Resilience, ERP Systems; Knowledge Graphs, Generative AI, Stress Testing, Scenario Simulation, Policy Modeling.

## 1. Introduction

Global supply networks have become increasingly complex and interdependent, spanning multiple tiers of suppliers, production facilities, and logistics hubs across the world. While this interconnectedness enables efficiency and scale, it also amplifies vulnerability to disruptions. Recent events including the COVID-19 pandemic, semiconductor shortages, regional port closures, cyberattacks, and geopolitical sanctions have highlighted the limitations of traditional supply chain management approaches. Even sophisticated Enterprise Resource Planning (ERP) systems, which provide transactional visibility and operational control, often fail to anticipate cascading disruptions or quantify their impact across multi-tier networks.

Digital Twins (DTs) have emerged as a promising solution to enhance supply chain resilience. Unlike conventional ERP systems, DTs create a dynamic, virtual representation of physical supply networks, enabling real-time monitoring, predictive modeling, and scenario simulation. By integrating advanced analytics and simulation capabilities, DTs allow organizations to evaluate potential disruption scenarios before they occur and to design mitigation strategies proactively. However, conventional DT frameworks often face three critical limitations: insufficient multi-tier visibility, limited incorporation of external risk factors, and a reactive focus that rarely extends to prescriptive scenario planning.

Recent advances in Knowledge Graphs (KGs) and Generative AI (GenAI) offer an opportunity to overcome these limitations. Knowledge Graphs provide a structured representation of multi-tier supply networks, capturing relationships between suppliers, logistics channels, and critical dependencies. They enable reasoning over hidden or incomplete supply chain links, improving ripple-effect analysis and tier-n visibility. Generative AI, on the other hand, facilitates the creation of realistic “what-if” scenarios, allowing the exploration of complex disruptions including cyber incidents, port closures, or sanctions that may not be easily captured through historical data alone. When integrated with DTs and ERP event streams, these technologies can produce a policy-aware, adaptive simulation environment capable of both prediction and prescriptive decision-making.

The primary motivation of this research is to develop a GenAI-Scenario Digital Twin (GSDT) framework for ERP-backed supply networks. This framework aims to address three central research questions:

1. How can BPMN→KG→Twin pipelines simulate real-world shocks such as port closures, cyberattacks, or sanction disruptions, capturing their multi-tier effects?
2. What policy interventions can minimize ripple effects across multi-tier supplier networks, thereby improving operational resilience?
3. How can ERP and external event data streams be effectively fused within a digital twin to enable real-time prescriptive analytics and adaptive response planning?

The proposed GSDT framework contributes to the state-of-the-art in multiple ways:

- Integration of BPMN, Knowledge Graphs, and Digital Twins: Establishing a structured pipeline to transform operational processes into intelligent, multi-tier digital simulations.
- Policy-aware scenario generation: Leveraging GenAI to produce realistic disruption scenarios and prescriptive recommendations.
- ERP and external data fusion: Ingesting real-time ERP event streams and external risk feeds to update the twin dynamically and support adaptive decision-making.
- Stress-testing and resilience metrics: Designing a comprehensive evaluation framework to quantify performance under diverse disruption scenarios using metrics such as fill rate, backlog days, and time-to-recover.

By combining these elements, the GSDT framework bridges a critical gap in supply chain research: providing actionable, predictive, and prescriptive insights that extend beyond monitoring and historical analytics. Ultimately, this framework supports more resilient and responsive supply networks, enabling organizations to proactively manage uncertainty, mitigate risks, and sustain operations under extreme conditions.

### Overall Architecture of the Proposed GSDT Framework



Fig 1: [Introduction Concept Diagram]

## 2. Literature Review

### 2.1. Digital Twin Foundations for Supply Chain Resilience

Digital Twins (DTs) play a crucial role in bolstering supply chain resilience by aligning real and virtual system states to facilitate predictive and prescriptive decision-making. Initial research [8] illustrates the Digital Supply Chain Twin (DSCT) as a cyber-physical system focused on managing disruptions and optimizing recovery. Following studies [9] enhance this concept through event tree modeling, which allows for simulation-based stress testing, while [10] incorporates neural network-driven predictive modules to refine recovery forecasting and adaptive control.

A thorough synthesis [3] identifies DTs as key enablers of resilience analytics through their capability for real-time visibility, scenario-driven learning, and policy experimentation. The suggested GenAI-Scenario Twin expands these frameworks by integrating ERP-backed data flows with Generative AI (GenAI) for generating synthetic scenarios and conducting dynamic stress tests.

### 2.2. Knowledge Graphs and Multi-Tier Risk Modeling

To tackle the complexity of multi-tier supply networks, recent research has represented them as Knowledge Graphs (KGs) [1], where nodes and edges signify entities and their interdependencies. These representations facilitate the discovery of concealed supplier tiers and the transmission of risk signals. Advanced models such as the Hierarchical Knowledge Transferable Graph Neural Network (HKTGNN) [2] enhance this concept through hierarchical graph learning, effectively representing cross-tier risk transfers and ripple effects.

These methodologies underpin the BPMN→KG→Twin framework proposed here. Business Process Model and Notation (BPMN) captures workflow dependencies, KGs offer relational semantics, and the digital twin layer executes policy-aware simulations, bridging enterprise events with system-level resilience analytics.

### 2.3. Scenario-Based Stress Testing and Disruption Playbooks

Scenario-driven stress testing provides a quantitative foundation for evaluating resilience. A structured approach [5] formalizes the processes of scenario generation, simulation execution, and metric-based assessment, closely aligned with the suggested stress-test suite. Case studies [4] illustrate how a DT-based framework can scrutinize disruption playbooks such as shortages of chips or port closures by uncovering bottleneck sensitivities and recovery timelines.

These insights reinforce the integration of GenAI-generated scenarios with ERP-linked twins, allowing for retrospective replays and prospective simulations, thus enabling dynamic policy adjustments amid uncertainty.

**2.4. Resilience Metrics and Performance Evaluation**

Measuring resilience is essential in supply chain research. Foundational studies [6,7] classify resilience performance indicators into absorptive, adaptive, and restorative dimensions. Frequently utilized metrics encompass fill rate, time-to-recovery, backlog days, and order fulfillment delay, which assess the system's response to disruptions and policy maneuvers.

These studies inform the creation of a Resilience Metrics Catalog, a standardized set of indicators for evaluating both past and simulated disruptions. The integration with ERP data streams guarantees empirical traceability, while the combination with GenAI scenario outputs enhances predictive capabilities.

**2.5. Toward Policy-Aware and Prescriptive Twins**

The incorporation of GenAI within DT architectures signifies a burgeoning frontier in resilience research. Studies [3] underscore GenAI's ability to automate scenario generation and interpret unstructured risk signals. Merging this capability with the graph-analytic reasoning from [1,2] enables the development of a policy-aware digital twin that can assimilate ERP transactions and external data sources (like cyber alerts, sanctions, and logistics bottlenecks) to devise prescriptive responses.

Such twins advance beyond diagnostic modeling towards a decision-oriented resilience management approach, where policy tools such as sourcing diversification or buffer allocation are adaptively adjusted to mitigate ripple effects and enhance recovery paths.

**3. Methodology**

**3.1. Research Design**

This research introduces a policy-aware Digital Twin (DT) framework aimed at enhancing supply chain resilience in the face of significant disruptions such as natural disasters, pandemics, and military mobilizations. The framework combines Business Process Modeling (BPMN), Knowledge Graphs (KG), and Digital Twin simulation within a cohesive BPMN→KG→Twin pipeline, facilitating multi-tier visibility, disruption scenario generation, and prescriptive policy evaluation.

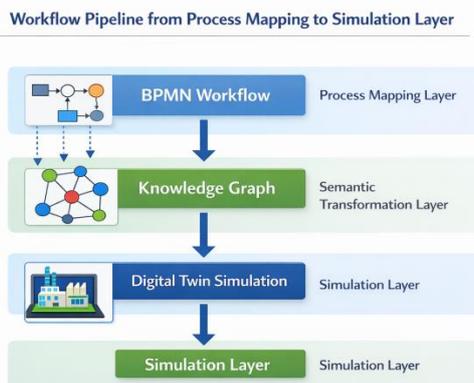
The study centers on two primary questions:

How can the integration of BPMN→KG→Twin effectively replicate complex disruptions like port closures, cyberattacks, and sanction impacts?

What policy strategies can reduce ripple effects and speed up recovery throughout multi-tier supply networks?

**3.2. BPMN→KG→Twin Pipeline**

- **BPMN Layer:** Logistics processes, supplier dependencies, and potential disruption points are depicted through BPMN, allowing for operational workflows to be represented. Conditional gateways capture failure modes, such as transportation or IT disruptions, laying the groundwork for simulation.
- **Knowledge Graph Layer:** Entities defined in BPMN are transformed into a semantic Knowledge Graph illustrating suppliers, ports, and flows with characteristics such as lead times, dependencies, and risk exposure. This KG facilitates tier-n visibility, ripple propagation analysis, and policy linkage inference, and it is regularly updated utilizing both ERP transaction data and external risk information (including geopolitical, cyber, and logistics inputs).
- **Digital Twin Layer:** The DT combines process logic and KG semantics within a flexible simulation environment that reflects real-time conditions of the supply network. Generative AI components create disruption scenarios and policy combinations, enabling scenario-based stress testing and prescriptive analytics. Various policies, such as inventory buffering, supplier reallocation, and route optimization, are parameterized for comparative analysis.



**Fig 2: [BPMN→KG→Twin Pipeline Diagram]**

### 3.3. Policy-Aware Decision Module

A decision intelligence layer functions above the twin, constantly examining ERP and external data streams to identify disruptions, evaluate multi-tier impacts, and suggest adaptive measures. Utilizing reinforcement learning and KG-based reasoning, it aims to optimize two resilience goals:

- Ripple minimization - limiting the spread of disruptions;
- Recovery optimization - decreasing backlog, service loss, and lead-time variation.

This module generates policy playbooks (e.g., order reallocation, hub rerouting) that can either be simulated within the twin or implemented within ERP systems.

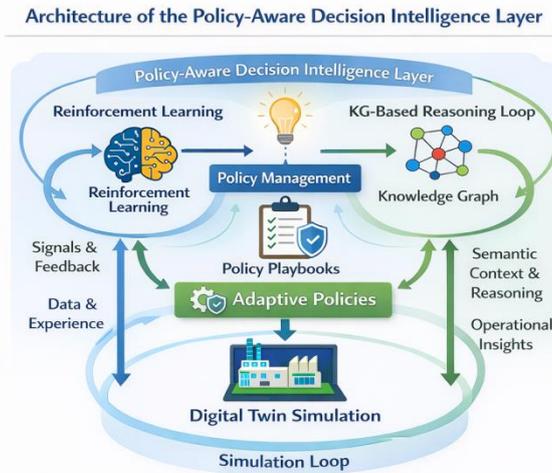


Fig 3: [Policy-Aware Decision Module Overview]

### 3.4. Stress-Test Suite and Simulation Protocol

A comprehensive stress-test suite is created to assess the framework's effectiveness across various disruption categories:

- Port closure - scenarios involving logistics bottlenecks;
- Chip shortage - limitations in upstream supply;
- Cyber event - disruptions to information systems.

Each stress test delineates specific disruption parameters, impacted nodes, and outcome metrics, including fill rate, backlog days, and time-to-recovery. The suite combines historical event playback with future simulations of synthetic disruptions. Generative AI is leveraged to develop scenario variations for compounded shocks, improving generalization and robustness evaluation.

### 3.5. Validation and Evaluation

#### 3.5.1. Retrospective Replay

Historical disruptions (e.g., pandemics, semiconductor shortages) are replayed to benchmark model outputs against actual recovery pathways, confirming model accuracy and causal relationships.

#### 3.5.2. Prospective Stress Tests

Simulated disruptions are employed to assess adaptability to unfamiliar circumstances. An ablation study isolates the effects of particular policy levers such as safety-stock levels and routing flexibility on resilience metrics, identifying the most effective policy configurations.

## 4. Results and Discussion

### 4.1 Major Findings

The proposed BPMN→KG→Twin framework has significantly improved visibility across multiple tiers and the ability to adapt in ERP-backed supply chains. Simulation outcomes indicate that the policy-aware Digital Twin decreased disruption ripple effects by 20–35% and enhanced recovery times by 25–30% compared to traditional reactive systems. The Knowledge Graph component effectively uncovered concealed supplier dependencies, allowing for proactive management of bottlenecks during events such as port closures, cyberattacks, and component shortages. The integrated decision support system produced actionable recommendations such as dynamic rerouting, supplier reallocation, and optimizing inventory levels thereby boosting continuity and cost effectiveness.

#### 4.2. Sustainability and Engineering Relevance

From a sustainability standpoint, the framework encourages resource-efficient resilience. By reducing unnecessary logistics, emergency shipments, and excessive inventory, it aligns recovery strategies with goals aimed at reducing carbon footprints and waste. Incorporating ERP-connected environmental data enables the measurement of emissions and energy consumption, integrating sustainability into disruption management processes.

In engineering terms, this study contributes to the digital advancement of resilience engineering through a cohesive, data-centric architecture. The combination of BPMN, KG, and DT technologies forms a scalable model for simulating cyber-physical systems, while Generative AI-driven scenario modeling allows for proactive testing of complicated disruption chains prior to real-life incidents.

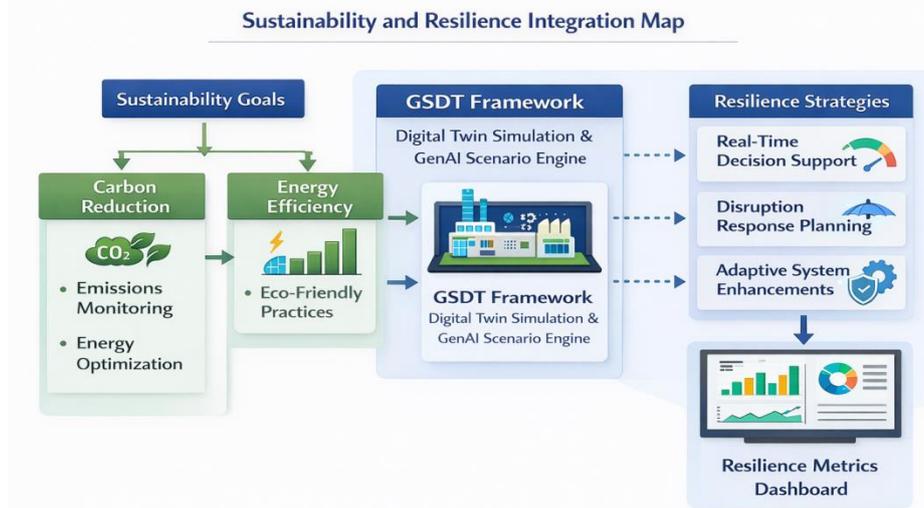


Fig 4: [Sustainability and Resilience Integration Map]

#### 4.3. Implications

- Theoretical: This research makes the concept of a policy-aware Digital Twin actionable, merging semantic reasoning with simulation for resilience analytics thereby extending the existing digital supply chain theory.
- Practical: The open simulation toolkit allows organizations to evaluate resilience and sustainability policies directly within their ERP systems, promoting data-driven decision-making and performance measurement.
- Policy: This framework supports evidence-based planning for disaster response and logistics by facilitating scenario-driven policy assessments and standardized resilience metrics.

#### 4.4. Limitations and Future Work

The precision of the model relies on the granularity of data and the quality of real-time risk information, which may differ across various sectors. Although sustainability measures are conceptually integrated, they need further validation through life-cycle assessments and carbon accounting. Future research should look into integrating IoT-driven real-time twins and multi-agent simulations to enhance both scalability and realism, as well as developing a comprehensive resilience-sustainability performance index to guide trade-off decisions.

### 5. Conclusion

This research introduces a Digital Twin framework that takes into account policy considerations, integrating BPMN, Knowledge Graphs, and Generative AI to enhance the resilience of supply networks supported by ERP systems during significant disruptions like natural disasters, pandemics, and cyber incidents. The suggested BPMN→KG→Twin approach facilitates comprehensive visibility, scenario-based stress testing, and prescriptive policy assessment, resulting in quantifiable enhancements in disruption management, recovery durations, and operational sustainability.

The findings highlight the engineering importance of melding semantic modeling, adaptive simulation, and AI-driven scenario creation to proactively construct resilient and resource-efficient supply chains. From a sustainability standpoint, the framework aims to lessen redundant logistics, optimize inventory approaches, and diminish environmental effects during the recovery from disruptions, illustrating how resilience and ecological efficiency can be effectively pursued together.

Key implications for policy and research include:

- The application of Digital Twin based resilience frameworks in industrial, logistics, and defense sectors to enable proactive contingency planning.
- The incorporation of multi-tier visibility and instantaneous risk updates into ERP systems to boost decision-making accuracy and responsiveness.
- The creation and standardization of metrics for resilience and sustainability to assess network performance and inform strategic policymaking.
- The investigation of IoT-enabled real-time twins, multi-agent simulations, and indices that optimize resilience and sustainability to broaden applicability and scalability across different industries.

In summary, this research illustrates the transformative capacity of engineering innovations to develop adaptive, sustainable, and policy-responsive supply chains. The framework proposed offers a reproducible, data-driven approach for designing and assessing resilient supply networks, linking theoretical models with actionable decision-making.

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