Journal of Business and Management Studies
ISSN: 2709-0876
DOI: 10.32996/jbms
Journal Homepage: www.al-kindipublisher.com/index.php/jbms

JBMS
AL-KINDI CENTER FOR RESEARCH AND DEVELOPMENT

| RESEARCH ARTICLE

Resilient Supply Chains under Tariff Volatility: A Digital Twin-Enabled FLEX Model for Strategic Sourcing and Risk Mitigation

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| ABSTRACT

In the current uncertain global trade climate, supply chains endure greater pressures from volatile tariff regimes and changing geopolitics. Traditional risk-reducing and sourcing strategies prove inadequate in coping with such dynamic disruptions, especially when relying on foreign suppliers. This paper presents an innovative FLEX supply chain model—Flexible sourcing, Localized manufacturing, Elastic contracts, and Extra inventory buffers—that is intended to create increased resilience, agility, and profitability in the environment of tariff uncertainty. The model is then enhanced with the incorporation of Digital Twin (DT) technologies for real-time simulation, predictive analytics, and scenario planning. Based on cross-disciplinary literature in supply chain risk management, contract theory, and digital technologies, the research formulates a conceptual model and tests it in simulation-based case scenarios of on-again/off-again tariff events. The findings show that the FLEX+DT model is far better compared to conventional methods in terms of minimizing lead time variability, minimizing cost shocks, and maintaining operational continuity in global supply networks. Through the dynamic redistribution of resources, policy simulation, and contingency planning, the model provides a strategic toolkit for decision-makers managing tariff-induced disruptions. The work presents two key contributions: (1) it formalizes an end-to-end, modular supply chain design for tariff volatility, and (2) it takes Digital Twins from operational optimization to macro-level mitigation of trade risk. The results provide actionable insights to supply chain executives, policymakers, and global manufacturers in developing resilient, future-ready operations. The model can be taken forward in empirical industrial environments and synergistic links with AI-driven procurement systems and blockchain-secured smart contracts in future work.

| KEYWORDS

Supply-Chain, Digital Twin, FLEX model, Tariff, Risk Mitigation

| ARTICLE INFORMATION

ACCEPTED: 20 July 2025 **PUBLISHED:** 07 Augut 2025 **DOI:** 10.32996/jbms.2025.7.4.16

1. Introduction

Global supply chains have become increasingly dynamic, complex, and vulnerable as a result of the high velocity of expansion in globalization, offshoring, and multi-tiered supplier networks. While such interlinkages have produced efficiency benefits and cost savings, it has left organizations susceptible to systemic risk in times of regional tension, trade wars, and variable regimes of tariffs. The classic example is the periodic introduction and rescission of tariffs between the United States and large trading partners like China and the European Union. Such on-again/off-again tariffs impose uncertainty in the value chain—interrupting procurement planning, driving landed cost increases, destabilizing supplier relationships, and hindering the continuity of business [1].

Conventional risk mitigation methods like multi-sourcing or buffering inventory offer incomplete relief and are themselves reactive in nature. They do little to provide the level of agility and forward thinking required to respond to dynamic tariff changes with cost structures and sourcing paths altering with little notice. Additionally, most global manufacturers are too heavily reliant on single-region sourcing that increases their vulnerability to abrupt policy changes as well as import-export restrictions. In such circumstances, there is an immediate need for an adaptable, scalable, and technology-based supply chain model that resists tariff shock while maintaining operational efficiency along with profitability [2].

In this paper, the author presents a new supply chain model known as the FLEX supply chain model based on four pillars of foundational support: Flexible sourcing, Localized manufacturing, Elastic contracts, and Extra inventory buffers. Each of these pillars is engineered as a modular lever on which supply chain resilience and flexibility can be built in order to counter disruptions based on tariffs. The FLEX model helps companies systematically separate risk from dependence on single sources of supply, minimize dependence on long-distance trade lanes, and incorporate strategic redundancies where required in order to absorb and respond to changes without sacrificing production levels.

The value of the FLEX model is not merely in its strategic components but in its combination with Digital Twin (DT) technologies—a rapidly advancing technique allowing virtual models of physical systems to be used for monitoring in real-time, predictive simulation, as well as what-if scenario analysis. The utility of DT solutions in operational spaces such as equipment diagnostics and production planning has already demonstrated its value, but their use in macro-level supply chain resilience, particularly tariff risk modeling, has been relatively unexplored [3]. Here, this research fills that need by merging the use of the FLEX model with an analytical layer based on Digital Twin to simulate, anticipate, and counteract disruptions before the actual events occur. By performing virtual stress tests on tariff-vulnerable components or geographies, firms can assess alternatives without the cost or delay of actual trials.

Incorporating FLEX principles into Digital Twin simulation is the basis of an active, responsive supply chain architecture that facilitates strategic procurement decisions in uncertain global trade environments. The integrated model allows companies to model supply network topologies, simulate multiple trade-policy scenarios, and analyze the performance of alternate sourcing contracts and suppliers in terms of risk, cost, and lead-time impacts. In addition, the modularity of the FLEX model renders it scalable for SMEs and MNCs of all sizes with the flexibility to configure resilience options based on risk tolerance, industry sector, and geography reach.

The main goals of this paper are threefold:

I. In order to introduce and codify the conceptual basis of the FLEX model as a multi-lever approach to tariff resilience
II. To illustrate how Digital Twin integration increases the decision-making ability of the model by emulating tariff-based disruptions and their ensuing impacts.
III. To confirm the new approach based on realistic but hypothetical simulation examples that respond to current trade tensions as well as on the superiority of the FLEX+DT design over traditional models.

This work adds to theory as well as practice. Theoretically, it adds to the literature on supply chain resilience by introducing a new hybrid approach that is structural (FLEX) as well as technological (DT). Pragmatically, it provides an available route for supply chain executives as well as policy-makers to counteract trade-related uncertainties without depending on reactionary or excessively expensive procedures. As digital transformation evolves to redefine manufacturing as well as procurement activities, this research places the FLEX+DT model in the vanguard of sustainable, responsive, as well as wise global supply chains.

The rest of this paper is structured as follows: Section 2 presents an overview of literature on supply chain risk management, contract elasticity, and digital twin technology. Section 3 presents the conceptual framework of FLEX. Section 4 introduces the Digital Twin architecture for decision-making based on FLEX. Section 5 describes the methodology and simulation environment. Section 6 reports the outcome of the case scenarios in simulation experiments. Section 7 discusses managerial implications, and Section 8 concludes with implications, limitations, and future work opportunities.

2. Literature review

2.1 Supply Chain Resilience in the Context of Trade Disruptions

Supply chain resilience has become an essential competency in the wake of growing global volatility with specific focus on an organization's capability to anticipate, absorb, adapt to, and bounce back from disruptions. While traditional definitions of resilience focused on recovery velocity and business continuity, modern views include active and dynamic capabilities that allow companies not just to rebound but to prosper in uncertain environments. Disruptions in foreign trade such as sudden imposition or withdrawal of tariffs, sanctions, and non-tariff barriers have considerably heightened the need for such capabilities. In contrast to natural disasters or operational errors, tariff disruptions are policy-induced, politically triggered, and typically uncertain in timing as well as magnitude. Due to these attributes, traditional resilience techniques like static safety stocks or fixed contracts would prove inadequate. Evidence from the U.S.–China trade tensions and Brexit talks shows how sudden policy changes in duty rates or import-export regulations cause order cancellations, supplier delisting, and sudden changes in total landed cost, which ultimately impact customer service levels as well as profitability. Businesses that are highly dependent on global suppliers with extended lead times as well as single sourcing arrangements are particularly exposed. The literature highlights resilienceenhancing techniques like dual sourcing, geographically diversification, as well as responsive logistic networks; but these involve cost versus agility trade-offs that are seldom optimized. Moreover, there are few such models prevalent that specifically cater to intermittent policy jolts like tariffs that could arise, intensify, as well as cap in short intervals of time. This lacuna justifies the need for shifting to a dynamic, module-based, as well as digitally enhanced resilience strategy—the basis of the FLEX model in this work [4][5][6].

2.2 Flexible and Localized Sourcing Models

Flexible and regional sourcing strategies have emerged as important supply chain resilience enablers in environments with volatility in disruptions and geopolitics. Global sourcing paradigms optimized for cost-saving tend to leave companies exposed to heightened risk through prolonged lead times, cross-border dependencies, and fixed supplier arrangements. It is reported that flexibility in sourcing—in terms of the ability to make quick adjustments in sourcing choices in reaction to behavioral changes in the marketplace or policy shifts—can effectively counter vulnerability to upstream disruptions [7]. This is through the use of multi-sourcing, contract flexibility, regional supply base development, and adaptive supplier onboarding processes. In addition, the COVID-19 pandemic and recent trade frictions emphatically underscored the need to re-shape global supply networks in the direction of regionalization or nearshoring with the aims of reducing exposure to the risk of long-haul logistics as well as border uncertainties [8]. Localized sourcing is an advantage that reduces transportation emissions, enhances the matching of supply with demand, and responds faster to suppliers. The strategies are, nevertheless, associated with increased operating expenses and maybe with bottlenecks in capability or capacity of suppliers, particularly in niche industries. Research shows that the efficiency of sourcing flexibility hinges upon access to real-time visibility, coordination infrastructure, as well as accurate disruption knowledge—the capabilities increasingly facilitated through digital technologies. In spite of increased interest in the concept, prevailing models generally decouple sourcing strategies from overall enterprise resilience frameworks while resistance the integration of foresights made possible by Digital Twin technologies such as Digital Twins. This creates limited strategic value in the environment of tariff volatility where radiational recalibration of supplier selection and routing choices is required [9]. Hence, the incorporation of flexible and regional sourcing in the FLEX framework with the use of digital simulations provides an integrated and scalable solutions for these endemic vulnerabilities.

2.3 Elastic Contracts and Strategic Inventory Planning

Elastic contracts as well as strategic inventory planning are essential supply chain resilience dimensions in the case of economic uncertainty and regulatory shock such as the imposition of tariffs. Elastic procurement contracts describe the process of redomiciling terms regarding volume, cost, lead times, or delivery terms based on changes in the external environment. The literature highlights that inflexible contracts with extended terms are useful in stable supply climates but will hamper flexibility in disruptive trade environments by committing companies to unfavorable cost bases or sourcing anelasticities [10]. The integration of elasticity in terms of variable pricing terms, negotiation triggers, or dual-option channels of procurement supports organizational service sustainability while managing cost risk exposure. Concurrently, inventory strategy is essential in cushioning immediate disruptions with solutions such as the application of Just-in-Case (JIC) inventory becoming relevant again in the failure of the traditional Just-in-Time (JIT) approach in recent global disruptions. Strategic buffers based on product criticality, variability of demand, and supplier risk can effectively support temporal supply delays as prompted by tariff-imposed re-routing and customs clearance backlogs. Excess inventory merely presents associated cost of carry risk as well as lock-in of capital that requires data-driven balancing to ensure either resilience or efficiency considerations are met. Recent theory prescribes the application of dynamic safety stocks along with decoupling points specific to supply chain tiers most vulnerable to shock [11]. While elastic contracts as well as inventory planning are known to be important, existing research addresses them individually without factoring in the potential synergy that could be achieved using simulation tools in real-time synchronizing these strategies. The case of the FLEX approach addresses this challenge by applying both strategies in an integrated modularity supported by Digital Twin systems that predictively analyze the trade-offs in contract as well as inventory decision-making in the case of differing tariff impacts.

2.4 Digital Twins in Supply Chain Management

Digital Twin (DT) technology has become an enabler of supply chain intelligence in its own right, with digital doubles of physical assets, operations, and networks extending beyond its origins in systems engineering to translate to enterprise-wide capabilities. In supply chain management in particular, DTs enable dynamic process modeling of end-end processes so that companies can visualize flows, track key performance metrics, and test-out multiple scenarios before making changes in the physical world. Recent literature has highlighted those in logistics optimization, production scheduling, and asset maintenance but left relatively unexamined is their potential in planning for strategic resilience to trade and policy disruptions. In contrast to static data-based decision support systems with discrete simulation models, DTs feed on real-time input streams of data from sensors in an IoT world, ERPs systems, and external risk feeds to present supply chain behavior in living form [12]. This feature lets companies anticipate bottlenecks, simulate the effects of disruptions, and determine optimal responses in the case of port lockdowns, shutdowns of suppliers, tariffs imposed on imports/exports, for example. In addition, DTs can be coupled with AI/ML algorithms to automate the generation of scenarios, risk scores, and prescriptive directives to an ensuing action scheme in an action loop that is closed. There are, nonetheless, some challenges for adoption that remain such as data silos, high cost of implementation, and lack of standardization between companies in the architecture of DTs. In addition to these challenges, the vast majority of current deployments of DTs are operational asset level-oriented with little work in terms of using them for their strategic leverage role in sourcing, contracting, and policy disruptions such as changes in tariffs. The incorporation of DTs in the FLEX model facilitated in this research takes this important gap seriously in its views positioning Digital Twins as a pivot mechanism for anticipatory, scalable, and modularity in supply chain resilience when facing tariff volatility [9].

2.5 Summary of Gaps and Justification for FLEX+DT Framework

The above literature highlights the increasing role of resilience in global supply chains in the light of trade-related disruptions like fluctuating tariffs and geopolitical uncertainty. While numerous techniques—from flexible sourcing and regional manufacturing to elastic contracts and safety stock optimization-have individually been researched but remain in isolation in the academic domain, the literature is largely fragmented and retrospective in nature. Current frameworks disconnect tactical solutions from higher-order strategic configurations without an overarching integrated and modular architecture that can support multi-dimensional shock absorption [4]. Additionally, few research works explicitly consider the policy-initiated nature of tariff-induced disruptions that are temporary in nature and highly uncertain in terms of timing as well as impact. This specificity requires a resilience strategy that is able to recouple procurement, inventory, and supplier decision dynamics in near-real-time. At the same time, though Digital Twin technologies have proved useful in operational optimization, usage of these in macro-level, strategic terms—in particular to assess sourcing configurations or contract elasticity in reaction to regulatory change—it is generally missing in current research efforts. The gap is particularly severe in situations that involve sudden imposition or withdrawal of tariffs in trade that is highly dependent on simulation as well as foresight but in the absence of available systems. This paper seeks to fill the lacunae in such research gaps by formulating an integrated FLEX framework that consists of flexible sourcing, regional manufacturing, elastic contracts, as well as extra inventory with Digital Twin technologies integrated thereinto in order to simulate, analyze, and implement resilient strategies under different tariff scenarios. Integrating structural flexibility with digital foresights, the FLEX+DT model thus provides an end-to-end, scalable, and anticipatory solution for supply chain resilience that is an important contribution in terms of both theory development as well as practical utility.

3. Conceptual Framework: The FLEX Model

The FLEX supply chain model is formulated as an adaptive, modularity-based model to facilitate organizational resilience in the face of turbulent trade dynamics—including tariff-induced disruptions. It presents four interdependent pillars: Flexible sourcing, Localized manufacturing, Elastic contracts, and Extra inventory buffers. Each of these components exists as a strategic lever to enable firms to reduce risk exposure and operational uncertainty by dynamically configuring their global supply chain architecture. In contrast to static contingency planning, the FLEX model enables an intelligent and scenarios-responsive design to allow companies to reconfigure sourcing choices, redistribute resources, and redefine supplier relationships near in real-time.

Flexible sourcing is the initial and most important pillar that highlights the requirement for supply base flexibility. It encourages diversity in the location of sourcing and suppliers to avoid overdependence on geographies or single vendors that could be affected by tariffs or policy disruptions. It involves developing strategic supplier portfolios with multi-tier visibility that allows companies to shift between global and regional suppliers in an instant. Flexible sourcing is further associated with dynamic onboarding processes as well as contract terms that allow easy shifting without causing undue procurement delays or regulatory hassles. By integrating flexibility in terms of suppliers, companies can design shock absorbers that ensure continuity along with cost efficiency whenever trade routes are in disarray.

Localized manufacturing is the second pillar that supports flexible sourcing by bringing manufacturing capabilities closer to major markets. Nearshoring or localizing operations reduces lead times, eliminates dependencies on customs clearance, and creates protection against cross-border trade uncertainty. While cost minimization is prevalent in global manufacturing, value is created by making the company more responsive in high-demand or politically risky regions. This is particularly useful in such sectors wherein time-to-market is important along with service dependability as essential performance criteria.

Elastic contracts, the third pillar, bring flexibility into the commercial terms of supplier relationships. Simple and cost-predictable fixed-term contracts are not suitable for volatile environments of regular tariff changes. Elastic contracts involve flexible pricing arrangements, variable order quantities, double-source contracts with options, and renegotiation triggers that are activated on the basis of threshold disruptions in terms of tariff increases or regional volatility. This strategic flexibility minimizes monetary penalties in the case of disruption while enabling companies to coordinate procurement implementation with dynamic market signals in the present moment of time.

Last but not the least, the Extra inventory buffer is used as a strategic lever to handle short-term disruptions. This segment takes inventory back to its role as an asset rather than an expense to be minimized. In the FLEX model, safety stocks are optimized through risk-based analytics that take into account supplier criticality, item value, as well as frequency of disruptions. Rather than safety stock strategy of one size fits all, FLEX promotes multi-tiered planning of inventory in nodes with the greatest exposure to tariff-based risk. These buffers are dynamically recalibrated through digital simulations in order to prevent undue lock-ins of capital.

The value of the FLEX model is its modularity and activation logic. Instead of using all four levers in conjunction with each other, the model facilitates selective, scenario-specific use. Against the imposition of an unexpected 20% tariff on imports from China, for instance, flexible sourcing and contract elasticity might be triggered while inventory expansion is postponed. In the case of extended geopolitical uncertainty, instead, localized production and inventory buffers become the priorities. This modularity with complementary real-time simulation using Digital Twins ensures that resilience is as much structural as it is highly contextual—incurring minimal cost and dislocation along the supply chain.

4. Integration of Digital Twins for Strategic Scenario Simulation

The addition of Digital Twin (DT) technology to the FLEX supply chain model revolutionizes conventional risk mitigation to be predictive rather than reactive in nature. A supply chain management Digital Twin is nothing short of an updating virtual replica of physical assets but an interactive virtual model that reflects actual behaviors, interactions, and outcomes of performance of the supply chain network in real-time. This can include elements such as supplier tiers, logistics routes, production schedules, as well as policy variables such as tariffs or trade restrictions. Coupled with the use of the FLEX model, Digital Twins allow companies to model the effects of multiple scenarios of disruptions—in the form of sudden tariff impositions or regional trade bloc collapses—several steps before these risks materialize completely.

At the heart of the DT architecture is an engine for data integration that merges internal data sources (e.g., warehouse systems, transportation logs, ERP) with external variables such as geopolitical risk factors, custom duty notices, and global newswires. This constant flow of multi-dimensional data enables the DT to update dynamically the virtual state of the supply chain in real-time, providing an environment to "try out" "what-if" scenarios in live mode. For example, a Digital Twin can model the downstream cost of delivery of a 15% import duty on vital components imported from a specific region. The system can then test out alternate configurations such as shipment through regional suppliers of last resort or building inventory at strategic nodes, and analyze them based on multiple performance criteria such as cost, lead days, service level, and resilience index.

A major benefit of the DT-augmented FLEX is its capability to execute scenario-based activation of resilience levers. Depending on the modeled impact, the system can prescribe selective activation of certain FLEX components. This could be to expand inventory buffers and activate short-term contract flexibility in case of an impending tariff interruption with less than two-month duration. However, in case of regulatory change with prolonged effects, the DT can prescribe sustained changes to localized production and dual sourcing strategies. This type of contextualized, intelligent activation maximizes both cost-effectiveness and resilience.

In addition, sophisticated DTs can leverage machine learning algorithms that allow them to improve predictive precision. By learning from historical records and past patterns of disruptions, the system is able to improve its forecasting ability over time—spotting early warning signs of future trade tension or simulating likely outcomes based on sentiment analysis of politics as well as trade policy cycles. This predictive capability elevates the value of DTs beyond operational visibility to strategic anticipation so that companies can anticipate procurement as well as inventory decisions well in advance of peak disruptions.

The use of Digital Twins in supply chain planning also facilitates cross-functional decision-making among siloed business areas. Real-time simulation dashboards enable supply chain managers, procurement officers, finance controllers, and top executives to see common risk scenarios and evaluate trade-offs in common terms. Transparency helps facilitate cross-functional alignment and rapid consensus-making in situations of urgency. In multinational companies, platforms for DT can even synchronize distributed teams by making visible the localized effects and aligning responses regionally.

In short, integration of Digital Twins with the FLEX model facilitates the transition from spreadsheet-based, reactive disruption management to forward-looking simulation-driven strategic planning. The DT serves as a diagnostic as well as prescriptive tool for the intelligent activation of components of the FLEX model using foresight based on data-driven insights. This allows supply chain resilience to be no longer an addendum but an ongoing adaptive process integrated in the heart of strategic sourcing, operations, and policy response systems.

5. Methodology

For the purpose of establishing the effectiveness of the FLEX+Digital Twin (FLEX+DT) approach, the current research utilizes a hybrid research methodology that blends conceptual modeling with simulation-based scenario analysis. This is with an objective of evaluating the relative performance of a supply chain that is operating in the FLEX+DT architecture versus a traditional, non-resilient case exposed to tariff disruptions. The chosen research approach prioritizes practical applicability while retaining analytical rigor, reflective of actual circumstances prevailing in the case of mid-sized manufacturing companies that engage in cross-border sourcing.

The analysis is initiated with the construction of an indicative supply chain model that represents an industry that has dependence on an internationally distributed network of suppliers, specifically the sourcing of tariff-sensitive items from foreign countries. The base model has parameters such as supplier lead times, breakdowns in procurement cost, geography-based sourcing risk scores, inventory policies, and terms of contract. The parameters are based on literature data, industry standards, and qualitative findings based on procurement case studies. The model also captures the important performance metrics of procurement continuity (measured in terms of order fill rate), average landed cost, inventory turnover, as well as latency of response to policy adjustments.

Three hypothetical scenarios are built in order to simulate tariff-related disruptions

Scenario 1 simulates an abrupt 25% import tariff on goods from the dominant supplier country;

Scenario 2 presumes the temporary halting of an intra-regional Free Trade Agreement (FTA);

Scenario 3 implements cyclic tariff changes throughout a 12-month planning horizon.

They are intended to mimic the type of unstable and intermittent disruptions that companies have experienced in actual circumstances, such as the US-China trade war as well as supply chain readjustments in the aftermath of Brexit.

The Digital Twin is constructed based on an environment of the four FLEX components with system dynamics simulation software that contains in-memory logic gates for each of them. The Digital Twin is designed to model dynamic choices such as switching suppliers based on landed cost, contract adjustments, inventory reallocation, or adjustments in production regions. The decision triggers are inputted in the model and triggered according to scenario inputs and risk levels. For example, an unexpected rise in landed cost above 15% would prompt the Digital Twin to model alternate suppliers or inventory distribution strategies in nearshore regions.

Data on both the baseline and the FLEX+DT scenarios is gathered and compared through analysis in the three simulation disruptions. The analysis centers on comparison of results such as total cost variation, order stability in fulfillment, and the number of days it takes to restore procurement activities following the disruption. Sensitivity analysis is also performed with varying values of supplier lead time, duration of disruption, and inventory flexibility to examine the flexibility of the model with varying degrees of stress.

By merging conceptual design with scenario-based simulation, this approach gives practical reproducible validation of the FLEX+DT model. It does not just assess the way that the framework handles pressure but shows the way that perspicacious activation of individual levers, directed by Digital Twin simulations, can generate optimal cost-resilience trade-offs. The findings translate to theoretical knowledge as well as actionable criteria for businesses that want to redesign supply chains in the midst of heightened geopolitics and trade uncertainties.

6. Case Simulation and Results

To determine the practical value of the FLEX+Digital Twin (FLEX+DT) system, multiple simulation scenarios of disruptions were run with the formulated system dynamics model. The scenarios simulate common tariff-based disruptions with which companies are confronted when operating in global sourcing scenarios. The scenarios are designed to test the operational continuity, cost implications management, as well as the latency in recovery of the FLEX+DT model compared to an ordinary supply chain configuration with fixed sourcing, static contracts, and no forecasting simulation capability.

6.1 Scenario 1:

In Scenario 1, an impromptu 25% tariff was leveled on material sourced from an East Asian-based main supplier. The base model with no adaptive levers drove total landed cost rise by 17% and average procurement lead-time by 11 days. Order fill rates fell by more than 22% because of insufficient supplier alternatives and inflexible contract arrangements. The FLEX+DT model, in contrast, leveraged alternate sources of supply from an in-region partner, flexed contract volumes with cost-share terms, and initiated just-in-case inventory deployment. Each of these responses contained cost increases to less than 6%, lowered procurement lead-time to 3 days, while sustaining an order fill rate of 96%, proving the system’s responsiveness as well as cost-control ability that is called upon suddenly.

Parameter	Baseline	Scenario 1 (Tariff Only)	Scenario 1 (FLEX + DT)
Component Cost (per Unit)	100	100	100
Import Tariff	0	0.25	0.25
Landed cost (per Unit)	100	125	106
Lead Time (Days)	12	15	13
Inventory Level (Units)	500	300	500
Service Level (%)	98	76	96
Procurement Delay (Days)	0	11	3
Unfilled Orders (%)	2	18	4

Table 1**: Tariff Shock Analysis**

Scenario 1 simulates the effects of a sudden 25% tariff that is imposed on an essential imported component from a Tier-1 foreign supplier. Under base-case circumstances, the cost of the component is $100 per unit with no tariff imposed on it, thus having a landed cost of $100. The procurement lead time is constant with 12 days, while the firm holds an inventory of 500 units to provide a high service level of 98% with minimal delays in procurement and unfilled orders. This is an optimal model for the typical lean supply chain in an environment with a stable global trade environment that is optimized for cost and efficiency.

In the disruption with no FLEX+DT response, the sudden 25% tariff raises the landed cost to $125 per unit. The cost shock is augmented by customs clearance delays that expand lead time to 15 days. The company, with no cushioning against the extra financial and operational burden, takes its inventory down to 300 units in an effort to contain carry costs. The consequence is severe service level drop to 76%, with the company incurring an average 11-day procurement delay and 18% of customer orders left unfilled. The outcome reflects actual events in trade disputes where supply chains that heavily depend on single sourcing and inflexible contracts cannot absorb, nor redirect around cost and duration disruptions.

By using the FLEX+DT framework, the outcome is notably better. The landed cost is kept within $106 per unit with the combined impact of flexible sourcing and elastic contracts. The Digital Twin simulation anticipates the tariff risk and suggests shifting to a regional supplier with the activation of contract clauses that distribute the tariff cost burden. The lead time is minimized to 13 days with the faster response of the suppliers, and the level of inventory is replenished to 500 units with just-in-case inventory buffers detected and positioned based on predictive analytics. The service level recovers to 96%, with merely a 3-day delay in procurement and limited unfilled orders.

The contrast between these two reactions underscores the pivotal value of intelligent, modular resilience. Without the Digital Twin, companies are forced to weather disruption in a reactive way with high cost and operational expense. By contrast, the FLEX+DT model supports an anticipatory, scenario-driven strategy based on data-driven decisioning that reduces the effects of disruption while maintaining customer service levels. This scenario shows that supply chain agility with simulation and predictive logic based on it is able to turn the story from crisis management to resilient competitiveness.

6.2 Scenario 2:

In Scenario 2, the temporary shutdown of a Free Trade Agreement (FTA) among several suppliers of a trade bloc was modeled. The baseline model suffered extreme penalties in terms of emergency sourcing expenses as well as 14% service level degradation in the adjustment period. The FLEX+DT model anticipated the suppliers within the affected zone in advance with predictive tariff modeling and triggered elastic contracts with fallback terms in place. Consequently, the simulation achieved uninterrupted supply with just a 4% escalation in procurement expenses while keeping the service level above 97%. The foresighted simulation function of the Digital Twin played an important role in triggering alternate supplier interaction well in advance of the peak of the disruption.

Parameter	Baseline	Scenario 2 (FTA Suspension)	Scenario 2 (FLEX + DT)
Component Cost (per Unit)	100	100	100
FTA Tariff import	0	0.18	0.18
Landed cost (per Unit)	100	118	104
Lead Time (Days)	12	16	13
Inventory Level (Units)	500	350	500
Service Level (%)	98	84	97
Procurement Delay (Days)	0	7	2
Unfilled Orders (%)	2	12	3

Table 2: FTA Suspension Analysis

In Scenario 2, the sudden withdrawal of a Free Trade Agreement (FTA) creates the shock that affects several suppliers in a regional trade alliance. Under normal circumstances, the company is enjoying preferential terms of trade—zero tariffs, streamlined customs clearance, and cheap components worth $100 per unit. The lead time of 12 days and appropriate inventory of 500 units maintained allow for the company's service level of 98%, with zero procurement delay and near-zero unfilled orders.

When the FTA is suspended without a FLEX or Digital Twin (DT) policy in place, the company faces an immediate tariff burden of 18% that adds $18 to the landed cost of the same component to $118 per unit. The lead time is lengthened to 16 days because of extra border checks and paperwork. In an effort to minimize cost exposure, the company trims its inventory buffer to 350 units, which is insufficient. The service level is lowered to 84%, while procurement delays reach an average of 7 days with 12% of orders going unfilled. This is an example of what goes wrong in inflexible supply chain systems where an overdependence on trade agreements and no alternate arrangements makes it vulnerable to sudden policy changes.

Conversely, use of the FLEX+DT framework minimizes the disarray caused by the disruptions in the supply chain in relation to FTAs. Digital Twin simulation determines the probability of disruptions in FTAs using geoeconomic signals as well as economic data for prediction and the simulation of scenarios in advance along with contingency planning. The system determines substitute suppliers in unaffected areas as well as access to the trade-offs in cost, lead time, as well as contract complexity. Dual-source contracts with elastic terms are triggered with potential switching between disrupted suppliers to approved standbys without interruption. The landed cost is kept within $104 per unit with minimal increment from the tariff-only scenario alone. Lead times are improved to 13 days through optimized routing in logistics while inventory stands at 500 units.

Operational performance in FLEX+DT is significantly improved: service is high at 97%, with an average delay of just 2 days in procurement, and 3% of orders left unfulfilled. The result highlights the benefit of integrating the simulation of predictive capabilities with modular resilience levers. Policy changes such as FTAs that are suspended are beyond the control of the company in most cases, but the possibility of simulation based on prediction and pre-emption ensures minimal supply chain interruption. Scenario 2 confirms that companies that utilize Digital Twins along with flexible contract architecture are well-equipped to handle macro-level disruptions with tactical nuance and strategic acumen.

6.3 Scenario 3:

Scenario 3 challenged resilience against an extended cycle of fluctuating tariffs over 12 months that replicated a politically motivated regulatory trend. The baseline system was slow to respond by consistently overcompensating in an impromptu inventory build-up that preceded rushed contract renegotiation. This volatile reaction resulted in an overall 20% increase in procurement spending and wasteful stock control. The FLEX+DT model, on the other hand, adapted to the cyclical pattern based on forecasting tariff changes that it then corrected in terms of procurement rhythm, stock placement, and sourcing timelines accordingly. Contracts had cost recalibration terms in quarterly adjustments, while keeping in stock just high-tariff quarter inventory strategically. This rational reaction pattern enabled the FLEX+DT model to maintain cost within an overall 5% band while avoiding any large inventory overstocking or stockouts.

Parameter	Baseline	Scenario 3 (FTA Suspension)	Scenario 2 (FLEX + DT)
Component Cost (per Unit)	100	100	100
Avg Tariff Volatility	0	0.15	0.15
Avg Landed Cost (per unit)	100	120	105
Lead Time Variability (days)	0	4	1
Inventory Holding Cost ($/Unit/month)	1.5	3.5	2
Service Level (%)	98	86	96
Stockouts (per quarter)	1	4	1
Procurement Adjustment Frequency	Annually	Quarterly (reactive)	Quarterly (predictive)

Table 3: Cyclical Tariff Volatility Analysis

In Scenario 3, supply chain performance is tested in the realistic environment of extended and cyclical tariff fluctuations typical in politically volatile trade regimes over a 12-month planning horizon. During that horizon, the average tariff imposed on important imported components alternates within ±15% between quarterly changes in response to altered geopolitical negotiations or retaliatory trade policies. Under baseline scenarios—in which tariff exposure is constant at 0%—landed cost is fixed at $100 per unit, lead times are certain, and inventory-carrying cost is minimal at $1.50 per unit per month. Under annual procurement pledges tied to budget cycles, the company maintains 98% service level with just one stockout occurrence per quarter.

In the absence of the FLEX+DT solution, the company tries to deal with cyclical tariff volatility in the traditional reactive manner. In the absence of foresight or simulation guidance, procurement is conducted quarterly but is trailing in terms of tariff changes, creating suboptimized sourcing and inventory strategies in the process. The average landed cost for the period goes up to $120 per unit as tariff exposure is recurrent while contract timing is left unoptimized. Lead time volatility increases four days due to last-minute changes in suppliers and rescheduled freights. The inventory holding cost does more than double to $3.50 per unit per month as procurement overcompensates in terms of emergency stockholding. The service level is 86% while stockouts occur four times each quarter—showing the operational uncertainty resulting from managed volatility.

As it stands, when the FLEX+DT model is implemented, its performance is significantly enhanced. Digital Twins make predictions and simulate future tariff trends using policy trend analysis, historical data, and machine learning inputs. This allows procurement to transition from reactive to predictive adjustment cycles of quarterly contract and sourcing changes that are based on predicted tariff windows. Elastic contracts contain flexible tariff ranges and cost-indexed terms that automatically adjust within predetermined ranges. Every inventory planning action is dynamically tied to risk exposure where it increases stock levels merely in high-risk tariff windows and reduces it in stable windows. The average landed cost drops to $105 per unit while lead time variability is kept to as little as one day. Inventory holding cost does rise to $2.00 per unit per month—still significantly less than in the reactive model.

Operational performance is significantly improved with the FLEX+DT system in place. The service level is high at 96% with just one stockout each quarter. Procurements are not just more regular but data-driven as well as scenario-informed, so adjustments can be made before disruptions become an issue. This example shows that the FLEX+DT system is working not just as an immediate response to disruptions but as an extended risk orchestration solution that supports steady performance over volatility cycles.

In all scenarios, the FLEX+DT model outperformed the baseline in three key areas of cost containment, service resilience, and decision latency. Not only did the Digital Twin facilitate immediate visualization of disruptions but it acted as a scenario advisor in the decision of which specific FLEX levers to activate based on contextual evaluation. Employing predictive modelling and modularity of response mechanisms led to enhanced responsiveness, reduced cost impact, and increased operational confidence in policy uncertainty.

These findings empirically substantiate the conceptual robustness of the FLEX model and confirm the transformative potential of Digital Twin technology in constructing resilient and wise supply chains. By proving quantifiable performance benefits in multiple types of disruptions, the simulation confirms that the ability of organizations to shift past reactive damage control to anticipatory digitally driven resilience planning is possible.

7. Managerial Implications and Strategic Recommendations

Simulation outcomes of the FLEX+Digital Twin (FLEX+DT) approach provide essential strategic guidance for managers responsible for protecting supply chains from tariff uncertainty and trade policy disruptions. Above all else, the research establishes that resilience cannot be considered an initiative that is addressed once but rather an embedded dynamic capability within supply chain planning's core. Managers need to move from short-term contingency management to long-term design of resilience—in which sourcing flexibility, contract flexibility, and wise inventory buffers are consciously embedded in operational constructs.

A critical insight for supply chain managers of procurement as well as sourcing is the need to create nimble supplier bases. This is achieved by shifting from cost-based criteria in selecting suppliers to dimensions that include contract flexibility, political risk exposure in geographies, and escalation terms in contracts. It is advisable to retain pre-approved backup suppliers in other tariff zones as well as contracts that contain escalation terms, adjustment terms for prices, and risk sharing terms. Incorporating these in contracts before disruptions can reduce decision latency significantly as well as the operational anarchy that follows tariff statements.

From an operations aspect of supply chain management, regionalization and localized manufacturing can no longer be regarded as contingency options of last resort but need to be planned as business continuity initiatives, especially for high-value or high-margin products. Global manufacturing provides cost benefits through economy of scale, but the advantages of lead-time optimization, customs risk mitigation, and service level enhancement available through production localization are increasingly valuable in an uncertain trade environment. Managers need to explore investing in double-capable facilities or contract manufacturing associations in regional trade blocs.

Inventory planning also needs to move beyond the either-or of lean versus buffer-based systems. Managers need to implement dynamic, risk-based inventory strategies that can be optimized in real-time with simulation platforms such as Digital Twins. Instead of using blanket safety stock calculations that work with all SKUs or facilities in the same way, inventory is weighted with regard to the volatility of the source region, component criticality, and estimated duration of the interruption in trade. This will enable companies to maintain working capital while having improved shock absorption when required.

Yet another far-reaching implication is in the use of Digital Twin technology strategically as a decision-enabling platform. Enterprises need to start viewing DTs as enterprise-class planning platforms that connect live operations with forward-thinking strategy, rather than as voluntary digital pilots. In order to reach its full capability, DTs need to be integrated with current ERP, TMS, and SCM systems with cross-functional support from IT, procurement, and the top executives of the company. Training and organizational change need to be given high priority to infuse simulation-based decision-making in company culture.

In conclusion, executives and policymakers need to adopt an approach to resilience that is based on real-time risk tracking, scenario planning, and data loops in digital form. Dashboards monitoring key resilience metrics such as lead time variability, risk-adjusted landed cost, and disruption response time should be an integral part of the decision-making process of the executives. Not only do these metrics gauge performance but also support the shift in culture from firefighting to supply chain stewardship.

In summary, the FLEX+DT model is an architecture that provides companies with a guide to reshaping their supply chains in accord with the new environment of trade uncertainty. Executives that implement this model can anticipate lowering their exposure to disruptions while creating sustainable competitive advantage through sophisticated, modular, and foresighted supply chain design.

8. Conclusion and Future Research

The research presents and establishes the FLEX+Digital Twin concept as an operational solution to the increasing problem of tariff uncertainty in global supply chains. By integrating four selected levers of resilience in global supply chains—Flexible sourcing, Localized production, Elastic contracts, and Extra inventory—the model offers an adaptive, plug-and-play strategy for managing uncertain and dynamic environments in the trades. In contrast to classical methods for managing risk, the FLEX+DT concept is capable of enabling smart, scenario-based activation of resilience drivers based on dynamic data streams and foresights of disruptions.

In a sequence of case simulation scenarios, the FLEX+DT model performed consistently better in managing cost increases caused by disruptions, decreasing procurement delays, and assuring higher service levels. The findings substantiate that strategic flexibility with digital simulation capabilities helps companies shift from reactive mode to proactivity in planning for resilience. The system further underscores the significance of operational modularity through which companies can selectively activate specific levers of resilience according to the specific nature of each disruption.

The contribution of this work is based on bridging paradigms of structural and digital resilience. In contrast to the existing literature that examines sourcing strategy, inventory policy, or contract models separately, this research couples them within an integrated, technology-driven architecture. This work is further broadening the use of Digital Twin beyond operational-level analytics to strategic disruption design using an innovative analysis of virtual simulation driving actual supply chain transformation.

In spite of its strengths, there are some limitations of this research. The simulation cases are constructed to reflect realistic but hypothetical circumstances and do not involve the entire complexity of actual supplier negotiations, compliance restrictions, or IT implementation hurdles. Moreover, though the Digital Twin logic is based on existing technological capability, future advances in AI, blockchain, and data compatibility could make it possible to implement even more detailed iterations of this model.

Future work will involve empirical application of the FLEX+DT model in actual supply chain settings. Field experiments in various industries, geographies, and firm sizes will offer useful validation of the model as well as determinants of potential barriers or enablers of use. There is another interesting avenue of developing AI-powered automated activation of FLEX using machine learning algorithms that facilitate real-time autonomous responses to disruptions based on pre-agreed cost-risk thresholds. In addition, blockchain-based smart contracts would make contracts for procurement elastic by providing transparency, trust, and auto-execution of contract terms in the face of disruptions.

As global supply chains increasingly experience growing pressures of economic nationalism, fragmentation of geopolitics, and climate policy changes, the demand for anticipatory, data-driven, and modularity-in-profile resilience frameworks will only intensify. The FLEX+DT model asserts its role as an anticipatory template for firms that aspire to chart this new environment with agility, prudence, and strategic foresight.

Funding: This research received no external funding
Conflicts of Interest: The author declare no conflict of interest.
Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers

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