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A fuzzy prescriptive analytics framework for supply chain resilience under geopolitical disruptions in the Strait of Hormuz

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ABSTRACT

Geopolitical disruptions have become a source of systemic risk for global supply chains across interconnected transportation, energy, fertilizer, and food systems. Conventional descriptive and predictive analytics are often inadequate under deep uncertainty because geopolitical crises are characterized by ambiguity, limited historical observations, and cascading cross-sector effects. This study proposes an integrated fuzzy prescriptive analytics framework for resilience-oriented supply chain decision-making under geopolitical uncertainty. The framework combines historical evidence, expert elicitation, a Mamdani fuzzy inference system, a weighted aggregation model for food-system stress assessment, and mixed-integer linear programming (MILP). The fuzzy inference system evaluates five disruption drivers—Geopolitical Tension, Maritime Accessibility, Energy Supply Shock, Logistics Delay, and Fertilizer Input Risk—to estimate the Supply Chain Disruption Risk Index (SCDRI). The Food System Stress Index (FSSI) is then estimated through an expert-informed weighted aggregation of the SCDRI, Energy Supply Shock, and Fertilizer Input Risk. These disruption indicators are translated into deterministic optimization parameters that adjust transportation costs and shortage penalties. The Strait of Hormuz serves as a numerical case study. A MATLAB-based MILP model determines supplier activation, shipment allocation, inventory deployment, emergency procurement, and demand allocation. The results demonstrate that increasing disruption severity raises operating costs and food-system stress while promoting supplier diversification, inventory deployment, transportation reconfiguration, and emergency procurement to maintain supply continuity. The proposed framework provides a transparent, explainable, and reproducible prescriptive analytics methodology that transforms qualitative geopolitical intelligence into quantitative operational decisions, extending supply chain resilience research toward decision support under geopolitical uncertainty.

1. Introduction

Global supply chains have become increasingly vulnerable to geopolitical disruptions that extend beyond traditional operational and economic risks. During the past decade, major events such as the COVID−19 pandemic [1], the Russia–Ukraine war [2], maritime chokepoint disruptions [3], trade sanctions [4], and regional energy conflicts [5] have exposed the structural fragility of highly interconnected global supply networks [6]. These events have demonstrated that modern supply chains, although highly efficient under stable conditions, remain extremely sensitive to disruptions that propagate rapidly across regions, industries, and economic sectors [7].

The increasing interdependence of global production, transportation, and energy systems has amplified systemic vulnerability. Disruptions affecting maritime transportation, energy supply, or geopolitical relations may generate cascading effects throughout production networks, logistics systems, inventories, and final consumption [8]. These interdependencies are particularly evident within the energy–fertilizer–food nexus. Natural gas and petroleum products constitute essential inputs for fertilizer production, while fertilizer availability directly influences agricultural productivity, food supply, and food prices [9]. Consequently, disruptions occurring at critical maritime chokepoints may affect not only transportation and energy markets but also food-system resilience and broader economic stability [10].

Recent advances in supply chain analytics have substantially improved organizations' ability to monitor operations and forecast future events. Descriptive analytics provides insights into historical and real-time operational performance, whereas predictive analytics employs statistical and machine-learning techniques to estimate future events and disruption probabilities [11,12]. Nevertheless,

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decision-makers operating in geopolitical crises frequently face deep uncertainty, where probability distributions are unknown, information is incomplete, and disruption dynamics evolve rapidly [13]. Under such conditions, predictive insights alone are often insufficient for supporting timely and effective operational decisions. Increasing attention has therefore shifted toward prescriptive analytics, which combines predictive information with optimization, simulation, artificial intelligence, and expert knowledge to recommend appropriate actions under uncertain conditions [14].

In parallel, fuzzy logic has become an important methodological approach for supporting supply chain decision-making under uncertainty. Recent studies have successfully applied fuzzy methods to supplier selection, resilience assessment, multi-criteria decision-making, and disruption-risk evaluation [15]. However, most existing studies focus primarily on disruption identification, risk prioritization, or resilience assessment. Despite these advances, comparatively little research has developed integrated prescriptive analytics frameworks that combine explainable fuzzy disruption assessment, downstream impact evaluation, and optimization-based operational decision support across interconnected energy, logistics, fertilizer, and food systems under geopolitical uncertainty [16,17].

To address these research gaps, this study develops an integrated fuzzy prescriptive analytics methodology for resilience-oriented supply chain planning under geopolitical uncertainty. The methodology combines explainable fuzzy modelling, expert knowledge, downstream food-system stress assessment, and mixed-integer optimization within a unified analytical workflow. The proposed approach systematically transforms qualitative geopolitical assessments into quantitative operational decisions by linking disruption assessment with optimization-based decision support.

The Strait of Hormuz is employed as an illustrative numerical case study because it represents one of the world's most strategically significant maritime chokepoints for global energy transportation [18]. The case study demonstrates how geopolitical disruptions propagate across interconnected energy, logistics, fertilizer, and food systems. Beyond operational resilience, the case study also demonstrates how the proposed framework supports more sustainable and resilient supply chain planning by explicitly considering downstream food-system impacts alongside economic performance.

The principal contribution of this study lies not in developing new fuzzy inference techniques or optimization algorithms, but in establishing an integrated fuzzy prescriptive analytics methodology that systematically combines explainable fuzzy modelling, expert knowledge, and mathematical optimization. The proposed methodology integrates a Mamdani fuzzy inference system for disruption assessment with an expert-informed weighted aggregation model for food-system stress assessment, clearly distinguishing overall disruption severity from its downstream consequences. The resulting disruption indicators are translated into deterministic optimization parameters, providing a transparent mechanism for linking qualitative geopolitical assessments with resilience-oriented operational decision-making. By integrating disruption assessment, downstream food-system stress evaluation, and optimization-based operational planning within a unified analytical workflow, the study extends existing research beyond disruption assessment toward actionable prescriptive decision support. Finally, the study provides a fully reproducible MATLAB implementation, including expert-informed membership functions, a transparent fuzzy rule base, complete numerical datasets, a fully specified optimization model, and comprehensive sensitivity analyses to facilitate independent validation, benchmarking, and future methodological extensions.

To guide the analysis, the study addresses the following research questions:

RQ1. . How can a fuzzy prescriptive analytics framework support resilient supply chain decision-making under geopolitical disruptions?

RQ2. . How do different geopolitical disruption scenarios influence supply chain disruption severity, downstream food-system stress, and optimization-based operational decisions?

RQ3. . How can disruption assessments generated through fuzzy inference and downstream food-system stress analysis be translated into optimization parameters that support resilience-oriented operational planning under deep geopolitical uncertainty?

The remainder of the paper is organized as follows. Section 2 reviews the literature on geopolitical supply chain disruptions, fuzzy decision-support methodologies, and prescriptive analytics. Section 3 presents the proposed fuzzy prescriptive analytics framework, including the Mamdani fuzzy inference system, the food-system stress assessment methodology, and the mixed-integer linear programming model. Section 4 develops the Strait of Hormuz numerical case study and presents the disruption assessment, food-system stress analysis, optimization results, sensitivity analysis, and synthesis of the findings. Section 5 discusses the findings in relation to the existing literature and presents their practical implications, theoretical contributions, study limitations, and directions for future research. Finally, Section 6 concludes the paper by summarizing the principal findings and contributions of the proposed fuzzy prescriptive analytics framework.

2. Literature review

2.1. Evolution of supply chain analytics

Supply chain analytics has evolved through four principal stages reflecting increasing analytical sophistication and decision-support capability: descriptive, diagnostic, predictive, and prescriptive analytics. Descriptive analytics focuses on understanding what has happened through the analysis of historical data. Diagnostic analytics seeks to explain why particular events or performance outcomes occurred. Predictive analytics uses statistical, econometric, and machine-learning techniques to estimate future events and disruption probabilities. Prescriptive analytics extends these capabilities by recommending actions that decision-makers should implement under alternative future scenarios [19,20].

The distinction between predictive and prescriptive analytics is particularly important. Predictive analytics primarily addresses the question of what is likely to happen, whereas prescriptive analytics focuses on determining what actions should be taken in response to anticipated conditions. Prescriptive approaches frequently combine forecasting, optimization, simulation, and decision-support mechanisms to evaluate alternative courses of action under uncertainty. Prescriptive analytics answers the questions “What should I do?” and “Why should I do it?” [20].

Prescriptive analytics represents the most advanced stage of the business analytics continuum because it not only evaluates past performance and predicts future events but also recommends appropriate courses of action to support decision-making. Its primary objective is to identify decisions that optimize organizational performance under anticipated future conditions by combining predictive insights with optimization techniques, artificial intelligence, and expert knowledge. Rather than simply forecasting potential outcomes, prescriptive analytics determines how organizations should respond to achieve specific operational or strategic objectives [20,21].

Depending on the application, prescriptive analytics can support decision-making at different levels. At the decision-support level, the system provides recommendations that assist managers in selecting among alternative actions. At the decision-automation level, the analytical framework is capable of executing predefined responses with limited or no human intervention. The quality of prescriptive recommendations depends on the framework’s ability to integrate heterogeneous sources of information, including both quantitative and qualitative data, accurately represent the decision environment, and evaluate the operational consequences of alternative decisions under uncertainty [20,22,23].

Despite significant progress in predictive analytics, the application of prescriptive analytics in supply chain management remains comparatively limited, particularly in environments characterized by deep uncertainty, geopolitical instability, and complex interdependencies, [15]. Existing studies frequently focus on disruption forecasting, risk identification, or resilience assessment, while fewer studies develop integrated decision-support frameworks capable of linking disruption assessment with operational decision-making [23].

The challenge becomes even more significant in geopolitical disruption environments, where uncertainty is difficult to represent through conventional probabilistic approaches. Geopolitical disruptions often involve non-linear escalation patterns, incomplete information, strategic behavior by state actors, and cascading effects across interconnected supply networks [24]. These characteristics have motivated increasing interest in analytical approaches capable of supporting decision-making under ambiguity and deep uncertainty. Predictive analytics is limited under uncertainty and that prescriptive approaches are intended to fill that gap [14,21,22].

2.2. Geopolitical risk and supply chain vulnerability

Recent research highlights the growing dependence of global supply chains on critical chokepoints, including major maritime corridors, ports, and logistics hubs that facilitate the movement of energy resources, raw materials, and manufactured goods [25].

For geopolitical crises, the supplied evidence supports the inference that decision-makers need decision-prescriptive, uncertainty-aware analytics, not prediction alone, because the environment is too dynamic and information is too incomplete for forecasts to fully determine action [21].

Disruptions affecting these strategic locations can generate consequences that extend far beyond the directly affected region, creating cascading effects across production, transportation, and distribution networks [26,27].

Among these chokepoints, maritime corridors are particularly important because they support a substantial share of global energy transportation. Disruptions affecting oil and natural-gas flows can rapidly influence transportation costs, industrial production, inflation, and broader supply-chain performance, [10,28]. Consequently, geopolitical instability increasingly represents a supply-chain risk that extends beyond traditional operational and market uncertainties.

The literature highlights the strong interdependencies between energy systems and food systems, emphasizing that energy is a foundational input throughout the entire food supply chain. Natural gas constitutes a critical feedstock for nitrogen-based fertilizer production, while energy is also essential for agricultural mechanization, irrigation, food processing, storage, transportation, and distribution [28–30].

Consequently, disruptions in energy supply may simultaneously reduce fertilizer availability, increase agricultural production costs, and compromise food availability and affordability. These interdependencies create complex vulnerability pathways through which geopolitical disruptions propagate across multiple sectors rather than affecting individual industries in isolation, [23,30].

Food supply chains are among the most energy-intensive industrial systems, accounting for a substantial share of total energy consumption and greenhouse gas emissions. Despite the growing adoption of renewable energy sources, fossil fuels continue to dominate energy use within food systems, making them particularly vulnerable to geopolitical energy disruptions, [31].

Supporting this view, Bortolini et al. [32] showed that agriculture and food processing account for 34% and 24% of total energy consumption within the European Union food supply chain, respectively, while fossil fuels still represent approximately 70% of the gross available energy. These findings underline the importance of analysing energy, fertilizer, logistics, and food systems as an integrated nexus when assessing geopolitical supply chain resilience.

Despite increasing recognition of these relationships, existing studies primarily focus on risk identification, vulnerability assessment, or resilience evaluation. Comparatively less attention has been devoted to analytical approaches capable of examining the combined effects of geopolitical disruptions across interconnected energy, fertilizer, logistics, and food systems within a unified decision-support context [33].

2.3. Fuzzy logic in supply chain decision-making

Fuzzy Inference Systems (FISs) constitute a well-established branch of Artificial Intelligence (AI), belonging to the family of symbolic or knowledge-based AI. Unlike many artificial intelligence techniques, fuzzy inference systems (FISs) express knowledge through linguistic IF–THEN rules formulated in natural language. This knowledge-based representation makes FISs inherently more transparent and interpretable than data-driven approaches such as artificial neural networks (ANNs), genetic algorithms (GAs), and machine learning (ML) models, which are often regarded as black-box techniques [15].

Fuzzy logic has been widely adopted in supply chain management as a tool for representing uncertainty, ambiguity, and incomplete information. Unlike conventional probabilistic approaches, fuzzy logic enables the use of linguistic variables and expert judgments when precise numerical information is unavailable or difficult to estimate. This characteristic makes fuzzy methods particularly suitable for complex decision environments involving qualitative assessments and uncertain conditions [34,35].

The application of fuzzy logic in supply chain research spans a wide range of domains, including supplier selection, risk assessment, inventory management, transportation planning, resilience evaluation, and demand forecasting. Fuzzy multi-criteria decision-making approaches such as fuzzy AHP [34], fuzzy TOPSIS, fuzzy ANP, and fuzzy DEMATEL [36], have been extensively employed to prioritize risks, evaluate suppliers, identify resilience capabilities, and analyze causal relationships among disruption factors. Recent studies have also applied fuzzy optimization and fuzzy stochastic programming techniques to support decision-making under uncertainty and disruption conditions [37].

Within the supply chain resilience literature, fuzzy approaches have proven particularly valuable because disruption risks are frequently characterized by ambiguity, limited historical data, and subjective expert assessments. Fuzzy methods allow decision-makers to represent uncertainty through linguistic concepts such as low, moderate, high, and critical risk levels, thereby improving the realism and interpretability of resilience assessments [38].

Despite the extensive application of fuzzy logic in risk evaluation and resilience assessment, its use in prescriptive supply chain analytics remains comparatively limited. Existing studies primarily focus on identifying, prioritizing, or evaluating risks, whereas fewer studies develop integrated frameworks that combine fuzzy risk assessment with optimization-based decision support capable of generating resilience-oriented operational decisions under geopolitical disruption conditions [12].

This limitation is particularly evident in the context of maritime geopolitical disruptions, where uncertainty is difficult to represent through conventional probabilistic approaches and where disruptions may propagate simultaneously across interconnected energy, fertilizer, logistics, and food systems [39].

2.4. Research gap

Despite significant advances in supply chain analytics and disruption management, several important gaps remain in the existing literature.

First, many studies addressing supply chain disruptions rely on deterministic or probabilistic approaches that assume the availability of reliable probability distributions and quantitative data. Such assumptions are often difficult to justify in geopolitical environments, where disruption dynamics are characterized by ambiguity, incomplete information, strategic behaviour, and rapidly evolving conditions. Consequently, representing uncertainty remains a significant challenge in geopolitical supply chain risk analysis [16].

Second, very few studies integrate disruption assessment, downstream food-system stress assessment, and optimization-based decision support within a unified prescriptive analytics framework [17].

Third, the literature has largely examined energy systems, logistics systems, fertilizer supply chains, and food systems as separate analytical domains. However, geopolitical disruptions generate cascading effects that propagate simultaneously across these interconnected sectors. Energy disruptions influence fertilizer production, transportation costs, and agricultural productivity, while food-system outcomes are affected by changes in energy availability and logistics performance. Despite these interdependencies, relatively few studies explicitly analyse the cascading relationships among energy, fertilizer, logistics, and food systems within a unified analytical framework [28].

Finally, although recent studies increasingly recognize the interdependence among energy systems, logistics networks, fertilizer supply, and food security, very few studies integrate disruption assessment, downstream food-system stress assessment, and optimization-based decision support within a unified prescriptive analytics framework. Existing research typically addresses disruption assessment, resilience evaluation, and optimization as separate analytical tasks rather than as components of an integrated decision-support methodology capable of systematically transforming disruption assessments into operational decisions under geopolitical uncertainty [28–30].

Addressing these research gaps requires an integrated fuzzy prescriptive analytics framework that systematically transforms qualitative geopolitical assessments into quantitative operational decisions through explainable fuzzy modelling, downstream food-system stress assessment, and optimization-based decision support.

2.5. Research contribution

This study addresses the identified research gaps by developing an integrated fuzzy prescriptive analytics framework for resilience-oriented supply chain decision-making under geopolitical disruption and deep uncertainty. Rather than proposing a new fuzzy inference methodology or optimization algorithm, the study contributes a transparent analytical architecture that systematically links disruption assessment, downstream food-system stress assessment, and optimization-based operational planning.

The proposed framework contributes to the literature in several important respects.

First, it integrates explainable fuzzy modelling, expert knowledge, and mixed-integer optimization within a single prescriptive analytics framework. While previous studies have typically examined disruption assessment, resilience evaluation, and optimization as separate analytical problems [28,29], the proposed methodology establishes a continuous analytical workflow that systematically transforms qualitative geopolitical assessments into quantitative operational decisions.

Second, the framework introduces a two-stage analytical workflow that clearly distinguishes overall disruption severity from downstream food-system stress. In the first stage, a Mamdani fuzzy inference system estimates the Supply Chain Disruption Risk Index (SCDRI). In the second stage, the Food System Stress Index (FSSI) is estimated through an expert-informed weighted aggregation of the SCDRI, Energy Supply Shock, and Fertilizer Input Risk. This separation enhances conceptual clarity by distinguishing disruption severity from its downstream consequences while avoiding circular relationships between disruption indicators and food-system stress.

Third, the proposed methodology establishes a transparent mechanism for translating disruption assessments into optimization parameters. Rather than embedding fuzzy numbers directly within the optimization model, the SCDRI is transformed into a disruption-risk multiplier that adjusts transportation costs, whereas the FSSI modifies the effective shortage penalties associated with unmet demand. This sequential parameterization preserves the interpretability of fuzzy reasoning while maintaining the computational efficiency, scalability, and reproducibility of deterministic mixed-integer optimization.

Fourth, the framework adopts a systems perspective by explicitly modelling the interdependencies among geopolitical disruption, maritime transportation, energy markets, fertilizer supply, and downstream food systems. This integrated representation demonstrates how disruptions propagate across interconnected critical infrastructures and influence resilience-oriented operational decisions. In addition, it provides a foundation for more sustainable and digitally enabled supply chain resilience, contributing to the objectives of the twin transition.

Fifth, the study provides a fully reproducible MATLAB implementation of the proposed methodology. The implementation includes expert-informed membership functions, a transparent fuzzy rule base, the weighted Food System Stress Index formulation, a fully specified mixed-integer optimization model, complete numerical datasets, and comprehensive sensitivity analyses. This high level of methodological transparency facilitates independent validation, benchmarking, and future methodological extensions.

Finally, the Strait of Hormuz case study demonstrates the practical applicability of the proposed framework within one of the world's most strategically significant maritime chokepoints. The case study illustrates how geopolitical disruption scenarios can be systematically translated into resilience-oriented operational strategies through the sequential integration of disruption assessment, downstream food-system stress assessment, and optimization-based decision support.

Overall, the principal contribution of this study lies in establishing an integrated fuzzy prescriptive analytics methodology that combines explainable fuzzy modelling, expert knowledge, downstream food-system stress assessment, and mathematical optimization within a unified analytical workflow. By systematically translating qualitative geopolitical assessments into quantitative operational decisions, the proposed methodology extends existing research beyond disruption assessment toward transparent, reproducible, and resilience-oriented decision support under conditions of deep geopolitical uncertainty.

3. Methodology: Fuzzy logic–based prescriptive framework

3.1. Rationale for the Fuzzy approach

Geopolitical disruptions represent a distinctive class of decision-making problems characterized by ambiguity, incomplete information, rapidly evolving conditions, and complex interactions among political, economic, and logistical systems. Unlike operational risks that can often be modelled using historical observations or probabilistic distributions, geopolitical events are inherently uncertain, infrequent, and context-dependent. Military conflicts, sanctions, maritime restrictions, and energy supply disruptions rarely occur under identical conditions, making conventional forecasting approaches difficult to apply reliably [40].

Three principal considerations motivate the adoption of the proposed fuzzy prescriptive analytics framework.

First, geopolitical disruptions are associated with limited historical observations, making statistical estimation and probabilistic forecasting inherently challenging. Although historical events provide valuable contextual information, they rarely constitute sufficiently large or homogeneous datasets for developing reliable predictive models.

Second, disruption assessment frequently relies on expert judgement rather than precise quantitative measurements. Decision-makers typically describe geopolitical conditions using linguistic concepts such as *low*, *moderate*, *high*, or *critical* disruption instead of exact numerical probabilities. Fuzzy logic provides an effective mechanism for representing such qualitative knowledge through linguistic variables and membership functions while preserving transparency and interpretability.

Third, geopolitical disruptions generate cascading effects across interconnected systems. A disruption affecting maritime transportation may subsequently influence energy availability, fertilizer production, agricultural supply chains, and food security. These interdependencies introduce complex nonlinear relationships that are difficult to represent using conventional deterministic optimization models alone [41].

Fuzzy logic provides an appropriate methodological foundation for representing these characteristics because it enables gradual transitions between disruption states rather than imposing rigid threshold values. By combining linguistic reasoning with expert knowledge, a Mamdani fuzzy inference system provides transparent and explainable assessments of geopolitical disruption under conditions of deep uncertainty [13].

However, disruption assessment alone is insufficient for effective operational decision-making. While fuzzy inference can quantify overall disruption severity, organizations must also determine how available resources should be allocated once disruption conditions have been assessed. Consequently, the proposed methodology integrates a Mamdani fuzzy inference system, an expert-informed weighted aggregation model for food-system stress assessment, and mixed-integer optimization within a unified fuzzy prescriptive analytics framework. The fuzzy inference system estimates the Supply Chain Disruption Risk Index (SCDRI), while the Food System Stress Index (FSSI) is subsequently computed as a weighted aggregation of the SCDRI, Energy Supply Shock, and Fertilizer Input Risk. These disruption indicators are then translated into deterministic optimization parameters that adjust transportation costs and effective shortage penalties within the optimization model.

Accordingly, the objective of the proposed framework is not to predict future geopolitical events or statistically validate disruption mechanisms. Instead, it provides an explainable and operationally actionable decision-support methodology that sequentially combines explainable disruption assessment, downstream food-system stress analysis, and optimization-based operational planning under conditions of deep geopolitical uncertainty. By explicitly separating uncertainty representation from operational optimization, the proposed framework preserves the transparency of fuzzy reasoning while maintaining the computational efficiency, reproducibility, and mathematical tractability of deterministic mixed-integer optimization.

3.2. Framework architecture

The proposed fuzzy prescriptive analytics framework is organized into four sequential analytical stages integrating expert knowledge, explainable fuzzy modelling, food-system stress assessment, and mixed-integer optimization within a unified decision-support architecture. Rather than treating disruption assessment and operational planning as separate analytical tasks, the framework establishes a sequential information flow through which qualitative geopolitical assessments are progressively transformed into quantitative operational decisions. Fig. 2 illustrates the overall architecture of the proposed framework.

3.2.1. Stage 1: Knowledge acquisition and scenario development

The first stage establishes the knowledge base of the framework. Historical evidence on geopolitical conflicts, maritime transportation, energy markets, freight-rate volatility, fertilizer supply, and incidents affecting the Strait of Hormuz is systematically reviewed to support the development of realistic disruption scenarios. These historical observations provide contextual information rather than statistical calibration.

The historical review is complemented by a structured expert elicitation process through which disruption drivers, linguistic variables, triangular membership functions, fuzzy rule bases, and the weighting coefficients of the Food System Stress Index (FSSI) are specified. The resulting expert-informed knowledge base provides the foundation for the fuzzy inference system and the downstream food-system stress assessment.

3.2.2. Stage 2: Supply chain disruption risk assessment

The second stage evaluates overall disruption severity using a Mamdani fuzzy inference system. Five disruption drivers:

- Geopolitical Tension (GT),
- Maritime Accessibility (MA),
- Energy Supply Shock (ESS),
- Logistics Delay (LD), and
- Fertilizer Input Risk (FIR),

are represented using triangular membership functions and evaluated through an expert-defined fuzzy rule base. The aggregated fuzzy output is defuzzified using the centroid method to generate the Supply Chain Disruption Risk Index (SCDRI). The SCDRI represents the overall severity of geopolitical disruption under each scenario and constitutes the principal disruption indicator within the proposed framework.

3.2.3. Stage 3: Food system stress assessment

The third stage evaluates the downstream consequences of geopolitical disruptions through an expert-informed weighted aggregation model for food-system stress assessment. Rather than employing a second fuzzy inference system, the Food System Stress Index (FSSI) is computed as a weighted aggregation of the Supply Chain Disruption Risk Index (SCDRI), Energy Supply Shock (ESS), and Fertilizer Input Risk (FIR).

The resulting FSSI quantifies the vulnerability of downstream food systems under the prevailing disruption conditions. By separating disruption severity from downstream system consequences, the framework improves conceptual consistency, enhances interpretability, and avoids circular relationships between disruption drivers and downstream outcomes.

3.2.4. Stage 4: Prescriptive optimization

The fourth stage constitutes the prescriptive component of the framework. The disruption indicators generated during the previous stages are translated into deterministic optimization parameters before solving the mixed-integer linear programming (MILP) model.

The Supply Chain Disruption Risk Index determines the disruption-risk multiplier:

$$RM = 1 + \frac{SCDRI}{100} \tag{1}$$

Where, RM is the disruption-risk multiplier, SCDRI is the Supply Chain Disruption Risk Index, which proportionally adjusts transportation costs according to the estimated disruption severity.

The Food System Stress Index modifies the effective shortage penalty according to:

$$p_j^{eff} = p_j\left(1 + \beta\frac{FSSI}{100}\right) \tag{2}$$

where:

- p_j^{eff} denotes the effective shortage penalty for demand region j
- p_j is the baseline shortage penalty
- FSSI is the Food System Stress Index
- β is a non-negative sensitivity coefficient controlling the influence of food-system stress on shortage costs,

thereby increasing the economic consequences of unmet demand as downstream food-system stress intensifies.

Using these disruption-adjusted parameters, the optimization model simultaneously determines supplier activation, shipment allocation, transportation planning, strategic inventory deployment, emergency procurement, and potential unmet demand while minimizing the total disruption-adjusted operating cost.

The resulting operational plans represent resilience-oriented responses that balance transportation costs, supply continuity, inventory utilization, emergency sourcing, and downstream food-system resilience under alternative geopolitical disruption scenarios.

Unlike conventional approaches that treat disruption assessment and optimization as independent analytical processes, the proposed framework establishes a continuous information flow in which disruption indicators generated through fuzzy reasoning and downstream food-system assessment directly parameterize the optimization model.

Overall, the proposed framework establishes a transparent sequential workflow linking historical evidence, expert knowledge, fuzzy reasoning, food-system stress assessment, and mathematical optimization. The Mamdani fuzzy inference system estimates the Supply Chain Disruption Risk Index (SCDRI), the subsequent analytical stage computes the Food System Stress Index (FSSI) through an expert-informed weighted aggregation model, and the optimization model transforms these indicators into resilience-oriented operational decisions. This sequential integration provides a transparent, explainable, reproducible, and operationally actionable prescriptive analytics methodology that systematically transforms qualitative geopolitical assessments into resilience-oriented operational decisions under conditions of deep geopolitical uncertainty.

3.3. Mamdani Fuzzy Inference System (FIS): Supply chain disruption risk assessment

The Mamdani fuzzy inference system (FIS) constitutes the core disruption assessment component of the proposed fuzzy prescriptive analytics framework. It was implemented in MATLAB using the Mamdani Fuzzy Logic Toolbox to evaluate the overall severity of geopolitical disruptions affecting global supply chains. Rather than forecasting future geopolitical events, the objective of the system is to transform qualitative geopolitical information and expert knowledge into a structured disruption indicator suitable for operational decision support under conditions of deep uncertainty.

The fuzzy inference system integrates multiple disruption mechanisms into a single Supply Chain Disruption Risk Index (SCDRI), which serves as the principal disruption indicator throughout the proposed framework. The computed SCDRI subsequently supports the estimation of downstream food-system stress through the weighted aggregation model and the parameterization of the optimization model, thereby establishing the analytical link between qualitative geopolitical assessments and quantitative operational planning.

Input Variables

The input variables were identified through the expert elicitation process described in Section 4.3 and represent the principal mechanisms through which geopolitical disruptions propagate across interconnected supply chain networks.

- *Geopolitical Tension (GT)*, representing the overall intensity of geopolitical instability, military escalation, diplomatic conflict, and regional political uncertainty.
- *Maritime Accessibility (MA),* representing the operational accessibility of maritime transportation through the Strait of Hormuz, including navigational restrictions, shipping interruptions, and route availability.
- *Energy Supply Shock (ESS)*, representing disruptions affecting oil, natural gas, and broader energy availability that influence industrial production and transportation systems.
- *Logistics Delay (LD),* representing transportation delays, port congestion, shipping interruptions, and operational inefficiencies across international logistics networks.
- *Fertilizer Input Risk (FIR)*, representing disruptions affecting fertilizer availability and agricultural input supply, linking geopolitical disruption with downstream food-system stress.

Each disruption driver is represented using expert-informed fuzzy membership functions and linguistic categories (*Low*, *Moderate*, *High*, and *Critical*). This representation enables gradual transitions between disruption states while accommodating the ambiguity and uncertainty inherent in geopolitical assessments.

Output Variable

The single output of the Mamdani fuzzy inference system is the Supply Chain Disruption Risk Index (SCDRI), expressed on a continuous scale ranging from 0 to 100. For ease of interpretation, the resulting values are classified into four disruption categories:

- Low (0–25)
- Moderate (>25–50)
- Severe (>50–75)
- Extreme (>75–100)

The SCDRI provides an aggregated assessment of overall disruption severity across interconnected geopolitical, energy, transportation, logistics, and supply-chain systems. Within the proposed framework, it serves as the primary disruption indicator supporting both downstream food-system stress assessment and optimization-based operational decision-making.

Fuzzy Rule Base

The inference system operates through an expert-informed rule base composed of linguistic IF–THEN rules describing the interactions among the five disruption drivers. These rules represent structured expert knowledge rather than statistically estimated relationships, enabling the framework to model complex causal interactions that cannot be adequately represented using deterministic or probabilistic approaches. A representative rule is:

IF Geopolitical Tension is *High* AND Maritime Accessibility is *Restricted* AND Energy Supply Shock is *Severe*, *THEN* Supply Chain Disruption Risk is *Extreme*.

This rule illustrates how multiple disruption mechanisms are combined to estimate the overall disruption severity represented by the SCDRI. The compact expert-informed rule base captures the dominant combinations of disruption drivers identified during the expert elicitation process, allowing the inference system to evaluate realistic geopolitical scenarios while maintaining transparency, interpretability, and computational efficiency.

Inference and Defuzzification

The fuzzy inference process follows the standard Mamdani inference methodology. For each activated rule, the antecedent conditions are evaluated using the minimum operator to determine the rule firing strength. The outputs of all activated rules are subsequently aggregated using the maximum operator to generate a composite fuzzy representation of disruption severity.

The aggregated fuzzy output is converted into a crisp Supply Chain Disruption Risk Index (SCDRI) using the centroid defuzzification method, providing a continuous numerical measure of overall disruption severity.

Integration within the Prescriptive Analytics Framework

The computed Supply Chain Disruption Risk Index (SCDRI) serves as the principal output of the Mamdani fuzzy inference system and performs two complementary functions within the proposed framework.

First, it contributes to the computation of the Food System Stress Index (FSSI), where it is combined with Energy Supply Shock (ESS) and Fertilizer Input Risk (FIR) through an expert-informed weighted aggregation model to quantify downstream food-system stress.

Second, the SCDRI is transformed into the disruption-risk multiplier according to Eq. (1), which proportionally adjusts transportation costs within the mixed-integer linear programming model according to the estimated disruption severity.

The computed FSSI subsequently modifies the effective shortage penalty according to Eq. (2), thereby allowing downstream food-system stress to directly influence the optimization model by increasing the economic consequences of unmet demand.

Through this sequential integration, the Mamdani fuzzy inference system provides the analytical foundation of the proposed fuzzy prescriptive analytics framework. It transforms qualitative geopolitical assessments into a quantitative disruption indicator that supports downstream food-system stress assessment and optimization-based operational decision-making. In this way, the framework establishes a transparent and explainable analytical link between geopolitical disruption assessment and resilience-oriented supply chain planning under conditions of deep geopolitical uncertainty.

3.4. Translation of fuzzy outputs into optimization parameters

The proposed framework establishes a direct and transparent connection between fuzzy disruption assessment and optimization-based operational planning by transforming disruption indicators into quantitative optimization parameters. Rather than incorporating fuzzy variables directly into the optimization model, the framework first evaluates overall disruption severity using a Mamdani fuzzy inference system and subsequently computes downstream food-system stress through an expert-informed weighted aggregation model for food-system stress assessment. The resulting indicators are then translated into deterministic optimization parameters used by the mixed-integer linear programming (MILP) model.

This approach clearly separates uncertainty representation from operational optimization. Uncertainty arising from geopolitical conditions is represented through fuzzy reasoning during the disruption assessment stage, whereas the optimization model operates using deterministic parameters derived from the disruption indicators. This sequential architecture preserves the interpretability of fuzzy reasoning while maintaining the computational efficiency, reproducibility, and mathematical tractability of a conventional mixed-integer linear programming model.

A key methodological contribution of the proposed framework is the sequential transformation of disruption indicators into deterministic optimization parameters, enabling explainable fuzzy reasoning and mathematical optimization to operate in complementary rather than competing roles.

The Mamdani fuzzy inference system produces the Supply Chain Disruption Risk Index (SCDRI), which represents the overall severity of geopolitical disruption on a continuous scale from 0 to 100. The SCDRI is subsequently transformed into a disruption-risk multiplier that proportionally adjusts transportation costs according to the estimated disruption severity according the Eq. (1).

Higher disruption severity therefore increases transportation costs proportionally, reflecting additional logistics expenses associated with maritime restrictions, insurance premiums, vessel rerouting, longer transportation distances, and operational inefficiencies during geopolitical crises.

To capture the downstream consequences of geopolitical disruptions, the framework subsequently computes the Food System Stress Index (FSSI) as an expert-informed weighted aggregation of the Supply Chain Disruption Risk Index (SCDRI)**,** Energy Supply Shock (ESS), and Fertilizer Input Risk (FIR). Rather than introducing the FSSI as an additional optimization objective, the framework incorporates food-system stress by modifying the effective shortage penalty associated with unmet demand according the Eq. (2).

This formulation enables downstream food-system stress to influence operational decisions indirectly by increasing the economic consequences of unmet demand as food-system stress intensifies. Consequently, the optimization progressively prioritizes supply continuity over transportation cost minimization under increasingly severe geopolitical disruption scenarios.

The disruption-adjusted transportation costs and effective shortage penalties are subsequently incorporated into the mixed-integer linear programming model described in Section 3.5. Using these modified parameters, the optimization simultaneously determines supplier activation, shipment allocation, transportation planning, strategic inventory deployment, emergency procurement, and potential unmet demand while minimizing the total disruption-adjusted operating cost. The complete transformation process is illustrated in Fig. 2.

Accordingly, the proposed framework employs fuzzy reasoning and mathematical optimization in complementary rather than competing roles. The Mamdani fuzzy inference system transforms qualitative geopolitical assessments into a quantitative disruption indicator, while the expert-informed Food System Stress assessment captures the downstream consequences of disruption. These indicators are subsequently translated into deterministic optimization parameters that guide operational decision-making.

Unlike fuzzy optimization approaches that directly embed fuzzy numbers within mathematical programming models, the proposed methodology maintains a clear separation between disruption assessment and operational optimization. This design enhances transparency, facilitates reproducibility, and allows the optimization model to be solved efficiently using standard mixed-integer linear programming techniques while remaining fully responsive to uncertainty represented through explainable fuzzy reasoning and expert-informed downstream impact assessment.

3.4.1. Food System Stress Index (FSSI)

The Food System Stress Index (FSSI) is introduced to quantify the downstream consequences of geopolitical disruptions for food-system resilience. While the Supply Chain Disruption Risk Index (SCDRI) measures the overall severity of geopolitical disruptions across interconnected supply-chain systems, the FSSI evaluates how these disruptions propagate to agricultural production, food availability, and the overall resilience of downstream food systems.

A distinguishing feature of the proposed framework is the explicit separation between disruption assessment and downstream impact evaluation. The SCDRI represents the aggregated severity of geopolitical disruption estimated through the Mamdani fuzzy inference system, whereas the FSSI is computed subsequently as an expert-informed weighted aggregation indicator. Consequently, the FSSI is not generated through fuzzy inference but serves as a downstream impact indicator that translates disruption severity into downstream food-system stress.

The FSSI is computed from three complementary components:

- the Supply Chain Disruption Risk Index (SCDRI),
- the Energy Supply Shock (ESS)**,** and
- the Fertilizer Input Risk (FIR).

The weighted aggregation model is defined as:

$$FSSI = w_1(SCDRI) + w_2(ESS) + w_3(FIR) \quad (3)$$

subject to:

$$w_1 + w_2 + w_3 = 1 \quad (4)$$

where:

- SCDRI represents the overall severity of geopolitical supply-chain disruption
- ESS represents the disruption level affecting energy availability
- FIR represents the disruption level affecting fertilizer availability

- w_1, w_2, w_3 denote the weighting coefficients assigned to the three components.

The weighting coefficients adopted in this study were established through the expert elicitation process described in Section 4.3. The relatively higher weight assigned to the SCDRI reflects its role as an aggregated indicator summarizing the combined effects of the five geopolitical disruption drivers. Equal weights were assigned to ESS and FIR because they represent the two principal transmission channels through which geopolitical disruptions directly affect agricultural production and downstream food-system resilience.

The adopted weights are:

$$w_1 = 0.40, \quad w_2 = 0.30, \quad w_3 = 0.30 \tag{5}$$

Accordingly:

$$FSSI = 0.40(SCDRI) + 0.30(ESS) + 0.30(FIR) \tag{6}$$

It should be noted that ESS and FIR contribute to the framework at two complementary analytical levels. They influence the SCDRI through the Mamdani fuzzy inference system while also contributing directly to the computation of the FSSI. This modelling choice is intentional and reflects the dual role of energy availability and fertilizer supply as critical transmission mechanisms linking geopolitical disruption with downstream food-system stress. The objective is therefore not to construct statistically independent variables, but to preserve the causal relationships through which geopolitical disruptions propagate to downstream food systems. The adopted weighting scheme therefore represents an expert-informed modelling assumption rather than an empirically estimated statistical relationship.

Consequently, the FSSI should be interpreted as a decision-support indicator rather than a statistically calibrated predictive index. The weighting coefficients represent expert-informed modelling assumptions and can be refined in future studies as additional empirical evidence becomes available.

The FSSI is incorporated into the optimization model by modifying the effective shortage penalty according to:

$$p_j^{eff} = p_j\left(1 + \beta\frac{FSSI}{100}\right), \quad \beta \geq 0 \tag{7}$$

where p_j^{eff} denotes the effective shortage penalty for demand node j, p_j is the baseline shortage penalty, and β is a non-negative food-system sensitivity coefficient.

This formulation directly links downstream food-system stress to the endogenous shortage decision variable. As food-system stress increases, the economic cost associated with unmet demand also increases, encouraging the optimization model to prioritize supply continuity through appropriate supplier activation, inventory deployment, transportation planning, emergency procurement, and shortage allocation decisions.

The proposed formulation preserves the linear structure of the optimization model while allowing downstream food-system stress to influence operational decision-making through economically interpretable optimization parameters.

These qualitative categories facilitate managerial interpretation and scenario comparison while the optimization model operates exclusively on the underlying continuous FSSI values. Future research may investigate alternative weighting schemes, calibrate the weighting coefficients using observed disruption data, and compare the present additive formulation with hierarchical or non-compensatory aggregation approaches to further strengthen the robustness of the index.

3.5. Optimization formulation

The prescriptive component of the proposed framework is implemented through a mixed-integer linear programming (MILP) model that identifies resilience-oriented supply-chain decisions under geopolitical disruption. The optimization model integrates the disruption indicators generated during the analytical stages of the framework to determine operational strategies that simultaneously enhance supply-chain resilience, food-system resilience, and economic performance.

Unlike conventional supply-chain optimization models, which primarily focus on minimizing operational costs, the proposed formulation explicitly incorporates the downstream consequences of geopolitical disruptions into operational decision-making. The Supply Chain Disruption Risk Index (SCDRI) influences disruption-adjusted transportation costs through a disruption-risk multiplier, whereas the Food System Stress Index (FSSI) modifies the economic penalty associated with unmet demand. Consequently, the optimization model balances economic efficiency, supply continuity, and downstream food-system resilience under alternative geopolitical disruption scenarios.

Sets and Indices

$i \in I$ Supply nodes (suppliers)

$j \in J$ Demand nodes (destinations)

Decision Variables

x_{ij} Quantity transported from supplier i to demand node j

x_{Ej} Quantity supplied through emergency procurement to demand node j

I_j Strategic inventory released at demand node j

U_j Unmet demand (shortage) at demand node j

y_i Binary supplier activation variable

z Binary emergency procurement activation variable

Parameters

- C_{ij}: transportation cost (USD/unit)
- C_{Ej}: emergency procurement cost per unit delivered to demand node j (USD/unit)
- Cap_i: supplier capacity
- K_E: maximum emergency procurement capacity
- D_j: demand
- h_j: inventory release cost (USD/unit)
- p_j: baseline shortage penalty (USD/unit)
- p_j^{eff}: FSSI-adjusted shortage penalty
- F_i: supplier activation cost
- F_E: emergency supplier activation cost
- RM: disruption-risk multiplier derived from the SCDRI
- $FSSI$: Food System Stress Index
- β: non-negative food-system sensitivity coefficient ($\beta \geq 0$)

Objective Function

The objective of the optimization model is to minimize the total disruption-adjusted operating cost while explicitly accounting for downstream food-system stress.

$$\min Z = RM\sum_{i\in I}\sum_{j\in J}C_{ij}x_{ij} + \sum_{j\in J}h_jI_j + \sum_{j\in J}p_j^{eff}U_j + \sum_{i\in I}F_iy_i + F_Ez + \sum_{j\in J}C_{Ej}x_{Ej} \tag{8}$$

The first term represents disruption-adjusted transportation costs. The second term accounts for strategic inventory deployment. The third term represents the cost of unmet demand, whose penalty increases as downstream food-system stress intensifies. The fourth and fifth terms correspond to the fixed costs of supplier activation and emergency procurement activation, respectively, while the final term captures the variable cost of emergency procurement.

Rather than being introduced as an additive objective component, the Food System Stress Index (FSSI) influences the optimization model through the effective shortage penalty defined in Eq. (7). This formulation directly links downstream food-system stress to the endogenous shortage decision variable. As food-system stress increases, shortages become progressively more costly, encouraging the optimization model to modify supplier activation, inventory deployment, transportation planning, emergency procurement, and shortage allocation decisions.

The disruption-risk multiplier proportionally adjusts transportation costs according to the disruption severity represented by the Supply Chain Disruption Risk Index (SCDRI) defined in Eq. (1). Unlike conventional deterministic supply-chain optimization models, the proposed formulation is parameterized by disruption indicators derived from expert-informed disruption assessment, thereby preserving a direct analytical connection between qualitative geopolitical assessments and quantitative operational decision-making.

Constraints

Supply Capacity

$$\sum_{j\in J} x_{ij} \le Cap_i, \quad \forall i \in I \tag{9}$$

Demand Satisfaction

$$\sum_{i\in I} x_{ij} + x_{Ej} + I_j + U_j = D_j, \quad \forall j \in J \tag{10}$$

Inventory Availability

$$I_j \le M_j, \quad \forall j \in J \tag{11}$$

Supplier Activation

$$\sum_{j\in J} x_{ij} \le Cap_i\, y_i, \quad \forall i \in I \tag{12}$$

Emergency Procurement

$$\sum_{j\in J} x_{Ej} \le K_E z \tag{13}$$

Variable Domains

$$x_{ij}, x_{Ej}, I_j, U_j \ge 0, \quad y_i, z \in \{0, 1\} \tag{14}$$

The resulting mixed-integer linear programming model is solved using MATLAB's *intlinprog* solver. The model simultaneously determines supplier activation, transportation planning, strategic inventory deployment, emergency procurement, and shortage allocation while minimizing disruption-adjusted operating costs.

By integrating the Supply Chain Disruption Risk Index (SCDRI) through disruption-adjusted transportation costs and the Food System Stress Index (FSSI) through the effective shortage penalty, the proposed optimization framework systematically translates disruption assessments into resilience-oriented operational decisions that explicitly balance supply continuity, downstream food-system resilience, and economic performance under conditions of geopolitical uncertainty.

3.5.1. *Translation of fuzzy outputs into deterministic optimization parameters*

Unlike conventional fuzzy optimization approaches that directly incorporate fuzzy numbers into mathematical programming models, the proposed framework transforms the outputs of the disruption assessment stage into deterministic optimization parameters before solving the mixed-integer linear programming (MILP) model. This design clearly separates uncertainty representation from operational optimization, allowing each component to contribute according to its methodological strengths.

The Supply Chain Disruption Risk Index (SCDRI), generated by the Mamdani fuzzy inference system, is transformed into a disruption-risk multiplier (RM) that proportionally adjusts transportation costs according to the estimated severity of geopolitical disruption. In parallel, the Food System Stress Index (FSSI), computed through an expert-informed weighted aggregation of the SCDRI, Energy Supply Shock (ESS), and Fertilizer Input Risk (FIR), modifies the effective shortage penalty associated with unmet demand. Consequently, both disruption indicators influence the optimization model indirectly through economically interpretable parameters rather than by introducing fuzzy variables into the mathematical formulation.

This sequential transformation enables the optimization model to operate entirely with deterministic parameters while remaining fully responsive to the uncertainty represented during the disruption assessment stage. As a result, the framework combines the transparency and explainability of fuzzy reasoning with the computational efficiency, reproducibility, and scalability of conventional mixed-integer linear programming, providing an effective, transparent, and practical decision-support methodology for resilience-oriented supply chain planning under geopolitical uncertainty.

3.5.2. *Numerical optimization instance*

To ensure full reproducibility, a fully specified numerical optimization instance was developed and implemented in MATLAB using the built-in *intlinprog* solver for mixed-integer linear programming (MILP). All numerical parameter values are explicitly defined, enabling independent replication of the computational experiments. The numerical instance was designed as a benchmark problem to facilitate methodological transparency, independent verification, and future comparative studies.

The numerical instance represents a stylized international supply chain comprising five supply sources, including two Gulf suppliers, one pipeline-linked supplier, one non-Gulf supplier, and one emergency supplier, together with three demand regions representing Europe, South Asia, and East Asia. The model incorporates explicit transportation cost matrices, supplier production capacities, regional demand requirements, strategic inventory availability, fixed supplier activation costs, emergency procurement costs, emergency procurement capacities, and baseline shortage penalties. Together, these parameters provide a complete representation of the operational planning problem under alternative geopolitical disruption scenarios.

Transportation costs are adjusted according to the estimated disruption severity through the disruption-risk multiplier derived from the Supply Chain Disruption Risk Index (SCDRI), as defined in Eq. (1). Similarly, the effective shortage penalties are adjusted according to the Food System Stress Index (FSSI) using Eq. (7), allowing downstream food-system stress to influence operational decision-making through economically interpretable optimization parameters.

The optimization model is solved independently for each disruption scenario generated by the proposed analytical framework, namely Partial Closure, Severe Closure, and Full Closure. For each scenario, the corresponding values of the SCDRI and FSSI produce different disruption-adjusted transportation costs and shortage penalties, producing distinct operational planning problems that reflect different geopolitical conditions.

The optimization simultaneously determines supplier activation, shipment allocation, strategic inventory deployment, emergency procurement activation, emergency procurement quantities, transportation planning, and potential unmet demand while minimizing the total disruption-adjusted operating cost. The resulting solutions illustrate how the proposed fuzzy prescriptive analytics framework progressively adapts operational decisions as disruption severity increases by balancing transportation costs, strategic inventory utilization, emergency sourcing, shortage costs, and supply continuity.

The complete numerical optimization instance, including transportation cost matrices, supplier capacities, regional demand requirements, strategic inventory availability, fixed and variable cost parameters, emergency procurement data, and the corresponding SCDRI and FSSI values for each disruption scenario, is presented in Appendix B. The availability of these complete numerical datasets ensures the full reproducibility of the proposed methodology and facilitates independent validation, benchmarking, and future comparative studies.

3.6. *Solution method*

The proposed fuzzy prescriptive analytics framework integrates explainable fuzzy modelling and mixed-integer linear programming

(MILP) within a sequential decision-support process. The Mamdani fuzzy inference system evaluates the severity of geopolitical disruption, while downstream food-system stress is assessed through an expert-informed weighted aggregation model. The resulting disruption indicators are subsequently translated into deterministic optimization parameters that guide operational planning. Fig. 2 summarizes the overall computational workflow. This sequential solution procedure ensures that uncertainty is represented during the disruption assessment stage, whereas operational decisions are obtained through deterministic optimization.

The solution procedure consists of the following six steps:

Step 1. Assessment of Supply Chain Disruption Risk

The Mamdani fuzzy inference system evaluates the severity of geopolitical disruption by combining the five disruption indicators presented in Section 3.3. The fuzzy inference process produces the Supply Chain Disruption Risk Index (SCDRI), which represents the overall disruption severity on a continuous scale from 0 to 100.

Step 2. Assessment of Food System Stress

The Food System Stress Index (FSSI) is subsequently computed as an expert-informed weighted aggregation of the Supply Chain Disruption Risk Index (SCDRI), Energy Supply Shock (ESS), and Fertilizer Input Risk (FIR), following the methodology presented in Section 3.4.1. The resulting index quantifies the level of downstream food-system stress under the prevailing geopolitical disruption scenario.

Step 3. Translation into Optimization Parameters

The values of the SCDRI and FSSI are translated into deterministic optimization parameters before solving the operational planning model. The SCDRI determines the disruption-risk multiplier used to adjust transportation costs, whereas the FSSI modifies the effective shortage penalty associated with unmet demand. These transformations establish the analytical connection between disruption assessment and operational optimization.

Step 4. Mixed-Integer Linear Programming Optimization

The disruption-adjusted parameters are incorporated into the mixed-integer linear programming model presented in Section 3.5. The optimization simultaneously determines:

- supplier activation,
- shipment allocation,
- transportation planning,
- strategic inventory deployment,
- emergency procurement activation,
- emergency procurement quantities, and
- potential unmet demand.

These decisions collectively determine the resilience-oriented operational strategy under each disruption scenario. The objective is to minimize the total disruption-adjusted operating cost while satisfying all operational constraints.

Step 5. Scenario Analysis

The optimization model is solved independently for the three geopolitical disruption scenarios considered in this study, namely Partial Closure, Severe Closure, and Full Closure. Each scenario is characterized by different SCDRI and FSSI values, resulting in different transportation costs, shortage penalties, supplier selections, inventory utilization strategies, emergency procurement decisions, and overall operating costs.

Step 6. Decision Support and Managerial Interpretation

Finally, the optimization results are analysed to evaluate the operational implications of each disruption scenario. The framework provides decision-makers with recommended supplier selections, shipment plans, transportation strategies, inventory utilization levels, emergency procurement requirements, potential shortages, and total operating costs. These outputs provide a transparent, explainable, and reproducible basis for resilience-oriented operational decision-making by systematically linking explainable geopolitical disruption assessment with optimization-based supply chain planning under conditions of deep geopolitical uncertainty.

3.7. Scenario modelling

Scenario modelling is a central component of the proposed fuzzy prescriptive analytics framework. Rather than attempting to predict future geopolitical events, the framework evaluates a set of representative disruption scenarios reflecting different levels of geopolitical escalation and their potential implications for supply chain operations.

The scenario-based approach enables the framework to examine how increasing disruption severity affects supply chain resilience, downstream food-system stress, and resilience-oriented operational decision-making. Each scenario is characterized by a distinct combination of the five disruption drivers considered in the disruption assessment stage: Geopolitical Tension (GT), Maritime Accessibility (MA), Energy Supply Shock (ESS), Logistics Delay (LD), and Fertilizer Input Risk (FIR).

For each scenario, the Mamdani fuzzy inference system estimates the Supply Chain Disruption Risk Index (SCDRI), representing the overall severity of geopolitical disruption. Subsequently, the Food System Stress Index (FSSI) is computed as an expert-informed weighted aggregation of the SCDRI, Energy Supply Shock (ESS), and Fertilizer Input Risk (FIR). These disruption indicators are subsequently translated into deterministic optimization parameters that guide the mixed-integer linear programming model, enabling resilience-oriented operational decisions that jointly account for disruption severity, downstream food-system stress, and economic performance.

By evaluating multiple disruption scenarios within a unified analytical framework, the proposed methodology enables systematic comparisons of alternative resilience strategies under progressively more severe geopolitical conditions. This scenario-based analysis also provides decision-makers with insights into how operational planning should adapt as geopolitical risks intensify.

The three disruption scenarios, their corresponding input values, and the numerical implementation adopted for the Strait of Hormuz case study are presented in Section 4.

3.8. Decision outputs

The proposed framework generates prescriptive outputs designed to support resilience-oriented supply chain decision-making under conditions of geopolitical disruption. By integrating disruption assessment, downstream food-system stress evaluation, and optimization-based decision support, the framework systematically transforms qualitative geopolitical assessments into actionable operational recommendations.

The mixed-integer linear programming model produces the following decision outputs:

- Supplier activation decisions.
- Strategic inventory deployment and inventory release quantities.
- Transportation planning and shipment allocation decisions.
- Emergency procurement activation and procurement quantities.
- Shortage allocation across demand regions.
- Total disruption-adjusted operating cost.
- Expected implications for downstream food-system resilience.

The resulting operational plans are evaluated using multiple performance criteria, including economic efficiency, disruption-risk exposure, supply continuity, operational resilience, and downstream food-system resilience. Unlike conventional optimization models that primarily minimize operating costs, the proposed framework explicitly incorporates both the severity of geopolitical disruption, represented by the Supply Chain Disruption Risk Index (SCDRI), and downstream food-system stress, represented by the Food System Stress Index (FSSI).

Consequently, the proposed framework extends beyond disruption assessment by generating resilience-oriented operational recommendations that explicitly balance supply continuity, downstream food-system resilience, and economic performance under alternative geopolitical disruption scenarios. These decision outputs constitute the final stage of the proposed prescriptive analytics framework, translating explainable disruption assessments into practical operational strategies for resilient supply chain management under conditions of deep uncertainty.

3.9. *Advantages of the fuzzy approach*

The proposed framework adopts fuzzy logic because it offers several methodological advantages for supply chain decision-making under conditions of deep geopolitical uncertainty.

First, fuzzy logic enables the representation of ambiguity and incomplete information through linguistic variables and membership functions, allowing qualitative geopolitical assessments to be incorporated even when reliable probabilistic information is unavailable.

Second, the Mamdani fuzzy inference system facilitates the systematic integration of expert knowledge through transparent IF–THEN rules, providing greater interpretability and explainability than many purely data-driven black-box approaches.

Third, overlapping membership functions capture gradual transitions between disruption states, providing a more realistic representation of geopolitical escalation than rigid deterministic thresholds. This allows the framework to represent the continuous evolution of disruption severity rather than assuming abrupt changes between predefined states.

Fourth, the proposed framework separates uncertainty representation from operational optimization. Fuzzy reasoning is used to evaluate geopolitical disruption, while downstream food-system stress is quantified through an expert-informed weighted aggregation model. The resulting disruption indicators are then translated into deterministic optimization parameters, allowing the optimization model to retain the computational efficiency and scalability of conventional mixed-integer linear programming. Table 1 summarizes the principal differences between conventional deterministic approaches and the proposed fuzzy prescriptive analytics framework.

Within the proposed framework, the Mamdani fuzzy inference system transforms qualitative geopolitical assessments into a quantitative Supply Chain Disruption Risk Index (SCDRI), while the Food System Stress Index (FSSI) quantifies the downstream consequences of geopolitical disruption through an expert-informed weighted aggregation model. These indicators are subsequently incorporated into the mixed-integer optimization model as deterministic parameters that guide resilience-oriented operational decisions. By combining explainable fuzzy reasoning with mathematical optimization, the proposed framework provides an integrated decision-support methodology that supports operational decisions balancing economic efficiency, supply continuity, and downstream food-system resilience under alternative geopolitical disruption scenarios.

Table 1
Comparison between conventional deterministic approaches and the proposed fuzzy prescriptive analytics framework.

Conventional Deterministic Approaches	Proposed Fuzzy Prescriptive Analytics Framework
Require precise numerical data	Handle vague, uncertain, and incomplete information
Probability-based uncertainty representation	Possibility-based uncertainty representation
Rigid scenario definitions	Flexible linguistic scenario representation
Limited incorporation of expert judgement	Expert knowledge explicitly incorporated through linguistic variables and IF–THEN rules
Fixed deterministic thresholds	Gradual transitions captured through overlapping membership functions
Disruption assessment and optimization treated independently	Sequential integration of disruption assessment, food-system stress assessment, and optimization

4. Numerical case study: application to the Strait of Hormuz

4.1. *Purpose of the numerical case study*

This section demonstrates the application of the proposed fuzzy prescriptive analytics framework through an illustrative scenario-based numerical case study centred on the Strait of Hormuz. The primary objective of the case study is to demonstrate the practical applicability of the proposed methodology rather than to predict future geopolitical events or empirically validate specific geopolitical scenarios. Instead, the case study illustrates how representative geopolitical disruption scenarios can be systematically translated into disruption assessment, downstream food-system stress evaluation, optimization parameterization, and resilience-oriented operational decision-making.

The Strait of Hormuz was selected as the illustrative case study because it represents one of the world's most strategically important maritime chokepoints. According to the U.S. Energy Information Administration [42], approximately 20–25% of globally traded crude oil and nearly one-third of global liquefied natural gas (LNG) exports transit through the strait. As a narrow maritime corridor connecting the Persian Gulf with the Gulf of Oman and the Arabian Sea, the Strait of Hormuz plays a critical role in global energy security and international trade. Consequently, disruptions affecting this corridor may generate substantial impacts on energy markets, maritime transportation, and global supply chains [18,25].

The strategic importance of the Strait of Hormuz extends beyond energy transportation. Natural gas and petroleum products transported through the region constitute essential inputs for fertilizer production, particularly nitrogen-based fertilizers. Consequently, disruptions in energy supply may reduce fertilizer availability, increase agricultural production costs, and ultimately affect food-system resilience and food security [29].

The numerical case study therefore examines how geopolitical disruptions propagate across four interconnected domains:

- Energy systems, through oil and LNG supply disruptions;
- Logistics systems, through transportation delays, route restrictions, and increased shipping costs;
- Fertilizer supply, through reduced fertilizer availability and increased agricultural input costs;
- Food systems, through increased food-system stress, reduced food availability, and weaker supply continuity.

Three progressively more severe disruption scenarios are considered: Partial Closure, Severe Closure, and Full Closure. For each scenario, the Mamdani fuzzy inference system evaluates the five disruption drivers and estimates the Supply Chain Disruption Risk Index (SCDRI). Subsequently, the Food System Stress Index (FSSI) is computed as an expert-informed weighted aggregation of the SCDRI, Energy Supply Shock (ESS), and Fertilizer Input Risk (FIR), thereby quantifying the level of downstream food-system stress under each disruption scenario.

The FSSI is not used only as a downstream impact indicator. Together with the SCDRI, it directly parameterizes the optimization model. Specifically, the SCDRI is transformed into a disruption-risk multiplier that adjusts transportation costs, whereas the FSSI modifies the effective shortage penalties associated with unmet demand. Consequently, both disruption severity and downstream food-system stress directly influence the resulting operational decisions.

Overall, the numerical case study demonstrates how the proposed framework systematically transforms representative geopolitical disruption scenarios into quantitative operational decisions through the sequential integration of fuzzy disruption assessment, expert-informed food-system stress assessment, and mixed-integer linear programming. This integrated analytical workflow provides a transparent, reproducible, and explainable prescriptive analytics methodology for balancing economic efficiency, supply continuity, and food-system resilience under alternative geopolitical disruption scenarios.

4.2. Historical evidence review and expert-informed scenario development

The proposed framework is designed as an expert-informed prescriptive decision-support methodology rather than as a statistically calibrated forecasting model. Accordingly, historical evidence was not used for statistical parameter estimation or model calibration. Instead, it provided the contextual foundation for scenario development, disruption characterization, expert elicitation, and the specification of linguistic variables within the fuzzy prescriptive analytics framework.

To enhance the realism and practical relevance of the proposed methodology, historical information relating to geopolitical disruptions in the Strait of Hormuz was systematically reviewed during framework development. The reviewed evidence included historical oil-price shocks, maritime transportation disruptions, freight-rate volatility, and geopolitical incidents affecting regional energy transportation. These historical observations informed the expert elicitation process and ensured that the disruption scenarios reflected realistic geopolitical conditions.

Four principal categories of historical evidence were considered:

- Oil-price shocks associated with geopolitical escalation
- Maritime transportation delays and shipping disruptions
- Freight-rate volatility during major geopolitical crises
- Historical incidents affecting navigation and energy transportation in the Strait of Hormuz.

Rather than deriving numerical model parameters directly from historical observations, the reviewed evidence was used to evaluate whether the proposed disruption scenarios were broadly consistent with patterns observed during previous geopolitical crises. Consequently, the historical review supported the identification of disruption drivers, the definition of linguistic categories, and the development of representative disruption scenarios.

Expert knowledge was subsequently incorporated through the structured expert elicitation procedure described in Section 4.3. Six specialists with expertise in supply chain management, maritime logistics, energy markets, and geopolitical risk analysis participated in the elicitation process. Their expertise was used to identify the principal disruption drivers, define linguistic variables, specify triangular membership functions, construct the Mamdani fuzzy rule base, determine the weighting coefficients of the Food System Stress Index (FSSI), and establish the operational assumptions adopted throughout the optimization framework.

The combination of historical evidence and expert knowledge forms the analytical foundation of the proposed methodology. Historical evidence ensures that the disruption scenarios remain historically plausible, whereas expert knowledge provides the qualitative information required to specify the fuzzy inference system, the weighted food-system stress assessment, and the optimization model. Together, these complementary sources enable the framework to represent geopolitical uncertainty through explainable fuzzy reasoning while maintaining historically plausible disruption scenarios and operational realism.

Accordingly, the proposed methodology should be interpreted as an expert-informed fuzzy prescriptive analytics framework supported by historically plausible scenarios rather than as a statistically calibrated predictive model.

Table 2 summarizes the principal categories of historical evidence used during the development of the proposed framework. These sources supported expert discussions and scenario specification rather than statistical model calibration. Their primary role was to ensure that the disruption scenarios, linguistic variables, disruption pathways, and operational assumptions reflected historically plausible geopolitical conditions before being translated into disruption indicators and subsequently incorporated into the optimization model. This approach enhances methodological transparency by clearly distinguishing between historical evidence, expert-informed model specification, and optimization-based decision support.

Table 2
Historical Evidence Supporting Scenario Development and Expert Elicitation.

Evidence Category	Example Sources	Primary Purpose
Oil-price shocks	EIA, World Bank	Characterization of Energy Supply Shock (ESS)
Shipping delays	IMO, UNCTAD	Specification of Logistics Delay (LD)
Freight-rate volatility	Drewry, Baltic Exchange	Characterization of transportation-cost uncertainty
Strait of Hormuz incidents	EIA, IEA, publicly available reports	Scenario development and disruption characterization

4.3. Expert elicitation procedure

Given the inherent ambiguity, deep uncertainty, and limited historical observations associated with geopolitical disruptions. The expert elicitation process constitutes the knowledge-engineering component of the proposed methodology, systematically transforming qualitative domain expertise into formal analytical knowledge that supports disruption assessment, food-system stress evaluation, and optimization-based operational decision-making.

The elicitation process was designed to ensure methodological consistency, transparency, and reproducibility throughout the development of the framework. Expert knowledge was used to identify the principal disruption drivers, define the linguistic variables and their corresponding membership functions, construct the Mamdani fuzzy rule base, determine the weighting coefficients of the Food System Stress Index (FSSI), and establish the operational assumptions adopted within the optimization model.

4.3.1. Expert panel

A purposive sampling strategy was adopted to assemble a multidisciplinary panel of six experts with complementary expertise relevant to the Strait of Hormuz case study. The panel included specialists in supply chain management, maritime transportation, logistics operations, energy markets, geopolitical risk analysis, and strategic procurement. All participants possessed more than ten years of professional or academic experience in their respective fields.

Although relatively small, expert panels comprising five to ten experts are commonly employed in fuzzy knowledge engineering and expert-based decision-support research because the objective is the systematic acquisition of specialized knowledge rather than statistical inference. The selected panel therefore provided an appropriate balance between disciplinary diversity and efficient consensus building.

The multidisciplinary composition of the panel ensured that the elicited knowledge reflected complementary operational, logistical, energy, agricultural, and geopolitical perspectives relevant to the proposed framework. This diversity was particularly important because the methodology explicitly integrates supply chain disruption assessment, downstream food-system stress evaluation, and optimization-based operational planning within a unified prescriptive analytics framework.

Finally, structured expert elicitation enabled the proposed framework to incorporate knowledge that cannot be reliably inferred from historical observations alone, thereby improving the realism, interpretability, and practical applicability of the proposed methodology under conditions of deep geopolitical uncertainty.

4.3.2. Knowledge acquisition

The expert elicitation process was conducted through three sequential phases designed to transform expert knowledge into the analytical components required by the proposed fuzzy prescriptive analytics framework.

Phase 1: Identification of Disruption Drivers

The first phase focused on identifying the principal mechanisms through which geopolitical disruptions propagate across interconnected supply chains. Based on structured expert discussions supported by the historical evidence reviewed in Section 4.2, the panel identified five disruption drivers as the principal disruption drivers affecting supply chain resilience:

- Geopolitical Tension (GT)
- Maritime Accessibility (MA)
- Energy Supply Shock (ESS)
- Logistics Delay (LD) and
- Fertilizer Input Risk (FIR)

These variables capture the principal pathways through which disruptions in the Strait of Hormuz propagate across energy systems, maritime transportation, logistics operations, agricultural input supply, and downstream food systems.

Phase 2: Specification of Linguistic Variables, Membership Functions, and FSSI Weighting

During the second phase, the selected disruption drivers were represented as fuzzy linguistic variables suitable for the Mamdani fuzzy inference system. For each input variable, the experts defined four context-specific linguistic categories representing progressively increasing levels of disruption severity:

- Low
- Moderate
- High and
- Critical

Initial triangular membership functions were proposed during structured elicitation sessions and subsequently refined through iterative expert review until consensus was achieved. Historical information concerning oil-price shocks, maritime incidents, freight-rate volatility, logistics disruptions, and fertilizer supply disturbances served as contextual evidence to support expert judgment and ensure that the membership functions reflected historically plausible disruption conditions.

During the same phase, the experts also determined the weighting coefficients of the Food System Stress Index (FSSI). The adopted weighting structure, presented in Eq. (5), reflects the consensus that the Supply Chain Disruption Risk Index (SCDRI) should receive the highest weighting because it represents the aggregated severity of geopolitical disruption. The remaining weights assigned to Energy Supply Shock (ESS) and Fertilizer Input Risk (FIR) reflect their complementary roles as the principal transmission mechanisms linking geopolitical disruption with downstream food-system stress.

The resulting membership functions and FSSI weighting coefficients were iteratively reviewed and refined until full expert consensus was achieved. The finalized specifications were subsequently incorporated into the proposed fuzzy prescriptive analytics framework, ensuring consistency between disruption assessment, downstream food-system stress evaluation, and optimization-based operational planning.

Phase 3: Development of the Fuzzy Rule Base and Operational Assumptions

The third phase focused on constructing the expert-informed Mamdani fuzzy rule base and defining the operational assumptions required by the optimization model. Linguistic IF–THEN rules were developed to describe the interactions among the five disruption drivers and their influence on the Supply Chain Disruption Risk Index (SCDRI). These rules were designed to represent realistic geopolitical disruption mechanisms while maintaining transparency and interpretability.

In parallel, the panel established the principal operational assumptions adopted within the optimization framework, including supplier behaviour under disruption, strategic inventory utilisation, emergency procurement activation, and shortage management. These assumptions ensured consistency between disruption assessment and optimization, thereby providing a coherent analytical foundation for the proposed prescriptive analytics framework.

4.3.3. Knowledge formalisation

The third phase translated the elicited expert knowledge into a formal analytical representation suitable for implementation within the proposed prescriptive analytics framework. The experts collaboratively developed a set of linguistic IF–THEN rules describing the causal relationships between the disruption drivers and the overall severity of geopolitical supply chain disruption. Rather than enumerating every theoretically possible rule combination, the objective was to construct a compact, transparent, and operationally meaningful rule base capable of representing realistic disruption scenarios.

Each rule was systematically evaluated for logical consistency, causal plausibility, and practical relevance through an iterative review process. Differences in expert opinion were resolved through structured consensus-building discussions rather than numerical voting or weighting procedures. The iterative refinement process continued until consensus was reached that the resulting rule base adequately represented the principal causal mechanisms underlying geopolitical supply chain disruptions while remaining interpretable and suitable for operational decision support.

The validated rule base was subsequently implemented within the Mamdani fuzzy inference system, which estimates the Supply Chain Disruption Risk Index (SCDRI). The resulting SCDRI is then combined with Energy Supply Shock (ESS) and Fertilizer Input Risk (FIR) through the expert-informed weighted aggregation model used to compute the Food System Stress Index (FSSI). Together, these disruption indicators provide the quantitative inputs required by the subsequent mixed-integer linear programming model, thereby establishing a coherent analytical transition from qualitative expert knowledge to quantitative operational decision-making.

4.3.4. Integration into the prescriptive analytics framework

The expert elicitation process provided the knowledge foundation underpinning every analytical component of the proposed framework. Specifically, expert knowledge was used to:

- identify the principal disruption drivers
- define the linguistic variables and triangular membership functions
- construct the Mamdani fuzzy rule base
- determine the weighting coefficients of the Food System Stress Index (FSSI)
- support the development of representative geopolitical disruption scenarios and
- establish the operational assumptions incorporated into the optimization model

Consequently, expert knowledge is embedded throughout the entire analytical workflow. It first supports the estimation of the Supply Chain Disruption Risk Index (SCDRI) through the Mamdani fuzzy inference system, then supports the computation of the Food System Stress Index (FSSI) through the expert-informed weighted aggregation model, and finally informs the optimization model through disruption-adjusted transportation costs and effective shortage penalties. This sequential transformation enables qualitative geopolitical expertise to be systematically translated into quantitative operational decisions.

Overall, the proposed methodology should be interpreted as an expert-informed fuzzy prescriptive analytics framework supported by historically plausible disruption scenarios rather than as a statistically calibrated forecasting model. By integrating structured expert elicitation, explainable fuzzy reasoning, an expert-informed weighted food-system stress assessment, and mathematical optimization, the framework provides a transparent, reproducible, and operational decision-support methodology for supporting resilient supply chain decision-making under conditions of deep geopolitical uncertainty.

4.4. Fuzzy input variables and scenario specification

The proposed analytical framework evaluates geopolitical disruption conditions using five disruption drivers that represent the principal disruption drivers through which geopolitical disruptions in the Strait of Hormuz propagate across interconnected supply systems. These variables were identified through the structured expert elicitation process, supported by historical evidence and the theoretical relationships discussed in Sections 2 and 3.

The five disruption drivers constitute the input variables of the Mamdani fuzzy inference system:

- Geopolitical Tension (GT)
- Maritime Accessibility (MA)
- Energy Supply Shock (ESS)
- Logistics Delay (LD) and
- Fertilizer Input Risk (FIR)

The Food System Stress Index (FSSI) is not treated as an independent fuzzy input variable. Instead, it is computed separately through an expert-informed weighted aggregation model using the Supply Chain Disruption Risk Index (SCDRI), Energy Supply Shock (ESS), and Fertilizer Input Risk (FIR). This modelling structure improves conceptual consistency by clearly separating disruption drivers from their downstream consequences and avoiding circular relationships within the analytical framework. Table 3 summarizes the disruption drivers and their corresponding linguistic scales.

To evaluate the behaviour of the proposed framework under alternative geopolitical conditions, three representative disruption scenarios were developed: Partial Closure, Severe Closure, and Full Closure. These scenarios represent progressively increasing levels of disruption affecting maritime transportation, energy supply, logistics operations, and fertilizer availability.

The numerical values assigned to the disruption drivers are presented in Table 4. These values represent expert-informed scenario specifications developed to evaluate the performance of the proposed framework under progressively more severe geopolitical disruption conditions. They should therefore be interpreted as plausible scenario inputs rather than observed measurements or probabilistic forecasts.

The input values presented in Table 4 constitute the scenario vectors evaluated by the Mamdani fuzzy inference system. The resulting fuzzy outputs are defuzzified to produce the Supply Chain Disruption Risk Index (SCDRI). Subsequently, the Food System Stress Index (FSSI) is computed as an expert-informed weighted aggregation of the SCDRI, Energy Supply Shock (ESS), and Fertilizer Input Risk (FIR).

Both disruption indicators are then translated into deterministic optimization parameters. The SCDRI determines the disruption-risk multiplier applied to transportation costs, whereas the FSSI modifies the effective shortage penalties associated with unmet demand. This sequential integration enables the optimization model to simultaneously consider supply chain resilience, downstream food-system stress, and economic performance under alternative geopolitical disruption scenarios.

Table 3
Fuzzy Input Variables and Linguistic Scales.

Variable	Description	Linguistic Scale
Geopolitical Tension	Degree of geopolitical escalation, military confrontation, or diplomatic instability	Low, Moderate, High, Critical
Maritime Accessibility	Degree to which vessels can safely transit the Strait of Hormuz	Open, Restricted, Disrupted, Closed
Energy Supply Shock	Magnitude of disruption affecting oil and natural gas supply	Mild, Moderate, Severe, Extreme
Logistics Delay	Degree of transportation disruption, congestion, and delivery delay	Low, Moderate, High, Critical
Fertilizer Input Risk	Risk of fertilizer shortages and fertilizer price escalation	Low, Moderate, High, Severe

Table 4
Scenario Input Values Used in the Mamdani Fuzzy Inference System.

Variable	Partial Closure	Severe Closure	Full Closure
Geopolitical Tension	35	75	95
Maritime Accessibility	40	70	95
Energy Supply Shock	35	65	90
Logistics Delay	40	70	95
Fertilizer Input Risk	40	70	95

This modelling structure is consistent with previous research showing that energy supply disruptions and fertilizer availability are among the principal transmission mechanisms through which geopolitical shocks affect downstream food systems [30]. By explicitly linking disruption assessment, downstream food-system stress evaluation, and optimization-based operational planning, the proposed framework provides an integrated representation of how geopolitical disruptions propagate across interconnected energy, logistics, fertilizer, and food systems.

The *Partial Closure* scenario represents a moderate deterioration of operating conditions without a complete interruption of maritime traffic. Under this scenario, vessel inspections increase, transit times become longer, insurance premiums rise, and transportation capacity is partially reduced. Energy and fertilizer flows continue, although at reduced efficiency.

The *Severe Closure* scenario represents substantial operational restrictions affecting maritime transportation and regional energy flows. Shipping capacity is significantly reduced, logistics delays become widespread, and supply uncertainty increases across multiple sectors. Under these conditions, the optimization framework progressively recommends resilience-oriented strategies, including supplier diversification, strategic inventory deployment, and alternative transportation arrangements.

The *Full Closure* scenario represents the complete closure of the Strait of Hormuz. Maritime exports from Gulf suppliers become unavailable, prompting the optimization model to activate alternative supply sources, strategic inventories, non-Gulf suppliers, emergency procurement mechanisms, and revised transportation plans. This scenario corresponds to the most severe disruption condition considered within the proposed analytical framework.

4.5. Membership function design and expert-informed specification

The proposed fuzzy prescriptive analytics framework represents the five geopolitical disruption drivers using triangular membership functions. These membership functions constitute the input representation of the Mamdani fuzzy inference system, transforming quantitative and qualitative disruption information into linguistic variables used to estimate the Supply Chain Disruption Risk Index (SCDRI).

Several membership-function structures were evaluated during the framework development process, including Gaussian, generalized bell-shaped, trapezoidal, and triangular functions. Following expert consultation and comparative evaluation of alternative membership-function structures, triangular membership functions were selected because they provided the best balance between interpretability, computational simplicity, and modelling flexibility. Their piecewise linear structure facilitates transparent rule construction, simplifies expert knowledge elicitation, and enables decision-makers to understand the contribution of individual disruption drivers without introducing unnecessary mathematical complexity. The selection was therefore based on expert evaluation of interpretability, transparency, and computational efficiency rather than statistical goodness-of-fit criteria.

Triangular membership functions are particularly appropriate for geopolitical disruption assessment because disruption intensity rarely changes abruptly. Instead, geopolitical conditions typically evolve gradually, with neighbouring linguistic states partially overlapping. This overlap enables the fuzzy inference system to represent uncertainty and ambiguity more realistically while avoiding the rigid threshold effects commonly associated with deterministic classifications.

Each disruption variable is represented by a set of overlapping triangular membership functions defined through linguistic terms. The corresponding triangular fuzzy numbers are parameterised by three characteristic points:

$$\widetilde{X} = (x_L|x_M|x_U) \tag{15}$$

where:

- x_L denotes the lower-bound (optimistic) estimate
- x_M denotes the most representative estimate
- x_U denotes the upper-bound (pessimistic) estimate

The membership functions and their linguistic boundaries were established through the structured expert elicitation procedure described in Section 4.3. During this process, the experts considered historical evidence concerning energy-market disruptions, maritime security incidents, freight-rate volatility, fertilizer supply disturbances, and logistics delays to ensure that the linguistic boundaries reflected historically plausible geopolitical conditions. Consequently, the membership functions should be interpreted as expert-informed model specifications rather than statistically estimated probability distributions.

Tables 5 and 6 present representative linguistic categories and the corresponding triangular fuzzy numbers for two of the disruption variables. Table 5 summarizes the linguistic representation of Energy Supply Shock (ESS), whereas Table 6 presents the membership-function specification for Logistics Delay (LD).

Fig. 1 illustrates the triangular membership functions for the Fertilizer Input Risk (FIR) variable. Similar triangular membership-function structures are employed for the remaining disruption drivers. The overlapping linguistic categories enable smooth transitions between successive disruption levels, allowing the fuzzy inference system to represent geopolitical uncertainty more realistically than conventional crisp threshold-based classifications.

The resulting membership-function architecture provides the input representation for the disruption assessment stage of the proposed framework. By systematically transforming uncertain geopolitical information into interpretable linguistic variables, it enables the estimation of the Supply Chain Disruption Risk Index (SCDRI) through the Mamdani fuzzy inference system. The computed SCDRI is subsequently combined with Energy Supply Shock (ESS) and Fertilizer Input Risk (FIR) through the expert-informed weighted aggregation model to determine the Food System Stress Index (FSSI). Finally, both disruption indicators are translated into deterministic optimization parameters governing transportation costs, effective shortage penalties, supplier selection, strategic inventory deployment, emergency procurement, and other resilience-oriented operational decisions.

Table 5
Representative Triangular Membership Functions for Energy Supply Shock.

Linguistic Term	Triangular Fuzzy Number
Mild	(0, 10, 20)
Moderate	(15, 30, 45)
Severe	(40, 60, 80)
Extreme	(70, 90, 100)

Table 6
Representative Triangular Membership Functions for Logistics Delay.

Linguistic Term	Triangular Fuzzy Number
Low	(0, 15, 30)
Moderate	(20, 40, 60)
High	(50, 70, 90)
Critical	(80, 95, 100)

4.6. *Fuzzy rule base*

The fuzzy rule base constitutes the core reasoning mechanism of the proposed fuzzy prescriptive analytics framework. It transforms combinations of geopolitical disruption drivers into linguistic assessments of supply chain disruption severity through a structured collection of expert-defined IF–THEN rules. Unlike statistical or machine-learning approaches that infer relationships directly from historical observations, the proposed rule base explicitly represents expert knowledge, providing a transparent and explainable reasoning process under conditions of limited historical data and high geopolitical uncertainty.

The Mamdani fuzzy inference system combines the five disruption drivers: Geopolitical Tension (GT), Maritime Accessibility (MA), Energy Supply Shock (ESS), Logistics Delay (LD), and Fertilizer Input Risk (FIR), to estimate the Supply Chain Disruption Risk Index (SCDRI). Each rule represents a plausible geopolitical disruption scenario by mapping a specific combination of linguistic input variables to one of the linguistic output categories describing the overall disruption severity. A representative rule is formulated as follows:

IF Geopolitical Tension is *Critical* AND Maritime Accessibility is *Closed* AND Energy Supply Shock is *Extreme* AND Logistics Delay is *Critical* AND Fertilizer Input Risk is *Severe*, THEN the Supply Chain Disruption Risk Index (SCDRI) is Extreme.

The expert-informed rule base was developed through the structured expert elicitation process described in Section 4.3. During this process, the experts evaluated the relative importance and interactions of the disruption drivers using historical geopolitical events, maritime security incidents, energy-market disruptions, fertilizer supply disturbances, and logistics disruptions as contextual references. Consequently, the resulting rules represent expert-informed causal reasoning rather than statistically calibrated relationships.

Given five input variables, each represented by four linguistic terms, the complete combinatorial rule space comprises $4^5 = 1,024$ possible rules. Constructing and validating every possible rule would substantially increase model complexity without providing additional practical value. Therefore, the proposed framework employs a compact expert-designed rule base containing only the combinations considered operationally meaningful for the disruption scenarios examined in this study. This approach preserves model transparency while substantially reducing rule-base complexity.

The inference process follows the standard Mamdani fuzzy inference methodology. For each activated rule, the antecedent conditions are evaluated using the minimum operator to determine the rule firing strength consistent with the standard Mamdani max–min inference mechanism. The outputs of all activated rules are subsequently aggregated using the maximum operator, producing a composite fuzzy representation of the overall disruption severity. Finally, the aggregated fuzzy output is converted into a crisp Supply Chain Disruption Risk Index (SCDRI) through the centroid defuzzification method.

The computed SCDRI constitutes the principal output of the fuzzy inference system. Subsequently, it is combined with Energy Supply Shock (ESS) and Fertilizer Input Risk (FIR) through the expert-informed weighted aggregation model to compute the Food System Stress Index (FSSI). Both disruption indicators are then translated into deterministic optimization parameters, where the SCDRI adjusts transportation costs through the disruption-risk multiplier and the FSSI modifies the effective shortage penalties associated with unmet demand.

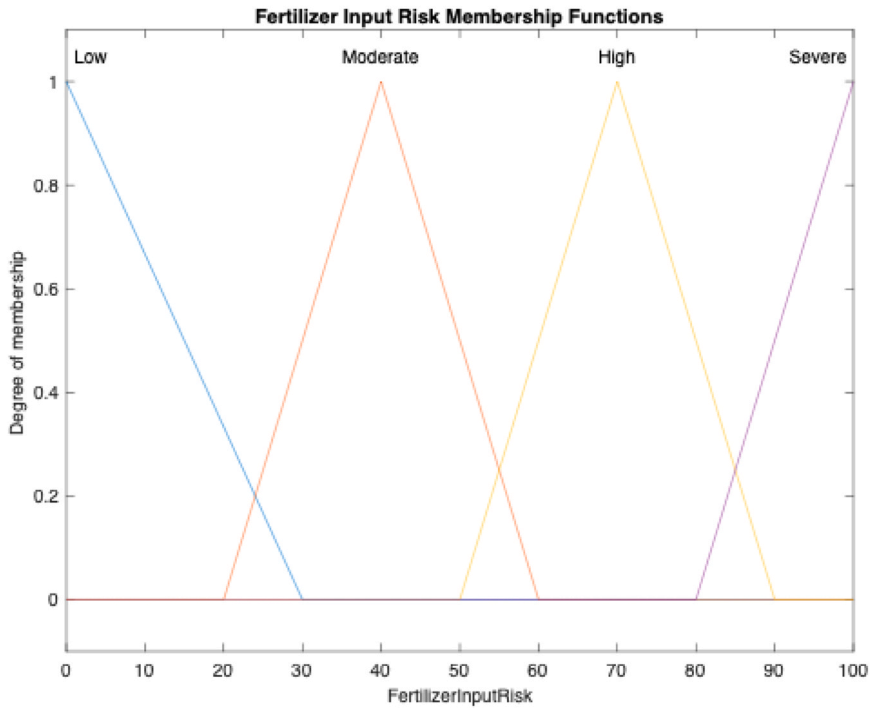

Fig. 1. Triangular membership functions for Fertilizer Input Risk.

The resulting analytical structure provides a transparent, explainable, and operationally applicable decision-support methodology integrating expert knowledge, fuzzy reasoning, downstream food-system stress assessment, and mathematical optimization. By maintaining a clear separation between disruption assessment and operational optimization, the proposed framework avoids the "black-box" characteristics often associated with purely data-driven approaches while providing a coherent methodology for translating qualitative geopolitical expertise into resilience-oriented operational decisions under conditions of deep geopolitical uncertainty.

4.7. Framework implementation logic

The proposed framework follows a sequential prescriptive analytics architecture that integrates fuzzy reasoning with optimization-based decision support. Rather than treating disruption assessment and operational planning as separate processes, the framework establishes a continuous analytical workflow in which disruption indicators are systematically translated into deterministic optimization parameters. This sequential integration enables qualitative geopolitical assessments to be transformed into resilience-oriented operational decisions under conditions of deep uncertainty.

The implementation begins with the evaluation of the five geopolitical disruption drivers: Geopolitical Tension (GT), Maritime Accessibility (MA), Energy Supply Shock (ESS), Logistics Delay (LD), and Fertilizer Input Risk (FIR). These variables are first transformed into linguistic representations through the triangular membership functions described in Section 4.5. The Mamdani fuzzy inference system subsequently evaluates the expert-defined rule base to estimate the Supply Chain Disruption Risk Index (SCDRI).

The computed SCDRI provides an integrated measure of the overall severity of geopolitical disruption and serves two complementary functions within the proposed framework. First, it is combined with Energy Supply Shock (ESS) and Fertilizer Input Risk (FIR) through the expert-informed weighted aggregation model to compute the Food System Stress Index (FSSI). Second, the SCDRI determines the disruption-risk multiplier applied to transportation costs, as defined in Eq. (1).

The Food System Stress Index (FSSI) quantifies the level of downstream food-system stress resulting from geopolitical disruption. Rather than appearing as an independent optimization objective, it influences the optimization model through the effective shortage penalty defined in Eq. (7). This formulation links downstream food-system stress directly to shortage costs, enabling the optimization model to place progressively greater emphasis on demand satisfaction as food-system stress increases.

Following the computation of the disruption-adjusted transportation costs and effective shortage penalties, the mixed-integer linear programming model is solved. These deterministic optimization parameters consist primarily of disruption-adjusted transportation costs and effective shortage penalties. The optimization simultaneously determines supplier activation, shipment allocation, transportation planning, strategic inventory deployment, emergency procurement activation, emergency procurement quantities, and potential unmet demand while minimizing the total disruption-adjusted operating cost subject to the operational constraints of the supply chain.

The framework is evaluated under three representative geopolitical disruption scenarios: Partial Closure, Severe Closure, and Full Closure of the Strait of Hormuz. Each scenario results in different values of the SCDRI and FSSI, resulting in different transportation costs, shortage penalties, supplier selections, inventory utilization strategies, emergency procurement decisions, and overall operating costs. Consequently, the optimization model generates operational plans that adapt automatically to the estimated disruption conditions.

Fig. 2 summarizes the complete implementation logic of the proposed framework. The architecture illustrates the sequential interaction among disruption assessment, fuzzy reasoning, downstream food-system stress assessment, optimization parameterization, and prescriptive decision support. This modular implementation improves

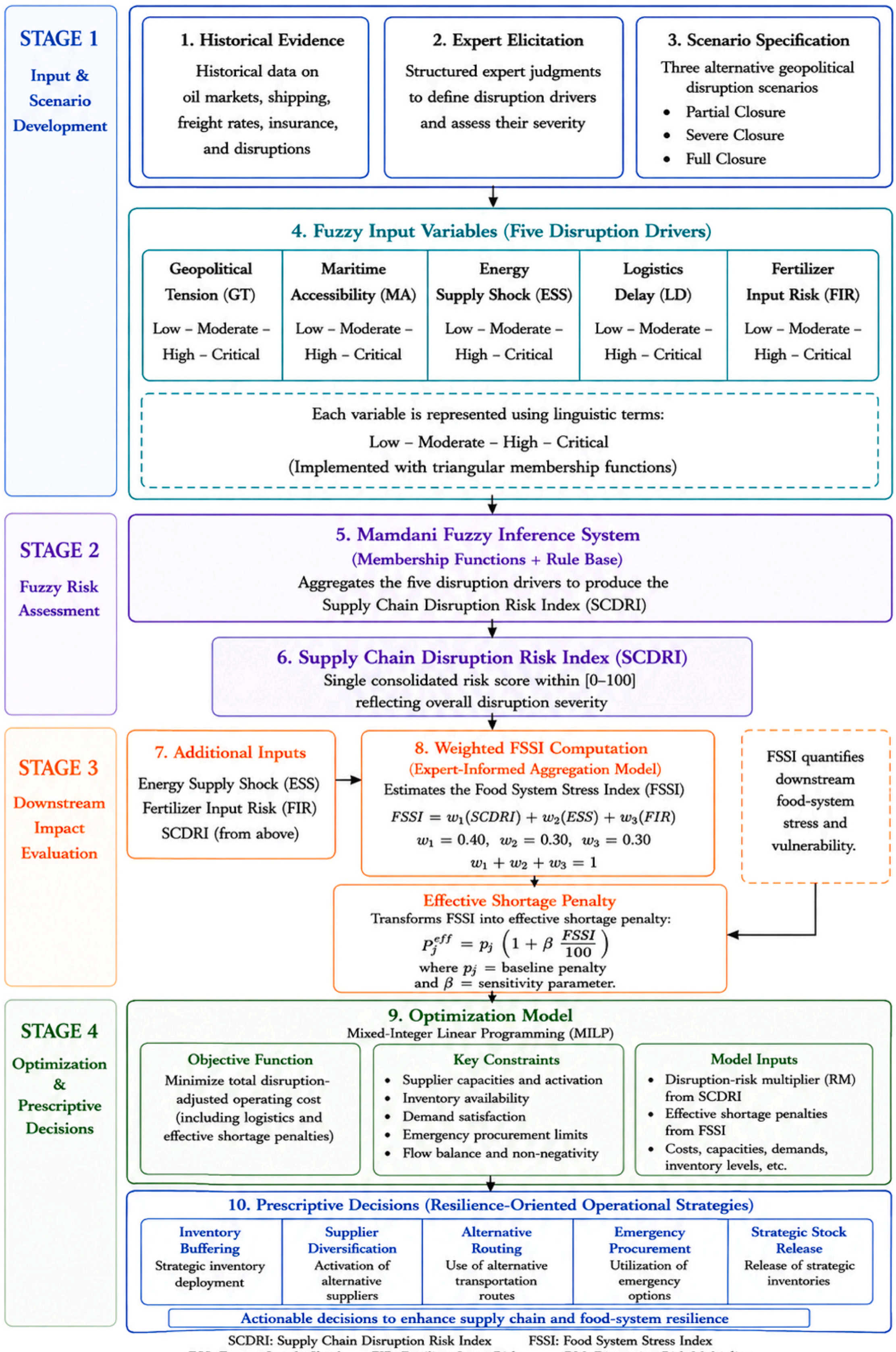

Fig. 2. Integrated Fuzzy Prescriptive Analytics Framework for Supply Chain Resilience under Geopolitical Disruptions.

transparency, facilitates future methodological extensions, and enables individual components of the framework to be updated independently as additional data or expert knowledge become available.

For transparency and reproducibility, all numerical input parameters and optimization datasets employed in the MATLAB implementation are reported in Appendix B. These datasets enable independent replication and validation of the computational experiments presented in this study.

Overall, the proposed implementation logic demonstrates how explainable fuzzy reasoning and deterministic optimization operate as complementary components of a unified prescriptive analytics architecture. By systematically transforming qualitative geopolitical expertise into quantitative operational decisions, the framework provides a transparent, reproducible, and operationally applicable methodology for resilient supply chain planning under conditions of deep geopolitical uncertainty.

4.8. Supply Chain Disruption Risk Assessment (SCDRI)

The Mamdani fuzzy inference system was applied to the three geopolitical disruption scenarios defined in Section 4.4 to evaluate the overall severity of supply chain disruption. The five disruption drivers: Geopolitical Tension (GT), Maritime Accessibility (MA), Energy Supply Shock (ESS), Logistics Delay (LD), and Fertilizer Input Risk (FIR)**,** were fuzzified using the triangular membership functions described in Section 4.5 and evaluated through the expert-defined rule base presented in Section 4.6.

The aggregated fuzzy outputs were converted into crisp values using the centroid defuzzification method, producing the Supply Chain Disruption Risk Index (SCDRI). The SCDRI provides a composite measure of disruption severity on a continuous scale from 0 to 100, where higher values indicate progressively more severe disruptions across interconnected energy, transportation, logistics, and supply-chain systems.

Within the proposed framework, the SCDRI performs two complementary functions. First, it constitutes the principal disruption indicator used in the computation of the Food System Stress Index (FSSI) through the expert-informed weighted aggregation model described in Section 3.4.1. Second, it determines the disruption-risk multiplier applied to transportation costs within the optimization model, thereby allowing disruption severity to directly influence operational planning through disruption-adjusted logistics costs.

The results presented in Table 7 demonstrate a progressive increase in disruption severity across the three geopolitical disruption scenarios. The reported values should not be interpreted as predictions of future geopolitical events, nor as evidence of a universal nonlinear amplification mechanism. Under moderate disruption conditions, the fuzzy inference system generates outputs that remain close to the underlying expert assessments because the activated rules are largely consistent. More pronounced nonlinear behaviour emerges only under extreme disruption conditions, when multiple high-risk inputs are activated simultaneously, strengthening the interactions among fuzzy rules and producing greater deviations from the underlying input values.

Under the Partial Closure scenario, the SCDRI reaches 35.00, corresponding to a Moderate disruption level. Although maritime transportation remains operational, increased vessel inspections, longer transit times, higher insurance premiums, and moderate energy-market volatility begin to affect overall supply chain performance and resilience.

Table 7
Supply Chain Disruption Risk Assessment Results.

Scenario	SCDRI	Risk Classification
Partial Closure	35.00	Moderate
Severe Closure	60.00	Severe
Full Closure	86.49	Extreme

Under the Severe Closure scenario, the SCDRI increases to 60.00, indicating a Severe disruption level. The deterioration of maritime accessibility, combined with increasing logistics delays and significant disruptions in energy and fertilizer supply, substantially reduces supply chain resilience. The resulting SCDRI reflects the combined interaction of multiple disruption drivers rather than the isolated effect of any individual factor.

Under the Full Closure scenario, the SCDRI reaches 86.49, corresponding to an Extreme disruption level. The complete interruption of maritime transportation through the Strait of Hormuz generates widespread disruption across interconnected energy, logistics, and agricultural supply systems. Under these conditions, resilience-oriented operational strategies—including supplier diversification, strategic inventory deployment, emergency procurement, and alternative transportation arrangements—become essential for maintaining supply continuity. The relatively larger increase in the SCDRI under this scenario illustrates the stronger interactions among multiple disruption drivers captured by the expert-informed fuzzy rule base under extreme geopolitical conditions.

It should be emphasized that the SCDRI is not intended to estimate the probability of future geopolitical events. Instead, it provides a structured, transparent, and interpretable disruption indicator that transforms expert-informed geopolitical assessments into quantitative measures suitable for operational decision support. Within the proposed framework, the SCDRI therefore serves as the analytical interface between qualitative disruption assessment and quantitative optimization, enabling resilience-oriented operational planning under conditions of deep geopolitical uncertainty.

4.8.1. Food System Stress Assessment (FSSI)

While the Supply Chain Disruption Risk Index (SCDRI) quantifies the overall severity of geopolitical supply chain disruption, the Food System Stress Index (FSSI) evaluates the level of downstream food-system stress resulting from geopolitical disruption. The FSSI captures how geopolitical disruption propagates through interconnected energy and agricultural supply systems, ultimately affecting food availability, agricultural production, and supply continuity.

Within the proposed framework, the FSSI is not estimated through fuzzy inference. Instead, it is computed as an expert-informed weighted aggregation model based on three complementary components:

- the Supply Chain Disruption Risk Index (SCDRI)
- Energy Supply Shock (ESS), and
- Fertilizer Input Risk (FIR)

These variables represent complementary dimensions of downstream food-system stress. The SCDRI captures the aggregated severity of geopolitical disruption, whereas ESS and FIR represent the two principal transmission mechanisms through which geopolitical disruptions affect agricultural production and food availability.

The relative contribution of each component was established through the structured expert elicitation process described in Section 4.3. Based on expert consensus, the weighting coefficients adopted in this study are presented in Eq. (3) and satisfy the normalization constraint defined in Eq. (4). Accordingly, the Food System Stress Index (FSSI) is computed using the weighted aggregation model defined in Eq. (6).

The adopted weighting structure reflects the expert assessment that overall disruption severity exerts the strongest influence on downstream food-system stress while preserving the direct contributions of energy availability and fertilizer supply as the principal transmission mechanisms linking geopolitical disruption with food-system resilience.

The calculated FSSI values are subsequently classified into four qualitative categories (*Low, Moderate, Severe,* and *Extreme*) to provide an interpretable assessment of downstream food-system stress.

The results indicate a substantial increase in downstream food-system stress as geopolitical disruption becomes progressively more severe. Under the Partial Closure scenario, food systems remain relatively resilient despite moderate disruption in maritime transportation and energy markets. Under the Severe Closure scenario, increasing instability in energy supply and fertilizer availability substantially reduces food-system resilience. Under the Full Closure scenario, the simultaneous disruption of maritime transportation, energy supply, and fertilizer availability generates Extreme food-system stress, highlighting the strong interdependence between geopolitical stability, agricultural production, and global food security. The progressive increase in the FSSI across the three scenarios demonstrates that downstream food-system stress intensifies systematically as geopolitical disruption becomes more severe.

Within the proposed prescriptive analytics framework, the FSSI is not treated as an independent optimization objective. Instead, it influences the optimization model by modifying the effective shortage penalty associated with unmet demand, as defined in Eq. (7). Consequently, increasing FSSI values increase the economic consequences of shortages, allowing downstream food-system stress to influence supplier activation, strategic inventory deployment, transportation planning, emergency procurement, and shortage allocation while preserving the linear structure of the mixed-integer linear programming model.

Together, the SCDRI and FSSI establish the analytical link between qualitative geopolitical disruption assessment and optimization-based operational decision support. The Mamdani fuzzy inference system estimates the overall disruption severity through the Supply Chain Disruption Risk Index (SCDRI), while the Food System Stress Index (FSSI) quantifies the downstream consequences of disruption through an expert-informed weighted aggregation model. These disruption indicators are subsequently translated into deterministic optimization parameters governing transportation costs and effective shortage penalties within the optimization model. This sequential integration enables the proposed framework to generate resilience-oriented operational decisions that simultaneously consider supply chain continuity, downstream food-system resilience, and economic performance under alternative geopolitical disruption scenarios.

4.9. Operational implications of Food System Stress

The Food System Stress Index (FSSI) provides an integrated measure of the downstream consequences of geopolitical disruptions for food-system resilience. While the Supply Chain Disruption Risk Index (SCDRI) measures the overall severity of geopolitical disruption across interconnected supply-chain systems, the FSSI evaluates how these disruptions propagate through energy markets and fertilizer supply chains, ultimately influencing agricultural production, food availability, and supply continuity.

The results presented in Table 8 demonstrate that downstream food-system stress increases progressively as geopolitical disruption becomes more severe. Under the Partial Closure scenario, the calculated FSSI indicates a Moderate level of food-system stress. Although transportation costs increase and energy markets experience temporary instability, agricultural supply chains remain largely functional. Consequently, food production and distribution continue with relatively limited operational disruption.

Table 8
Food System Stress Assessment Results.

Scenario	SCDRI	Energy Supply Shock	Fertilizer Input Risk	Food System Stress Index	Food System Stress Class
Partial Closure	35	35	40	36.5	Moderate
Severe Closure	60	65	70	64.5	Severe
Full Closure	86.49	90	95	90.10	Extreme

As disruption severity increases under the Severe Closure scenario, the FSSI rises substantially, reflecting the combined effects of energy supply instability, reduced fertilizer availability, and increasing logistics constraints. These interacting factors increase agricultural production costs, reduce productivity, and weaken the resilience of downstream food systems. Although food distribution remains feasible, maintaining supply continuity requires greater reliance on strategic inventories, supplier diversification, and alternative sourcing strategies.

Under the Full Closure scenario, the FSSI reaches the Extreme category, indicating severe downstream consequences for food-system resilience. The simultaneous disruption of maritime transportation, energy supply, and fertilizer availability substantially reduces the capacity of agricultural supply chains to respond effectively. Under these conditions, food availability declines, affordability deteriorates, and production capacity becomes increasingly constrained, requiring comprehensive resilience strategies throughout the supply network.

Within the proposed prescriptive analytics framework, the FSSI is not treated as an independent optimization objective. Instead, it influences the optimization model through the effective shortage penalty associated with unmet demand, as defined in Eq. (7). Consequently, increasing FSSI values increase the economic consequences of shortages, enabling downstream food-system stress to influence operational decisions while preserving the linear structure of the mixed-integer linear programming model.

As food-system stress intensifies, the optimization model progressively favours solutions that maintain supply continuity. Higher shortage penalties encourage the activation of additional suppliers, greater utilization of strategic inventories, increased emergency procurement, and the acceptance of higher transportation costs whenever these actions reduce the risk of unmet demand.

From a managerial perspective, these findings demonstrate that resilient supply chain planning should extend beyond the traditional objective of logistics cost minimization. Decision-makers should explicitly consider the broader systemic consequences of supply disruptions, particularly their cascading effects on interconnected energy, agricultural, and food systems. Incorporating downstream food-system stress into the optimization process enables alternative operational strategies to be evaluated not only from an economic perspective but also from the perspective of societal resilience and food security.

Overall, the integration of the Food System Stress Index (FSSI) significantly enhances the prescriptive capabilities of the proposed framework. By linking downstream food-system stress to operational optimization through economically interpretable shortage penalties, the framework provides a comprehensive decision-support methodology capable of supporting operational decisions that balance transportation costs, supply continuity, strategic inventory utilization, emergency procurement, and food-system resilience under alternative geopolitical disruption scenarios.

4.10. Prescriptive decision implications

The optimization results demonstrate how the proposed framework systematically translates qualitative geopolitical disruption assessments into quantitative operational decisions. Unlike conventional cost-minimization models, which primarily seek the least expensive allocation of available resources, the proposed framework explicitly incorporates both disruption severity and downstream food-system stress into the operational planning process. Consequently, resilience-oriented decisions are determined by jointly considering transportation costs, supply continuity, inventory availability, emergency procurement, and the broader systemic consequences of unmet demand.

Within the proposed framework, the Supply Chain Disruption Risk Index (SCDRI) and the Food System Stress Index (FSSI) influence the optimization model through two complementary mechanisms. The

SCDRI is transformed into the disruption-risk multiplier, which proportionally increases transportation costs as disruption severity intensifies. In parallel, the FSSI modifies the effective shortage penalty associated with unmet demand, thereby increasing the economic consequences of shortages under conditions of heightened food-system stress. This parameterization enables the optimization model to generate scenario-specific operational strategies while preserving the linear mathematical structure of the mixed-integer linear programming formulation.

The resulting operational strategies vary according to the severity of the geopolitical disruption. Under the Partial Closure scenario, the optimization solution relies primarily on the existing supplier network, supported by selective inventory deployment and limited supplier diversification. These measures are sufficient to maintain supply continuity while limiting additional operating costs.

As disruption severity increases under the Severe Closure scenario, the optimization progressively activates additional suppliers, expands the use of strategic inventories, and reallocates shipments to reduce dependence on disrupted transportation corridors. Although these strategies increase operating costs, they substantially reduce the likelihood of shortages and improve the overall resilience of the supply chain.

Under the Full Closure scenario, the optimization identifies a fundamentally different operational strategy. Alternative suppliers are activated, strategic inventories are extensively deployed, emergency procurement mechanisms are utilised, and transportation flows are reconfigured towards alternative supply routes. The higher effective shortage penalties generated by the FSSI make unmet demand increasingly costly, encouraging the optimization model to favour solutions that maintain supply continuity despite significantly higher logistics costs.

From a managerial perspective, these findings demonstrate that resilient supply chain planning should extend beyond the traditional objective of logistics cost minimization. Decision-makers should explicitly evaluate the economic consequences of transportation disruptions and the broader systemic implications of supply shortages for interconnected energy, agricultural, and food systems. By integrating disruption severity and downstream food-system stress within a unified optimization framework, the proposed methodology provides a more comprehensive basis for evaluating alternative resilience strategies under conditions of geopolitical uncertainty.

Overall, the proposed fuzzy prescriptive analytics framework establishes a transparent analytical link between disruption assessment and operational decision-making. The Mamdani fuzzy inference system estimates the overall severity of geopolitical disruption through the Supply Chain Disruption Risk Index (SCDRI), while the Food System Stress Index (FSSI) quantifies downstream food-system stress through an expert-informed weighted aggregation model. These disruption indicators are subsequently translated into deterministic optimization parameters that guide transportation planning, supplier selection, strategic inventory deployment, emergency procurement, and shortage management. This sequential integration enables organizations to proactively adapt operational strategies as geopolitical conditions evolve, thereby strengthening both supply chain resilience and downstream food-system resilience.

4.11. Optimization results

The mixed-integer linear programming (MILP) model was solved independently for each of the three geopolitical disruption scenarios using the disruption indicators generated by the proposed analytical framework. For each scenario, the Supply Chain Disruption Risk Index (SCDRI) determines the disruption-risk multiplier applied to transportation costs, whereas the Food System Stress Index (FSSI) determines the effective shortage penalties associated with unmet demand. This sequential integration enables the optimization model to adapt operational decisions according to both disruption severity and downstream

Table 9
Optimization Results under Geopolitical Disruption Scenarios.

Scenario	SCDRI	FSSI	Effective Shortage Penalty USD per Unit	Optimal Total Cost USD	Selected Route Structure	Strategic Inventory Released Units	Supplier Diversification Level	Emergency Route Activated	Recommended Resilience Strategy
Partial Closure	35	37	682,5	288,055	Hormuz maritime route + Non-Gulf / Mediterranean supply	250	High	No	Increase safety stock and pre-book alternative freight capacity
Severe Closure	60	65	1316	359,570	Hormuz maritime route + Pipeline-linked corridor + Non-Gulf / Mediterranean supply	370	Very High	No	Activate supplier diversification and prioritize critical goods
Full Closure	86.49	90	2281	442,482	Pipeline-linked corridor + Emergency external procurement	520	Very High	Yes	Emergency procurement and strategic inventory release

food-system stress.

The optimization simultaneously determines supplier activation, shipment allocation, transportation planning, strategic inventory deployment, emergency procurement activation, emergency procurement quantities, and potential unmet demand while minimizing the total disruption-adjusted operating cost. The resulting optimal solutions are summarized in Table 9. Effective shortage penalty values correspond to the FSSI-adjusted shortage penalties defined in Eq. (7).

The optimization results reveal a clear transition from cost-efficient operations to resilience-oriented planning as geopolitical disruption becomes progressively more severe. As the disruption level increases from Partial Closure to Severe Closure and ultimately Full Closure, both the Supply Chain Disruption Risk Index (SCDRI) and the Food System Stress Index (FSSI) increase substantially, leading to higher effective shortage penalties and progressively more comprehensive resilience strategies. Total operating costs increase from USD 288,055 under the Partial Closure scenario to USD 359,570 under Severe Closure and USD 442,482 under Full Closure. These increases reflect the implementation of increasingly sophisticated resilience measures rather than operational inefficiency.

Under the Partial Closure scenario, the optimization relies primarily on the existing maritime transportation network through the Strait of Hormuz, complemented by non-Gulf supply sources. Strategic inventory deployment remains limited, no emergency routes are activated, and the optimization recommends maintaining additional safety stock while reserving alternative transportation capacity as a precautionary resilience measure. The relatively moderate values of the SCDRI and FSSI produce only limited increases in transportation costs and effective shortage penalties, allowing supply continuity to be maintained without major structural adjustments.

Under the Severe Closure scenario, the optimization recommends a substantially more diversified supply strategy. Pipeline-linked suppliers are activated together with non-Gulf suppliers, while strategic inventory deployment increases considerably to compensate for the deterioration of maritime transportation reliability. The higher disruption-risk multiplier increases transportation costs, whereas the higher FSSI significantly raises the effective shortage penalties. Consequently, the optimization prioritizes supplier diversification and the allocation of available resources to critical demand while maintaining uninterrupted supply without activating emergency transportation routes.

The Full Closure scenario requires a fundamentally different operational configuration. Maritime transportation through the Strait of Hormuz becomes unavailable, forcing the optimization model to rely primarily on pipeline-linked transportation corridors together with emergency external procurement. Strategic inventory utilization reaches its highest level, emergency routes are activated, and supplier diversification remains very high. At the same time, the elevated value of the Food System Stress Index generates the highest effective shortage penalties, making unmet demand economically unacceptable. As a result, the optimization favours higher transportation and procurement costs in order to preserve supply continuity and minimize the broader consequences of shortages for downstream food systems.

An important finding is that no unmet demand occurs under any of the three disruption scenarios. Rather than accepting shortages, the optimization model progressively compensates for increasing disruption through supplier diversification, transportation reconfiguration, strategic inventory deployment, and emergency procurement. This behaviour demonstrates the effectiveness of the proposed resilience strategy in maintaining operational continuity despite progressively deteriorating geopolitical conditions.

From a managerial perspective, the results demonstrate that resilient supply chain planning should extend beyond traditional logistics cost minimization. As geopolitical disruption intensifies, organizations benefit from progressively adopting supplier diversification, strategic inventory utilization, transportation flexibility, and emergency procurement. The proposed framework enables decision-makers to identify when these resilience measures become economically justified by explicitly incorporating both disruption severity and downstream food-system stress into the optimization process.

Overall, the optimization results confirm the effectiveness of the proposed fuzzy prescriptive analytics framework. By integrating explainable fuzzy reasoning, expert-informed downstream food-system stress assessment, and mixed-integer linear programming, the framework systematically translates qualitative geopolitical disruption scenarios into quantitative operational decisions that balance transportation costs, supplier diversification, strategic inventory utilization, emergency procurement, and supply continuity. The resulting decision-support methodology extends conventional supply chain optimization by explicitly incorporating resilience considerations into operational planning under conditions of deep geopolitical uncertainty.

Finally, the results reinforce the well-established trade-off between operational efficiency and resilience. Although supplier diversification, strategic inventories, transportation flexibility, and emergency procurement increase operating costs under severe disruption scenarios, they substantially improve supply continuity and reduce the systemic consequences of geopolitical shocks. These findings are consistent with the broader supply chain resilience literature, which identifies flexibility, redundancy, and adaptive sourcing as essential capabilities for managing high-impact, low-probability disruptions [43,44].

4.12. Sensitivity analysis

A sensitivity analysis was conducted to evaluate the robustness of the proposed fuzzy prescriptive analytics framework and to investigate how moderate variations in the principal disruption drivers affect disruption assessment, downstream food-system stress, and the resulting operational decisions. The objective was to examine whether the framework produces stable and consistent recommendations under moderate perturbations of the disruption drivers while remaining sufficiently responsive to meaningful changes in geopolitical conditions.

The analysis was performed by increasing each disruption driver individually by 20%, while maintaining all remaining variables at their baseline values. The five disruption drivers considered were:

- Geopolitical Tension (GT)
- Maritime Accessibility (MA)
- Energy Supply Shock (ESS)
- Logistics Delay (LD) and
- Fertilizer Input Risk (FIR)

For each perturbation, the Mamdani fuzzy inference system was re-evaluated to estimate an updated Supply Chain Disruption Risk Index (SCDRI). The revised SCDRI was subsequently combined with the corresponding values of Energy Supply Shock (ESS) and Fertilizer Input Risk (FIR) through the expert-informed weighted aggregation model to estimate the Food System Stress Index (FSSI). The updated disruption indicators were then translated into optimization parameters by recalculating the disruption-risk multiplier and the effective shortage penalties before solving the mixed-integer linear programming model.

This sequential procedure made it possible to evaluate the influence of individual disruption drivers on transportation costs, effective shortage penalties, supplier activation, strategic inventory deployment, emergency procurement decisions, and total operating costs. Because both the fuzzy inference system and the optimization model exhibit threshold behaviour, moderate perturbations do not necessarily propagate to all operational decisions. In several cases, the input changes remain within the same fuzzy regions or do not modify the optimization parameters sufficiently to alter the optimal solution. Consequently, some perturbations produce measurable changes in the disruption indicators while leaving the optimal operational strategy unchanged.

The results are sumarized at Table 10 and reveal distinct sensitivity patterns across the three geopolitical disruption scenarios.

Table 10
Sensitivity Analysis Results (+20% Input Perturbations).

Scenario	Perturbed driver	Input Base → New	SCDRI Base → New (Δ)	FSSI Base → New (Δ)	Cost (USD) Base → New (Δ)	Effective shortage penalty (USD/unit)	Shortage units Base → New (Δ)	Inventory released Base → New	Emergency procurement Base → New	Emergency route	Recommended strategy
Partial Closure	Geopolitical Tension	35 → 42	35.00 → 35.00 (+0.00)	36.50 → 36.50 (+0.00)	288,055 → 288,055 (+0)	682.50	0 → 0 (+0)	250 → 250	0 → 0	No	Inventory buffering and contingency planning
Partial Closure	Maritime Accessibility	40 → 48	35.00 → 35.00 (+0.00)	36.50 → 36.50 (+0.00)	288,055 → 288,055 (+0)	682.50	0 → 0 (+0)	250 → 250	0 → 0	No	Inventory buffering and contingency planning
Partial Closure	Energy Supply Shock	35 → 42	35.00 → 35.00 (+0.00)	36.50 → 38.60 (+2.10)	288,055 → 288,055 (+0)	693.00	0 → 0 (+0)	250 → 250	0 → 0	No	Inventory buffering and contingency planning
Partial Closure	Logistics Delay	40 → 48	35.00 → 35.00 (+0.00)	36.50 → 36.50 (+0.00)	288,055 → 288,055 (+0)	682.50	0 → 0 (+0)	250 → 250	0 → 0	No	Inventory buffering and contingency planning
Partial Closure	Fertilizer Input Risk	40 → 48	35.00 → 35.00 (+0.00)	36.50 → 38.90 (+2.40)	288,055 → 288,055 (+0)	694.50	0 → 0 (+0)	250 → 250	0 → 0	No	Inventory buffering and contingency planning
Severe Closure	Geopolitical Tension	75 → 90	60.00 → 71.17 (+11.17)	64.50 → 68.97 (+4.47)	359,570 → 378,444 (+18,874)	1351.75	0 → 0 (+0)	370 → 370	0 → 0	No	Supplier diversification and alternative routing
Severe Closure	Maritime Accessibility	70 → 84	60.00 → 60.00 (+0.00)	64.50 → 64.50 (+0.00)	359,570 → 359,570 (+0)	1316.00	0 → 0 (+0)	370 → 370	0 → 0	No	Supplier diversification and alternative routing
Severe Closure	Energy Supply Shock	65 → 78	60.00 → 60.00 (+0.00)	64.50 → 68.40 (+3.90)	359,570 → 359,570 (+0)	1347.20	0 → 0 (+0)	370 → 370	0 → 0	No	Supplier diversification and alternative routing
Severe Closure	Logistics Delay	70 → 84	60.00 → 60.00 (+0.00)	64.50 → 64.50 (+0.00)	359,570 → 359,570 (+0)	1316.00	0 → 0 (+0)	370 → 370	0 → 0	No	Supplier diversification and alternative routing
Severe Closure	Fertilizer Input Risk	70 → 84	60.00 → 60.00 (+0.00)	64.50 → 68.70 (+4.20)	359,570 → 359,570 (+0)	1349.60	0 → 0 (+0)	370 → 370	0 → 0	No	Supplier diversification and alternative routing
Full Closure	Geopolitical Tension	95 → 100	86.49 → 86.49 (+0.00)	90.10 → 90.10 (+0.00)	442,482 → 442,482 (+0)	2281.17	0 → 0 (+0)	520 → 520	830 → 830	Yes	Emergency procurement and strategic inventory release
Full Closure	Maritime Accessibility	95 → 100	86.49 → 86.49 (+0.00)	90.10 → 90.10 (+0.00)	442,482 → 442,482 (+0)	2281.17	0 → 0 (+0)	520 → 520	830 → 830	Yes	Emergency procurement and strategic inventory release
Full Closure	Energy Supply Shock	90 → 100	86.49 → 86.49 (+0.00)	90.10 → 93.10 (+3.00)	442,482 → 442,482 (+0)	2317.17	0 → 0 (+0)	520 → 520	830 → 830	Yes	Emergency procurement and strategic inventory release
Full Closure	Logistics Delay	95 → 100	86.49 → 86.49 (+0.00)	90.10 → 90.10 (+0.00)	442,482 → 442,482 (+0)	2281.17	0 → 0 (+0)	520 → 520	830 → 830	Yes	Emergency procurement and strategic inventory release
Full Closure	Fertilizer Input Risk	95 → 100	86.49 → 86.67 (+0.17)	90.10 → 91.67 (+1.57)	442,482 → 442,567 (+84)	2300.00	0 → 0 (+0)	520 → 520	830 → 830	Yes	Emergency procurement and strategic inventory release

Under the Partial Closure scenario, increasing any individual disruption driver produces only negligible changes in the Supply Chain Disruption Risk Index (SCDRI). The disruption conditions remain within the same fuzzy decision region, resulting in an unchanged disruption assessment. Nevertheless, increases in Energy Supply Shock and Fertilizer Input Risk generate moderate increases in the Food System Stress Index (FSSI), indicating that downstream food-system stress responds more rapidly than the overall disruption assessment under relatively mild disruption conditions. Although these higher FSSI values increase the effective shortage penalties, the optimization model preserves the same operational strategy because the existing supplier network and available inventories remain sufficient to satisfy demand without activating additional resilience measures.

Under the Severe Closure scenario, the framework becomes considerably more responsive to changes in the disruption drivers. A 20% increase in Geopolitical Tension produces the largest increase in the Supply Chain Disruption Risk Index, reflecting the dominant influence of geopolitical escalation on the overall disruption assessment. This behaviour is consistent with the expert-defined fuzzy rule base, in which geopolitical escalation acts as the principal trigger for activating higher-risk disruption states that simultaneously influence multiple disruption mechanisms. The resulting increase in the SCDRI raises the disruption-risk multiplier, leading to higher transportation costs and increased total operating costs. At the same time, the higher disruption level contributes to a larger Food System Stress Index, thereby increasing the effective shortage penalties associated with unmet demand. Consequently, the optimization model increasingly favours resilience-oriented solutions that preserve supply continuity despite their higher operational cost.

In contrast, increases in Energy Supply Shock and Fertilizer Input Risk primarily influence the Food System Stress Index while producing only limited changes in the Supply Chain Disruption Risk Index. This behaviour confirms that energy availability and fertilizer supply constitute the principal transmission mechanisms through which geopolitical disruptions affect downstream food systems. Their influence is therefore reflected primarily through the effective shortage penalties rather than through transportation costs.

Under the Full Closure scenario, the framework exhibits a clear saturation effect. Most disruption variables already operate within the highest linguistic categories of the fuzzy inference system, and further increases produce only marginal changes in both the Supply Chain Disruption Risk Index and the Food System Stress Index. Consequently, the disruption-risk multiplier, effective shortage penalties, and optimization decisions remain almost unchanged. The resulting resilience strategy converges towards a stable operational configuration characterised by emergency procurement, extensive strategic inventory deployment, and maximum supplier diversification, demonstrating that the framework produces highly consistent recommendations under extreme disruption conditions.

Overall, the sensitivity analysis confirms the robustness of the proposed framework. Moderate perturbations of the disruption drivers do not generate unstable or contradictory operational recommendations, whereas meaningful increases in disruption severity produce logical and consistent adjustments in both disruption assessment and optimization decisions. The analysis also highlights the complementary roles of the two disruption indicators. The Supply Chain Disruption Risk Index (SCDRI) primarily influences transportation costs through the disruption-risk multiplier, whereas the Food System Stress Index (FSSI) affects operational decisions by increasing the effective shortage penalties associated with unmet demand. Their combined integration enables the optimization model to balance economic efficiency, supply continuity, and downstream food-system resilience within a unified prescriptive analytics framework.

In summary, the sensitivity analysis demonstrates that the proposed methodology remains both stable and responsive. Stability is achieved because moderate variations in the disruption drivers do not produce unrealistic changes in operational recommendations, while responsiveness is preserved because significant deterioration in geopolitical conditions progressively activates stronger resilience measures. These findings strengthen confidence in the practical applicability of the proposed fuzzy prescriptive analytics framework as a decision-support methodology for resilience-oriented supply chain planning under geopolitical uncertainty. The optimization results presented in this section are based on the numerical instance described in Appendix B**.**

4.13. Synthesis and Interpretation of the Results

The results obtained from the fuzzy disruption assessment, the optimization model, and the sensitivity analysis collectively demonstrate the effectiveness of the proposed fuzzy prescriptive analytics framework for supporting resilient supply chain planning under geopolitical uncertainty. Rather than analysing disruption assessment, downstream food-system stress, and

operational planning as separate processes, the framework integrates them into a unified decision-support methodology that systematically transforms qualitative geopolitical assessments into quantitative operational decisions.

The findings demonstrate that geopolitical disruptions should be viewed as systemic phenomena affecting multiple interconnected sectors rather than as isolated transportation disruptions. Escalating geopolitical tensions simultaneously influence maritime accessibility, energy availability, fertilizer supply, and ultimately the resilience of downstream food systems. The proposed analytical framework captures these cascading relationships through two complementary disruption indicators. The Supply Chain Disruption Risk Index (SCDRI) quantifies the overall severity of the disruption, whereas the Food System Stress Index (FSSI) quantifies downstream food-system stress through an expert-informed weighted aggregation model.This separation improves both the interpretability of the disruption assessment and the transparency of the subsequent operational decision-making process.

The numerical results further illustrate the complementary roles of the two disruption indicators within the optimization framework. The SCDRI affects transportation costs through the disruption-risk multiplier, thereby representing the direct operational consequences of geopolitical disruption. In contrast, the FSSI increases the effective shortage penalties associated with unmet demand, allowing downstream food-system stress to influence operational planning without modifying the mathematical structure of the mixed-integer linear programming model. This formulation provides a transparent mechanism for incorporating broader societal consequences into operational decision-making while preserving computational efficiency.

The optimization results reveal a progressive evolution of resilience strategies as disruption severity increases. Under moderate disruption conditions, maintaining supply continuity can be achieved through limited inventory deployment and selective supplier diversification. As geopolitical conditions deteriorate, the optimization progressively expands supplier diversification, reallocates transportation flows, increases the utilization of strategic inventories, and activates emergency procurement when necessary. Under the most severe disruption scenario, emergency sourcing and strategic inventory deployment become essential components of the optimal operational strategy, reflecting the substantially higher economic consequences associated with supply shortages under conditions of extreme food-system stress.

A particularly important finding is that the proposed framework maintains full demand satisfaction across all disruption scenarios. Rather than accepting shortages, the optimization systematically compensates for increasing disruption through supplier diversification, transportation reconfiguration, strategic inventory deployment, and emergency procurement. These results demonstrate that integrating disruption assessment with mathematical optimization enables proactive resilience planning capable of maintaining supply continuity even under severe geopolitical disruptions.

The sensitivity analysis further strengthens the credibility of the proposed methodology by demonstrating both robustness and responsiveness. Moderate perturbations of the disruption drivers do not produce unstable or contradictory operational recommendations, whereas meaningful increases in disruption severity generate logical and consistent adjustments in both disruption assessment and operational decisions. The analysis also highlights the differentiated influence of the disruption drivers. Geopolitical Tension emerges as the principal determinant of overall disruption severity, whereas Energy Supply Shock and Fertilizer Input Risk primarily affect downstream food-system stress. These findings confirm that resilient supply chain planning should simultaneously account for both the direct operational impacts of geopolitical disruptions and their broader systemic consequences.

Overall, the results confirm that the proposed framework successfully integrates explainable fuzzy modelling, expert knowledge, and mixed-integer linear programming within a unified prescriptive analytics methodology. By sequentially linking disruption assessment, downstream food-system stress evaluation, and optimization-based operational planning, the framework enables decision-makers to balance transportation costs, supplier diversification, strategic inventory deployment, emergency procurement, and supply continuity under alternative geopolitical disruption scenarios. Through this integrated analytical workflow, qualitative geopolitical assessments are systematically translated into transparent, reproducible, and resilience-oriented operational decisions, providing a comprehensive decision-support methodology for supply chain planning under deep uncertainty.

5. Discussion

5.1. Comparison with existing literature

The findings of this study are consistent with the growing body of research demonstrating that fuzzy methodologies provide an effective means for representing uncertainty, incorporating expert knowledge, and supporting supply chain decision-making when historical observations are limited or probabilistic information is unavailable [45–49]. Similar conclusions have been reported in studies addressing resilience assessment, supplier selection, risk management, and sustainability across agri-food, pharmaceutical, and humanitarian supply chains.

The optimization results are also consistent with the broader supply chain resilience literature, which emphasizes that flexibility, redundancy, supplier diversification, strategic inventories, and adaptive sourcing become increasingly valuable as disruption severity escalates [7,43,45]. Similar to previous research, the proposed framework demonstrates that resilience strategies evolve progressively from relatively limited operational adjustments under moderate disruption conditions to comprehensive responses involving supplier diversification, transportation reconfiguration, strategic inventory deployment, and emergency procurement under severe geopolitical disruptions.

Despite these similarities, the proposed framework extends the existing literature in several important respects.

First, previous studies generally employ fuzzy methodologies for disruption assessment, supplier evaluation, resilience measurement, or the prioritization of critical risk factors [28,29,50]. In contrast, the present framework moves beyond descriptive or diagnostic analysis by explicitly integrating disruption assessment into operational decision-making. Rather than producing disruption indicators solely for analytical interpretation, the proposed methodology systematically transforms these indicators into optimization parameters that directly influence operational planning.

Second, the framework distinguishes between overall supply chain disruption and downstream food-system stress through two analytically distinct indicators. The Supply Chain Disruption Risk Index (SCDRI) quantifies the severity of the geopolitical disruption, whereas the Food System Stress Index (FSSI) captures downstream food-system stress through an expert-informed weighted aggregation model. This separation provides greater conceptual clarity by distinguishing disruption severity from its systemic implications, thereby improving both the interpretability and transparency of the decision-support process.

Third, unlike fuzzy optimization approaches that directly embed fuzzy numbers within mathematical programming models, the proposed methodology adopts a sequential integration strategy. The fuzzy assessment produces disruption indicators that are subsequently translated into deterministic optimization parameters. Specifically, the SCDRI determines the disruption-risk multiplier that adjusts transportation costs, while the FSSI modifies the effective shortage penalties associated with unmet demand. This approach preserves the explainability of fuzzy reasoning while maintaining the computational efficiency, scalability, and reproducibility of a conventional mixed-integer linear programming model.

Fourth, the proposed framework adopts a broader systems perspective by explicitly representing the interdependencies among geopolitical instability, maritime transportation, energy availability, fertilizer supply, and downstream food systems. Whereas many previous studies examine these domains independently, the present methodology captures the cascading propagation of disruption across interconnected critical infrastructures. Consequently, the optimization process evaluates not only operational performance but also the broader implications of supply disruptions for food-system resilience.

Finally, the study provides a fully reproducible implementation of the proposed methodology. The complete MATLAB implementation, expert-informed membership functions, transparent fuzzy rule base, numerical optimization datasets, and comprehensive sensitivity analysis facilitate independent validation, benchmarking, and future methodological extensions. This level of methodological transparency addresses a frequently recognised limitation of fuzzy decision-support studies, many of which provide insufficient implementation detail for replication.

Overall, the proposed framework complements and extends the existing literature on fuzzy decision support, supply chain resilience, and prescriptive analytics. Rather than proposing a new fuzzy inference methodology or optimization algorithm, the study contributes an integrated prescriptive analytics framework that systematically combines explainable fuzzy disruption assessment, expert-informed evaluation of downstream food-system stress, and optimization-based operational planning. By systematically translating qualitative geopolitical assessments into transparent and reproducible operational decisions, the proposed methodology extends existing research beyond disruption assessment toward practical, resilience-oriented decision support for managing supply chains under conditions of deep geopolitical uncertainty.

5.2. Practical implications

The proposed fuzzy prescriptive analytics framework provides important practical implications for managers, policymakers, risk managers, and institutional investors responsible for enhancing supply chain resilience under geopolitical uncertainty. By integrating disruption assessment, downstream food-system stress evaluation, and optimization-based operational planning within a unified decision-support framework, the proposed methodology enables organizations to move beyond reactive crisis management toward proactive and resilience-oriented decision-making.

5.2.1. Implications for managers

From a managerial perspective, the findings demonstrate that resilient supply chain management requires more than conventional cost-minimization strategies. The optimization results show that effective operational responses evolve progressively as disruption severity increases. Under moderate disruption conditions, limited supplier diversification and selective deployment of strategic inventories are generally sufficient to maintain supply continuity. As disruption severity intensifies, however, organizations should progressively expand supplier diversification, reconfigure transportation networks, increase the utilization of strategic inventories, and activate emergency procurement mechanisms.

Consequently, resilience should be viewed as a dynamic organizational capability rather than a static inventory or sourcing policy. Unlike traditional resilience planning, which frequently recommends supplier diversification as a universal best practice, the proposed framework identifies the disruption conditions under which diversification becomes economically justified. By explicitly linking geopolitical disruption assessments with optimization-based decision support, the framework enables managers to determine when additional resilience investments generate operational benefits that outweigh their associated costs.

A further managerial contribution lies in transforming qualitative geopolitical assessments into quantitative operational decisions. The Supply Chain Disruption Risk Index (SCDRI) quantifies overall disruption severity, while the Food System Stress Index (FSSI) quantifies downstream food-system stress through an expert-informed weighted aggregation model. These indicators are subsequently translated into deterministic optimization parameters that directly influence transportation planning, supplier selection, inventory deployment, emergency procurement, and shortage management. Consequently, operational recommendations remain transparent, explainable, and directly linked to evolving geopolitical conditions.

The framework also demonstrates the importance of considering interdependent critical infrastructures when designing resilience strategies. The numerical results show that disruptions affecting maritime transportation rapidly propagate through energy systems, fertilizer supply chains, agricultural production, and downstream food systems. Accordingly, resilient supply chain planning should no longer be developed independently of energy security and food-system resilience but should instead adopt an integrated systems perspective.

5.2.2. Implications for policymakers

The proposed framework also provides several implications for public policy. Critical maritime chokepoints, such as the Strait of Hormuz, should be viewed not only as transportation corridors but also as strategic infrastructures whose disruption may simultaneously affect energy security, industrial production, agricultural inputs, and food availability. Consequently, resilience policies should integrate transportation infrastructure planning, strategic energy reserves, supplier diversification, emergency logistics planning, and food-system preparedness within a coordinated policy framework.

The proposed methodology enables policymakers to evaluate how alternative geopolitical scenarios translate into concrete operational consequences before disruptions fully materialize. This capability supports evidence-based prioritization of strategic reserves, emergency logistics investments, infrastructure protection, and contingency planning according to the assessed severity of alternative disruption scenarios.

An additional policy implication concerns the timing of intervention. Traditional policy responses frequently address food-system impacts only after major disruptions have occurred. In contrast, the proposed framework explicitly incorporates downstream food-system stress into operational planning by increasing the economic consequences of shortages as food-system stress intensifies. This enables preventive interventions to be implemented before disruptions generate widespread economic and societal consequences.

5.2.3. Implications for risk managers

The proposed framework also offers practical value for enterprise risk managers. Conventional financial risk indicators often underestimate the operational consequences of geopolitical disruptions because they focus primarily on market volatility rather than the physical performance of supply chains. The proposed methodology complements traditional financial risk assessment by providing operational indicators related to disruption severity, downstream food-system stress, supplier activation, emergency procurement requirements, strategic inventory utilization, and potential supply shortages. These insights enable organizations to identify operational vulnerabilities proactively during contingency planning rather than reacting after disruptions have already affected supply continuity.

5.2.4. Implications for institutional investors

Institutional investors may also benefit from the proposed methodology by incorporating operational resilience into investment evaluation. The framework enables the resilience of alternative supply chains to be compared under identical geopolitical scenarios, allowing resilience to complement conventional financial indicators as an additional investment-screening criterion. Such analyses can support investment decisions in sectors where supply chain continuity is critical to long-term organizational performance.

5.2.5. Stakeholder alignment and the twin transition

Beyond supporting individual decision-makers, the proposed framework facilitates coordination among multiple stakeholder groups involved in supply chain resilience. Managers, policymakers, risk managers, and institutional investors frequently pursue different objectives, including operational efficiency, public welfare, financial stability, and long-term resilience. By translating expert-informed geopolitical assessments into transparent disruption indicators and optimization-based operational recommendations, the framework provides a common analytical basis for evaluating alternative resilience strategies and reduces reliance on fragmented or inconsistent assessments.

This capability is particularly relevant in the context of the twin transition, where digital transformation and sustainability objectives must be pursued simultaneously. The digital dimension is represented through the integration of explainable artificial intelligence, fuzzy reasoning, and optimization-based decision support, while the sustainability dimension is reflected in the explicit consideration of food-system resilience, supply continuity, and the protection of interconnected critical infrastructures. By enabling coordinated, transparent, and evidence-based decision-making across multiple stakeholder groups, the proposed methodology contributes to the development of more resilient, sustainable, and adaptive supply chain ecosystems under conditions of geopolitical uncertainty.

Overall, the proposed framework demonstrates that effective decision-making under geopolitical uncertainty requires the systematic integration of disruption assessment, downstream food-system stress evaluation, and optimization-based operational planning. By transforming expert-informed geopolitical knowledge into actionable operational decisions, the methodology provides a transparent, reproducible, and practically applicable decision-support framework capable of balancing economic efficiency, supply continuity, and system-wide resilience across interconnected supply networks.

5.3. Theoretical contribution

This study contributes to the literature on supply chain resilience, geopolitical risk analysis, and prescriptive analytics by proposing an integrated fuzzy prescriptive analytics framework that systematically combines explainable fuzzy modelling, expert knowledge, and optimization-based operational planning. Rather than introducing a new fuzzy inference technique or a new optimization algorithm, the study advances the theoretical understanding of how qualitative geopolitical knowledge can be translated into quantitative operational decisions under conditions of deep uncertainty.

The first theoretical contribution concerns the integration of disruption assessment with operational decision-making. Existing studies frequently treat disruption assessment, resilience evaluation, and optimization as independent analytical processes. In contrast, the proposed framework establishes a continuous analytical workflow in which disruption assessments are directly transformed into optimization parameters that guide operational planning. This integration extends the role of fuzzy reasoning beyond descriptive risk assessment towards prescriptive decision support.

The second contribution concerns the conceptual distinction between overall disruption severity and downstream food-system stress. The proposed framework introduces two complementary disruption indicators with clearly differentiated analytical roles. The Supply Chain Disruption Risk Index (SCDRI) quantifies the severity of geopolitical disruption through the Mamdani fuzzy inference system, whereas the Food System Stress Index (FSSI) quantifies downstream food-system stress through an expert-informed weighted aggregation model. By separating disruption severity from its systemic implications, the framework enhances conceptual clarity, improves interpretability, and provides a more transparent representation of disruption propagation across interconnected systems.

A third contribution lies in the methodological integration of fuzzy reasoning with deterministic optimization. Unlike conventional fuzzy optimization approaches that directly incorporate fuzzy numbers into mathematical programming models, the proposed methodology adopts a sequential parameterization strategy. The disruption indicators generated during the analytical stage are transformed into deterministic optimization parameters, with the SCDRI determining the disruption-risk multiplier applied to transportation costs and the FSSI determining the effective shortage penalties associated with unmet demand. This formulation preserves the explainability of fuzzy reasoning while maintaining the computational efficiency, mathematical tractability, and reproducibility of mixed-integer linear programming.

The proposed framework also contributes to resilience theory by adopting an explicit systems perspective. Rather than examining maritime transportation, energy security, fertilizer supply, and food systems independently, the framework represents the cascading propagation of geopolitical disruption across interconnected critical infrastructures. This systemic representation extends existing resilience theory by demonstrating how disruptions propagate between sectors and how these interdependencies can be incorporated into operational decision-making.

A further theoretical contribution concerns the advancement of prescriptive analytics. Whereas previous studies have primarily focused on descriptive disruption assessment or predictive risk evaluation, the proposed methodology demonstrates how explainable fuzzy modelling and expert knowledge can be integrated with mathematical optimization to generate resilience-oriented operational recommendations. In this way, the framework establishes a methodological bridge between descriptive analytics, expert-informed disruption assessment, and prescriptive operational planning, thereby extending the emerging literature on intelligent decision-support systems for resilient supply chains.

Finally, the study contributes to methodological transparency by providing a fully reproducible implementation of the proposed framework. The complete MATLAB implementation, together with the expert-informed membership functions, transparent fuzzy rule base, numerical optimization datasets, and comprehensive sensitivity analysis, provides a reference architecture that supports independent validation, comparative benchmarking, and future methodological extensions. This high level of reproducibility strengthens both the theoretical credibility and the practical applicability of the proposed methodology.

Taken together, these contributions extend the current literature beyond disruption assessment and resilience measurement by establishing an integrated fuzzy prescriptive analytics framework that links explainable fuzzy reasoning, downstream food-system stress evaluation, and optimization-based operational planning. The proposed framework therefore provides a coherent theoretical foundation for resilience-oriented decision-making under conditions of deep geopolitical uncertainty while offering a flexible analytical architecture that can be adapted to a wide range of critical supply chain environments.

5.4. Limitations

Despite the methodological contributions of the proposed fuzzy prescriptive analytics framework, several limitations should be acknowledged.

First, the framework relies on structured expert knowledge for defining the disruption drivers, linguistic variables, membership functions, fuzzy rule base, and the weighting coefficients used to estimate the Food System Stress Index (FSSI). Although structured expert elicitation represents an appropriate approach for modelling geopolitical uncertainty when historical observations are limited or unavailable, alternative expert panels may define different linguistic boundaries, rule structures, or weighting schemes. Consequently, a degree of subjectivity remains inherent in the knowledge-engineering component of the proposed methodology.

Second, the proposed framework is evaluated through scenario-based numerical experiments rather than empirical observations obtained from real-time geopolitical disruptions. The disruption scenarios were constructed using historical evidence and expert knowledge to ensure internal consistency and practical realism. Nevertheless, actual geopolitical crises evolve under the influence of political decisions, military escalation, international interventions, market adaptation, and technological developments that cannot be fully anticipated within predefined scenarios. Accordingly, the proposed framework should be interpreted as a decision-support methodology for evaluating plausible disruption scenarios rather than as a forecasting model for future geopolitical events.

Third, the proposed methodology has not been empirically calibrated using longitudinal operational data. Instead, it has been designed as an expert-informed decision-support framework for evaluating alternative disruption scenarios and supporting resilience-oriented operational planning. Future calibration using large-scale operational datasets from logistics networks, maritime transportation, energy markets, and food supply chains would further strengthen the external validity and practical applicability of the proposed methodology.

Fourth, the optimization model is demonstrated through a stylized numerical case study based on the Strait of Hormuz. Although the numerical implementation is fully specified and reproducible, additional validation using industry-specific datasets, larger and more complex supply networks, and real-world operational environments would improve the generalizability of the proposed framework across different sectors and geopolitical contexts.

Fifth, the optimization model assumes that the operational consequences of disruption can be represented through deterministic parameter transformations derived from the disruption indicators. Although this formulation enhances transparency and computational efficiency, it does not explicitly capture the dynamic behavioral responses of supply chain participants. Market adaptation, supplier learning, demand substitution, speculative behaviour, panic buying, or evolving government interventions may alter disruption propagation over time and therefore cannot be fully represented within the current static optimization framework.

Finally, the proposed methodology employs a single-objective mixed-integer linear programming model in which resilience is incorporated indirectly through disruption-adjusted transportation costs and effective shortage penalties. While this formulation preserves mathematical tractability and enables efficient computation, alternative optimization paradigms—including multi-objective optimization, stochastic programming, robust optimization, dynamic optimization, and agent-based simulation—could provide additional insights into the trade-offs among economic efficiency, supply continuity, environmental sustainability, and societal resilience.

Despite these limitations, the proposed framework provides a transparent, explainable, and fully reproducible methodology for integrating explainable disruption assessment with optimization-based operational planning. By combining explainable fuzzy modelling, expert knowledge, and deterministic mixed-integer linear programming within a unified prescriptive analytics framework, the proposed methodology establishes a robust analytical foundation for resilience-oriented supply chain decision-making under conditions of deep geopolitical uncertainty. At the same time, its modular architecture facilitates future extensions through empirical calibration, real-time data integration, adaptive learning mechanisms, and advanced optimization techniques, thereby providing a flexible platform for the future development of intelligent decision-support systems for resilient supply chains.

5.5. Future research

The proposed fuzzy prescriptive analytics framework provides a flexible methodological foundation that can be extended in several directions to further enhance its analytical capabilities and practical applicability.

First, future research should focus on empirical calibration and external validation using large-scale longitudinal datasets from supply chains, maritime transportation, energy markets, and food systems. Integrating operational data with expert-informed knowledge would enable the refinement of membership functions, fuzzy rule bases, and the parameters used to estimate the Food System Stress Index (FSSI), thereby improving both the external validity and predictive reliability of the proposed framework.

Second, the proposed methodology could be applied to additional geopolitical environments characterized by complex supply chain disruption risks, including the South China Sea, the Red Sea, critical mineral supply networks, semiconductor supply chains, and climate-induced disruption scenarios. Comparative studies across different geopolitical contexts would improve understanding of how disruption propagation mechanisms differ across interconnected critical infrastructures and economic sectors.

Third, future studies could investigate the integration of explainable artificial intelligence and machine learning with the proposed framework. Hybrid AI approaches combining explainable machine learning, fuzzy modelling, and expert knowledge could support the adaptive updating of membership functions, fuzzy rule bases, disruption thresholds, and expert knowledge as new operational information becomes available, while preserving the transparency and interpretability that characterize fuzzy reasoning.

Fourth, future research may extend the optimization component beyond its current single-objective formulation. Multi-objective optimization, robust optimization, stochastic programming, dynamic optimization, reinforcement learning, and simulation-based optimization could provide a richer representation of the trade-offs among economic efficiency, supply continuity, environmental sustainability, food security, and societal resilience. Such developments would broaden the applicability of the framework to increasingly complex decision environments.

Fifth, the proposed framework could be extended to incorporate dynamic behavioral responses among supply chain participants. Market adaptation, strategic stockpiling, panic buying, supplier learning, demand substitution, and evolving government interventions influence disruption propagation over time and therefore represent important directions for extending the current static modelling approach toward adaptive resilience planning.

Finally, future research should investigate the integration of the proposed methodology with emerging digital technologies, including digital twins, the Internet of Things (IoT), satellite-based maritime monitoring, blockchain-enabled supply chain visibility, and real-time logistics information systems. Such integration would enable the development of adaptive prescriptive analytics platforms capable of continuously updating disruption assessments and operational recommendations as geopolitical conditions evolve.

More broadly, future research may also explore the role of the proposed framework within the emerging paradigm of intelligent and autonomous supply chains, where explainable artificial intelligence, human expertise, and optimization interact continuously to support real-time resilience management. Integrating prescriptive analytics with autonomous decision-support systems represents a promising direction for enhancing the responsiveness and adaptability of supply chains operating under persistent geopolitical uncertainty.

Taken together, these research directions provide a pathway towards the next generation of intelligent decision-support systems that combine explainable artificial intelligence, expert knowledge, fuzzy modelling, empirical data, and advanced optimization techniques. The framework proposed in this study therefore establishes not only a practical methodology for resilience-oriented operational planning but also a flexible analytical foundation for future research on intelligent, adaptive, resilient, and sustainable supply chain management under increasingly uncertain geopolitical environments.

6. Conclusion

This study proposed an integrated fuzzy prescriptive analytics framework for supporting resilience-oriented supply chain decision-making under conditions of geopolitical disruption and deep uncertainty. Using the Strait of Hormuz as an illustrative numerical case study, the research demonstrated how geopolitical disruptions propagate across interconnected transportation, energy, fertilizer, and food systems, and how these cascading effects can be systematically incorporated into operational planning.

The proposed framework combines historical evidence, structured expert knowledge, explainable fuzzy modelling, and mixed-integer linear programming within a unified analytical methodology. The Mamdani fuzzy inference system estimates the Supply Chain Disruption Risk Index (SCDRI), while the Food System Stress Index (FSSI) quantifies downstream food-system stress through an expert-informed weighted aggregation model. Rather than embedding fuzzy variables directly into the optimization model, the framework transforms these disruption indicators into deterministic optimization parameters, allowing geopolitical assessments to directly influence transportation costs and shortage penalties while preserving the computational efficiency and transparency of the optimization process.

The numerical results demonstrate that increasing disruption severity progressively changes optimal operational strategies. As geopolitical conditions deteriorate, the optimization model recommends broader supplier diversification, greater utilization of strategic inventories, transportation reconfiguration, and the activation of emergency procurement mechanisms in order to maintain supply continuity. At the same time, the incorporation of downstream food-system stress into the optimization process enables operational decisions to account not only for logistics efficiency but also for the wider societal consequences of supply disruptions.

From a methodological perspective, the study advances the literature by integrating explainable fuzzy modelling, expert knowledge, and deterministic optimization within a coherent prescriptive analytics framework. Rather than treating disruption assessment, downstream food-system stress assessment, and operational planning as independent analytical tasks, the proposed methodology establishes a transparent analytical workflow that systematically translates qualitative geopolitical assessments into quantitative, resilience-oriented operational decisions.

More broadly, the study contributes to the evolving field of supply chain resilience by demonstrating that geopolitical disruptions should be analysed as systemic phenomena affecting multiple interconnected critical infrastructures rather than isolated logistics operations. By explicitly modelling the relationships among maritime transportation, energy availability, fertilizer supply, and downstream food systems, the proposed framework provides a more comprehensive analytical perspective for understanding disruption propagation and supporting resilience-oriented planning under geopolitical uncertainty.

Overall, the proposed fuzzy prescriptive analytics framework demonstrates how explainable artificial intelligence, expert-informed knowledge, and mathematical optimization can be integrated within a unified decision-support methodology capable of supporting transparent, reproducible, and operationally applicable decisions. Although demonstrated using the Strait of Hormuz as an illustrative case study, the proposed framework is sufficiently flexible to be adapted to other critical supply chains exposed to geopolitical, environmental, technological, or other high-impact disruptions. As global supply chains become increasingly interconnected and exposed to systemic risks, integrated prescriptive analytics frameworks of this type have the potential to play an increasingly important role in supporting resilient, adaptive, and evidence-based operational decision-making.

CRediT authorship contribution statement

Atsalakis George: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ioanna Atsalaki:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Appendix A

The final MATLAB implementation employs a compact expert-informed rule base consisting of ten fuzzy IF–THEN rules. The complete rule base used to estimate the Supply Chain Disruption Risk Index (SCDRI) is presented below to ensure transparency, reproducibility, and independent validation of the proposed methodology. Rather than constructing an exhaustive combinatorial rule base, the proposed rule base captures the dominant disruption mechanisms identified through the expert elicitation process and corresponds exactly to the final MATLAB implementation used to generate all numerical results presented in Sections 4.8–4.12.

1. If (GeopoliticalTension is Critical) and (MaritimeAccessibility is Closed) then (SCDRI is Extreme)
2. If (EnergySupplyShock is Severe) and (LogisticsDelay is High) then (SCDRI is Severe)
3. If (FertilizerInputRisk is High) then (SCDRI is Severe)
4. If (MaritimeAccessibility is Restricted) and (LogisticsDelay is Moderate) then (SCDRI is Moderate)
5. If (EnergySupplyShock is Extreme) and (FertilizerInputRisk is Severe) then (SCDRI is Extreme)
6. If (GeopoliticalTension is High) and (MaritimeAccessibility is Disrupted) and (EnergySupplyShock is Severe) and (LogisticsDelay is High) and (FertilizerInputRisk is High) then (SCDRI is Severe)
7. If (GeopoliticalTension is Critical) and (MaritimeAccessibility is Disrupted) and (EnergySupplyShock is Severe) and (LogisticsDelay is High) and (FertilizerInputRisk is High) then (SCDRI is Extreme)
8. If (GeopoliticalTension is Moderate) and (MaritimeAccessibility is Restricted) and (EnergySupplyShock is Moderate) and (LogisticsDelay is Moderate) and (FertilizerInputRisk is Moderate) then (SCDRI is Moderate)
9. If (GeopoliticalTension is Low) and (MaritimeAccessibility is Open) and (EnergySupplyShock is Mild) and (LogisticsDelay is Low) and (FertilizerInputRisk is Low) then (SCDRI is Low)
10. If (GeopoliticalTension is Critical) and (MaritimeAccessibility is Closed) and (EnergySupplyShock is Extreme) and (LogisticsDelay is Critical) and (FertilizerInputRisk is Severe) then (SCDRI is Extreme).

Appendix B. Complete numerical optimization instance

Appendix B presents the complete numerical optimization instance used in the computational experiments. The following tables report all numerical input parameters required to reproduce the mixed-integer optimization model, including transportation costs, supplier capacities, emergency procurement parameters, demand quantities, strategic inventory levels, cost coefficients, and the scenario-specific disruption parameters derived from the Mamdani fuzzy inference system and the expert-informed weighted aggregation model. This information is provided to ensure the transparency, reproducibility, and independent validation of the proposed methodology.

The mixed-integer optimization model requires a transportation cost matrix defining the unit shipping cost between each supplier and demand region (Table B1). These costs represent the baseline logistics network before disruption-induced cost adjustments are applied through the risk multiplier.

Table B1
Regular Transportation Cost Matrix (USD per unit)

Supplier	Europe	South Asia	East Asia
S1 – Gulf A	120	90	100
S2 – Gulf B	130	95	105
S3 – Pipeline-linked	160	140	170
S4 – Non-Gulf	150	180	210

Emergency procurement constitutes an additional resilience mechanism that can be activated under severe disruption scenarios. Table B2 reports the unit procurement costs associated with emergency sourcing for each demand region.

Table B2
Emergency Procurement Cost (USD per unit)

Demand Region	Cost
Europe	300
South Asia	320
East Asia	350

Supplier capacities vary across disruption scenarios depending on the severity of geopolitical constraints. Table B3 reports the maximum available supply from each candidate supplier under the three disruption scenarios considered in this study.

Table B3
Supplier Capacities (Units)

Scenario	S1	S2	S3	S4
Partial Closure	600	500	400	500
Severe Closure	300	250	380	500
Full Closure	0	0	350	500

When conventional supply becomes insufficient, emergency procurement can supplement available capacity. Table B4 presents the maximum emergency procurement capacity available under each disruption scenario.

Table B4
Emergency Procurement Capacity (Units)

Scenario	Capacity
Partial Closure	0
Severe Closure	500
Full Closure	1000

The optimization model satisfies the demand requirements of three regional markets. Table B5 reports the demand quantities used throughout all computational experiments.

Table B5
Demand Requirements (Units)

Demand Region	Demand
Europe	650
South Asia	550
East Asia	500

Strategic inventory serves as an important resilience mechanism that can be released during supply disruptions. Table B6 reports the inventory available for each demand region under the examined disruption scenarios.

Table B6
Strategic Inventory Availability (Units)

Scenario	Europe	South Asia	East Asia
Partial Closure	100	80	70
Severe Closure	150	120	100
Full Closure	220	170	130

The optimization model includes fixed activation costs associated with opening regular suppliers and initiating emergency procurement. These costs are reported in Table B7.

Table B7
Fixed Cost Parameters

Parameter	Value (USD)
Regular supplier activation	20,000
Emergency supplier activation	50,000

Inventory holding costs are incorporated into the objective function to represent the cost of maintaining strategic inventories across demand regions. Table B8 summarizes these parameters.

Table B8
Inventory Holding Cost

Demand Region	Holding Cost (USD/unit)
Europe	25
South Asia	25
East Asia	25

The Mamdani fuzzy inference system generates the scenario-specific Supply Chain Disruption Risk Index (SCDRI), while the Food System Stress Index (FSSI) is subsequently computed through the expert-informed weighted aggregation model. Table B9 summarizes the resulting optimization parameters: the Supply Chain Disruption Risk Index (SCDRI), the corresponding transportation cost Risk Multiplier (RM), the Food System Stress Index (FSSI), the baseline shortage penalties, and the scaling coefficient used in the computation of the effective shortage penalty for each disruption scenario.

Table B9
Scenario Parameters

Scenario	SCDRI	Risk Multiplier (RM)	FSSI	Baseline Shortage Penalty (USD/unit)	β
Partial Closure	35.00	1.35	36.50	500	1.0
Severe Closure	60.00	1.60	64.50	800	1.0
Full Closure	86.49	1.865	90.10	1200	1.0

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