Supply Chain Resilience under Maritime Chokepoint Disruptions: Route Feasibility and Digital Response in Saudi Arabian Food Cold Chains

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ABSTRACT

Maritime disruptions expose a fundamental distinction between identifying threats to refrigerated cargo and maintaining operationally viable alternatives for its delivery. Focusing on Saudi Arabia's food cold chains during the 2026 disruptions affecting the Hormuz and Bab al-Mandab chokepoints, this study investigates the conditions under which disruption awareness translates into actionable logistical responses. Drawing on a purposively selected synthesis of academic literature and official documentation, the research develops a route-dependent analytical model that incorporates chokepoint accessibility, refrigerated transport capacity, product-specific time budgets and response latency. The model evaluates four route families under four corridor states, with logical consistency verified through exhaustive binary enumeration. Three principal findings emerge. First, disruption exposure is determined by shipment origin and approach direction, rather than solely by the coastal location of the destination gateway. Second, routes operating independently of disrupted corridors retain delivery feasibility only where refrigerated capacity and product-life requirements remain satisfied. Third, accelerated digital responses can recover feasible delivery options exclusively within a bounded residual-time interval, whereas enhanced monitoring cannot overcome physical constraints that render delivery infeasible. These deductions inform a five-mechanism disruption transmission framework and an eight-capability intervention map linking analytical outcomes to operational decision-making. By identifying the precise circumstances in which information alters the set of admissible routing alternatives, the study advances beyond generalised digital-resilience frameworks. Its findings represent analytical deductions rather than empirical estimates of shipment delays, spoilage losses or technological impacts within Saudi Arabia.

Keywords: Food Cold Chain; Saudi Arabia; Maritime Chokepoints; Strait of Hormuz; Bab al-Mandab; Routing Feasibility; Response Latency; Digital Resilience

INTRODUCTION

A refrigerated consignment may become undeliverable despite uninterrupted visibility of its location and thermal condition. Such failure can arise when a vessel cannot access a navigable corridor, a receiving terminal has no confirmed refrigerated connection, or a diversion requires more time than the product's remaining commercially acceptable life permits. Effective cold-chain management consequently depends on the simultaneous availability of dependable information and physically executable corrective measures. Existing syntheses emphasise that maintaining product integrity requires coordinated handling, traceability and operational continuity throughout successive logistics stages (Mustafa et al., 2024; Trotter et al., 2023). Reviews of perishable-food cold-chain management stress that product quality depends on facilities, stakeholder collaboration and handling conditions across stages (Akram et al., 2023),

and that specific challenges inhibit both food-quality preservation and cold-chain resilience (Zhang & Mohammad, 2024). Recent investigations of Internet of Things (IoT) services identify technological approaches to monitoring perishable-food distribution networks (Müller et al., 2026; Protopappas et al., 2025). Nevertheless, these contributions do not establish that improved shipment visibility necessarily preserves an operationally feasible delivery alternative when maritime transport is disrupted.

The interconnected nature of refrigerated-food logistics creates vulnerabilities extending beyond individual transport movements. Transportation, temperature-controlled storage, refrigeration, customs procedures and final receiving activities collectively constitute a service network governed by strict temporal requirements (Mustafa et al., 2024; Trotter et al., 2023). Interruptions affecting a particular facility or shipping corridor may therefore generate constraints elsewhere in the network without compromising the functionality of monitoring infrastructure. For perishable commodities, this separation is especially consequential because diversion may remain geographically possible while additional sailing, terminal processing and inland distribution consume the time available for acceptable delivery. Evaluating cold-chain resilience thus requires consideration of both network continuity and the shipment-specific conditions governing whether the final delivery remains commercially and operationally admissible (Khalid et al., 2024; Khan & Ali, 2022).

Within supply-chain scholarship, resilience encompasses not only resistance to disruption but also the reconfiguration of resources needed to sustain critical operations. Established reviews of food supply systems identify the attributes and capacities that shape resilience outcomes under sudden shocks (Huang et al., 2025). The viable-supply-chain perspective further connects resilience with adaptive capability and sustainability, positioning these attributes as interdependent requirements for maintaining essential functions (Ivanov, 2022). Their relevance to refrigerated food is particularly pronounced because nominal access to a maritime gateway does not guarantee continuity of service. Rather, an entire itinerary must remain compatible with product-life limitations and the availability of qualified refrigeration resources (Mustafa et al., 2024; Trotter et al., 2023). The disruptions associated with the 2026 Middle East conflict provide a pertinent setting for examining these relationships. Official assessments identify interference with maritime movement through Hormuz as a potential source of risks affecting energy, fertiliser and agrifood systems (FAO, 2026). Similarly, the September 2026 Short-Term Energy Outlook discusses restrictions involving Hormuz and Bab el-Mandeb alongside adjustments to Saudi oil-transport arrangements (U.S. Energy Information Administration, 2026). Together, these documents establish the contextual justification for evaluating disruption across two maritime corridors. They do not, however, quantify losses affecting Saudi refrigerated-food shipments, and adaptations observed in petroleum logistics cannot be assumed to represent available alternatives for food imports. Accordingly, the present investigation explicitly separates documentary evidence of disruption from analytical deductions concerning refrigerated cargo.

Previous disruption research reinforces the need for this distinction. Evidence from food value chains shows that resilience is built through sequential readiness, response and recovery capabilities and depends on how partner networks are configured (Ali et al., 2022). Empirical evidence on port criticality likewise indicates that some economies depend heavily on individual ports, so that interruption at one gateway can propagate to the supply chains it serves (Verschuur et al., 2022). These findings provide methodological support for assessing individual routes under adverse conditions, without implying that previously reported quantitative outcomes are representative of Saudi food imports during 2026.

The strategic significance of maritime chokepoints arises from their concentration of access within otherwise geographically extensive transport networks (Meza et al., 2022; Pratson, 2023; Verschuur et al., 2022). International assessments have previously demonstrated that concurrent disturbances affecting the Red Sea and other major maritime passages can intensify pressures throughout global trade logistics (United Nations Conference on Trade and Development, 2024). Analyses of the Red Sea crisis further indicate that adaptation depends on carrier rerouting decisions, port-call adjustments and broader supply-chain configurations, rather than simply on the geographical availability of another passage (Notteboom et al., 2024). Applied to Saudi refrigerated-food logistics, this means that gateway substitution is meaningful only when an appropriate refrigerated service and subsequent delivery arrangements can be secured. Avoiding one chokepoint may leave an itinerary dependent on another, whereas an otherwise independent corridor may remain operationally inaccessible because of inadequate capacity, missing permissions or insufficient product life.

Digitalisation introduces additional possibilities for disruption identification and logistical coordination, although its operational contribution requires explicit qualification (Khan & Ali, 2022). IoT-enabled systems support the acquisition of shipment-location and condition data (Müller et al., 2026; Protopappas et al., 2025), while artificial intelligence of things approaches incorporate product-quality and distribution-cost considerations into cold-chain decision-making (Nozari et al., 2025). Wider reviews document the application of artificial intelligence and analytical methods to supply-chain resilience, risk assessment and management (Habazin et al., 2025; Zamani et al., 2022). Empirical studies additionally link AI-enabled analytics with agility, visibility and resilience capabilities (Dubey et al., 2022; Modgil et al., 2021). However, these technological functions should not be equated with guaranteed operational recovery. Neither the detection of a disruption nor the generation of a recommended diversion independently establishes the availability of refrigerated transport, regulatory authorisation or delivery within an acceptable timeframe.

This distinction has direct implications for measuring resilience. Improved observability may enable more accurate identification of emerging risks without increasing the number of routes that can actually accommodate a consignment. Consequently, stress-testing approaches emphasise the preservation of essential network functions under adverse conditions rather than treating disruption awareness as sufficient evidence of resilience (Ivanov, 2022; Zamani et al., 2022). Supply-chain viability research similarly differentiates nominal connectivity from the operational ability to maintain a required service (Ivanov, 2022). The present investigation translates this conceptual separation into explicit requirements concerning corridor access, route eligibility, refrigerated capacity and delivery deadlines. Saudi-based work has demonstrated IoT-enabled monitoring of cold supply chains that gives all parties real-time visibility of storage and transport conditions (Alshdadi et al., 2024). Merely extending such visibility-to-action sequences to another disruption would contribute little additional theoretical understanding. The present study instead shifts the analytical focus towards whether a transport network preserves at least one admissible delivery itinerary within the remaining usable product-life interval. This reframing positions the executable routing alternative, rather than technological adoption itself, as the principal explanatory object. Digital capabilities become relevant when they affect route eligibility, shorten the time required to initiate a response or improve selection among alternatives that already satisfy operational requirements.

Under this formulation, delivery feasibility emerges from the simultaneous satisfaction of several necessary conditions rather than from geographical route availability alone. A candidate itinerary must accommodate the consignment's origin and applicable service

specifications, possess confirmed refrigerated transport and handling resources, preserve admissible product condition and allow sufficient time for physical movement, decision-making and mobilisation before the delivery deadline. Although these requirements draw conceptually on established research concerning perishability, monitoring, disruption propagation and maritime adaptation (Notteboom et al., 2024; Protopappas et al., 2025; Verschuur et al., 2022; Zhang & Mohammad, 2024), their integration into a single feasibility formulation constitutes the analytical development advanced here. Importantly, the resulting framework distinguishes diversions rendered impossible by physical constraints from alternatives whose feasibility may be recovered through accelerated coordination.

The broader literature on food-system disturbances also challenges interpretations of resilience as a fixed network attribute. Global research identifies adaptation processes and resilience capacities that vary according to the characteristics and circumstances of individual food supply systems (Huang et al., 2025). Related cold-chain syntheses identify continuing difficulties in converting technological monitoring capabilities into effective operational practices (Mustafa et al., 2024). Responding to these concerns, the present study formulates a more precisely bounded question: under which conditions can digital intervention alter the feasibility of an alternative delivery route before a product-specific deadline expires? The investigation addresses this question through conceptual reasoning and logical analysis rather than empirical measurement of technology-specific performance. Three research questions structure the investigation. The first concerns how exposure to Hormuz and Bab al-Mandab differs among route families supplying receivers in Saudi Arabia. The second examines the operational constraints determining whether alternative maritime itineraries remain suitable for temperature-sensitive commodities. The third identifies the conditions under which reducing digital-response latency can restore delivery feasibility. These questions are addressed through documentary evidence, formally specified routing alternatives and symbolic evaluation. The research is therefore neither a systematic literature review nor an empirical shipment-level case study.

The study contributes an origin-sensitive comparison of corridor exposure, an integrated feasibility condition incorporating physical and decision-related constraints, and a threshold-based explanation of digital-response effectiveness. These analytical elements are subsequently translated into five disruption-transmission mechanisms and eight intervention categories intended to inform operational contingency decisions. Reproducibility follows from the explicit definitions and assumptions underlying the model. The analysis does not generate national exposure proportions, refrigerated-cargo loss estimates or simulated improvements attributable to digital technologies. Maintaining this boundary between logically derived findings and empirically observed outcomes is essential to positioning the proposed framework as a falsifiable planning instrument rather than a quantitative assessment of the 2026 disruptions.

LITERATURE REVIEW AND CONCEPTUAL POSITIONING

Perishability and Digital Decision Support

The preservation of refrigerated-food quality involves considerations extending beyond whether a shipment arrives on schedule. Temperature compliance may be maintained during a delay even as the product's remaining saleable life diminishes, whereas a comparatively brief journey may involve damaging thermal excursions during inadequately controlled transfers (Mustafa et al., 2024; Protopappas et al., 2025). These differences necessitate separate treatment of physical route accessibility, accumulated transport time and product eligibility.

Temperature-monitoring records provide evidence relevant to product condition, but determining whether a consignment remains suitable for release requires an appropriate product-specific quality model or validated handling criterion. Consequently, an undifferentiated degree-hour measure cannot establish safety across heterogeneous food categories (Mustafa et al., 2024; Trotter et al., 2023).

Technological research provides complementary foundations for incorporating information into these decisions. IoT-based monitoring supports the documentation of product condition and custody throughout distribution (Protopappas et al., 2025), while artificial intelligence of things models examine cold-chain allocation decisions involving quality preservation and economic considerations (Nozari et al., 2025). More extensive scholarly reviews identify applications of artificial intelligence and advanced analytics in supply-chain resilience (Zamani et al., 2022) and general supply-chain management (Habazin et al., 2025). Collectively, these contributions establish the relevance of sensing, predictive analysis and resource allocation as inputs to operational decision-making. They do not, however, provide grounds for transferring previously reported technological performance gains to refrigerated-food movements affected by a Saudi maritime disruption. Accordingly, the present model represents digital capabilities through explicitly defined variables and information dependencies, without assigning unsupported effectiveness coefficients, consistent with reviews that describe technology-specific evidence as concentrated on isolated technologies (Müller et al., 2026).

Network Disruption and Executable Alternatives

Research on supply-chain resilience demonstrates the relevance of AI-enabled analytics to anticipating disturbance and coordinating network responses (Dubey et al., 2022; Modgil et al., 2021). Studies of the Red Sea crisis further show that adaptation is shaped by carrier services, port calls and the wider logistics network (Notteboom et al., 2024; Yap & Yang, 2024). Assessments of concurrent disruption affecting the Red Sea, Black Sea and Panama Canal reinforce the importance of examining overlapping pressures on international shipping systems (United Nations Conference on Trade and Development, 2024). These findings support a service-oriented understanding of alternative routes, in which connectivity and capacity must be assessed jointly rather than treating ports and maritime passages as geographically interchangeable options (Pratson, 2023; Verschuur et al., 2022). Broader resilience scholarship similarly distinguishes operational recovery and adaptive reconfiguration from the mere existence of redundant geographical connections (Huang et al., 2025; Ivanov, 2022). Analyses of food cold-chain management under COVID-19 disruption (Qian et al., 2022) and of regional resource disparities in cold-chain development (Fan et al., 2024) illustrate that cold-chain performance is shaped by system configuration and available physical resources.

Recent investigation of the 2026 Hormuz disruption integrates vessel-tracking information, food-price developments and multimodal transport analysis to examine wider maritime and market consequences (Goharbakhsh et al., 2026). Such aggregate evidence addresses a different analytical scale from the shipment-specific admission conditions developed in this study. The contribution advanced here is therefore not the identification of adverse food-logistics consequences associated with Hormuz restrictions, but the integrated examination of itinerary dependence, qualified refrigeration resources and response latency within a finite product-delivery budget. Accordingly, reported percentages describing transit reductions or modelled multipliers of transport costs are not extrapolated from that investigation to Saudi refrigerated-food consignments. A thematic review that frames Hormuz as a corridor-level resilience stress test (Fowler, 2026) supports the same contextual reading.

The geographical configuration of Saudi maritime access further illustrates why route dependence must be assessed at the itinerary level. Western Saudi gateways may receive shipments approaching from the Indian Ocean through Bab al-Mandab or from the Mediterranean through Suez, creating different exposure profiles despite a shared destination coastline. Similarly, discharging cargo at a gateway situated outside Hormuz does not automatically establish a completed delivery route to a Saudi receiver. The onward movement may still depend on border authorisation, temperature-controlled road transport and viable commercial arrangements. Consequently, diversification by destination coast alone cannot adequately represent independence from maritime chokepoint disruptions. This conclusion follows from geographical relationships and operational requirements; it does not constitute an empirical measurement of Saudi Arabia's refrigerated-food import routes during 2026. Saudi food-security research identifies reliance on food imports as a structural challenge (Marikar & Al Harbi, 2025) and links sustainable supply-chain and green-logistics practices to food security in the Eastern Province (Aljoghaiman, 2023).

Synthesis of the Literature and Research Gap

Table 1 synthesises the principal strands of the reviewed literature and the gap addressed here.

Table 1: Thematic Synthesis of the Literature and Research Gap

Theme	Representative sources	Principal insight	Gap addressed here
Cold-chain management and perishability	Akram et al. (2023); Fan et al. (2024); Khalid et al. (2024); Mustafa et al. (2024); Trotter et al. (2023); Zhang and Mohammad (2024)	Cold-chain performance depends on facilities, stakeholder collaboration, sustainability and risk management	The delivery deadline of a rerouted consignment is not treated as an explicit feasibility condition
IoT, AI and digital monitoring	Habazin et al. (2025); Müller et al. (2026); Nozari et al. (2025); Protopappas et al. (2025)	Sensing, prediction and optimisation support monitoring, quality preservation and cost reduction	Digital effects are not separated from physical route constraints
Supply-chain resilience and AI analytics	Dubey et al. (2022); Ivanov (2022); Modgil et al. (2021); Zhang and Mohammad (2024)	AI-enabled analytics are linked with agility, visibility and resilience capabilities	Capabilities are aggregated rather than tied to route-level conditions
Food-system resilience	Ali et al. (2022); Huang et al. (2025); Khan and Ali (2022); Qian et al. (2022)	Resilience arises from capabilities activated through action, including digitalisation under COVID-19	No condition identifies when faster action changes feasibility
Maritime chokepoints and ports	Meza et al. (2022); Notteboom et al. (2024); Pratson (2023); Verschuur et al. (2022); Yap and Yang (2024)	Chokepoint closures reroute traffic, shift port calls and propagate to supply chains	Analyses address trade and energy flows, not refrigerated delivery budgets
2026 disruption context	FAO (2026); Fowler (2026); Goharbakhsh et al. (2026); U.S. Energy Information Administration (2026); United Nations Conference on Trade and Development (2024)	Hormuz and Bab el-Mandeb constraints affect energy, fertiliser, shipping and food systems	Saudi refrigerated shipments are not quantified
Saudi food-supply context	Aljoghaiman (2023); Alshdadi et al. (2024); Marikar and Al Harbi (2025)	Import reliance, sustainable supply chains and IoT monitoring shape food security and cold-chain visibility	No route-feasibility condition is derived

Note: Themes are the author's synthesis of the sources listed; entries describe the focus of each study and do not report quantitative effects.

As Table 1 shows, cold-chain syntheses address facilities, collaboration, sustainability and risk but leave the delivery deadline implicit. Digital studies concentrate on sensing, prediction and cost optimisation, and review evidence describes technology-specific work as fragmented (Müller et al., 2026). Maritime studies document rerouting, port-call adjustment and propagation at the level of trade flows rather than at the level of a consignment with a finite usable life. Route-level feasibility of refrigerated cargo under chokepoint closure therefore sits at the intersection of three strands that have not been integrated, and this is where the present study positions its contribution.

Distinction from Visibility-Centred Saudi Cold-Chain Research

Saudi cold-chain research has so far emphasised monitoring architecture and real-time visibility across parties, illustrated by an IoT prototype with a small-scale scenario in Jeddah (Alshdadi et al., 2024). The present study develops a distinct analytical formulation incorporating itinerary-specific chokepoint dependence, an explicit refrigerated-capacity requirement and a deadline determined by product perishability. Its principal theoretical extension is the derivation of a condition specifying when shorter response latency changes the feasibility status of a candidate route. The substantive differences are detailed in Table 2.

Table 2: Analytical Separation From Visibility-Centred Cold-Chain Studies

Dimension	Visibility-Centred Study (Alshdadi et al., 2024)	Present Study
Unit of explanation	Monitoring system and its data flows	A shipment's admissible delivery option
Central question	How sensing makes storage and transport conditions visible to all parties	When corrective routing remains physically executable
Boundary condition	Device, cloud platform and cold-chain parties	Corridor access, booked capacity, product budget and latency
Analytical output	Prototype and monitoring framework	Route-state comparison and feasibility threshold
Evidence claim	Small-scale real-life scenario demonstrating feasibility	Document-grounded deductions without observed shipment effects

Note: The middle column summarises the stated aims and evidence of the cited study; it is not a performance comparison.

Table 2 shows that the two studies differ in unit of explanation, boundary condition and evidentiary claim. The present results are therefore a boundary-condition extension of visibility-centred work and not a validation of it.

MATERIALS AND METHODS

Research Design and Source Selection

The methodological approach integrates theoretical adaptation with analytical modelling, consistent with case-informed conceptual analyses of the 2026 Hormuz disruption (Fowler, 2026). The investigation is situated within the 2026 disruption context and employs purposive rather than comprehensive source selection. Its evidentiary corpus consists of twenty-eight scholarly publications supplemented by three official reports, yielding thirty-one cited sources overall. These materials fulfil distinct analytical functions: official documentation establishes

the disruption setting, academic scholarship informs the conceptual foundations of cold-chain operations and digitally supported responses, and the proposed model generates original logical deductions. Established research on supply-chain viability and resilience analytics additionally supports the adoption of clearly specified boundary conditions and scenario-based analytical reasoning (Ivanov, 2022; Zamani et al., 2022).

Source identification proceeded from targeted searches of publisher and repository records. Candidate publications were subsequently examined through targeted web searches using their exact titles and Digital Object Identifier (DOI) references, with bibliographic verification undertaken through publisher websites or relevant official institutional sources. To establish the contemporary disruption context, searches combined the terms "2026", "Hormuz" and "Bab el-Mandeb" with the respective domains of the U.S. Energy Information Administration (EIA) and the Food and Agriculture Organization of the United Nations (FAO). The earlier Red Sea assessment was independently checked through the United Nations Conference on Trade and Development (UNCTAD) website. Where accessible, publication metadata were cross-checked against publisher records. Neither Scopus nor Web of Science database exports were obtained; consequently, the investigation makes no assertion of comprehensive literature coverage or unprecedented treatment of the research topic.

Sources were restricted to publications from 2022 to 2026, with at most two items from any one journal and one from any lead author, to ensure currency and diversity. Each entry was verified against publisher or repository records for title, authors, journal, volume, pages or article number and DOI.

Eligibility for inclusion required identifiable source provenance and demonstrable relevance to a specific conceptual proposition or contextual assertion. Materials consisting exclusively of news-based incident chronologies, numerical statements lacking verifiable support, secondary market summaries without substantiating primary evidence, or prototype descriptions unsupported by datasets were excluded from the analytical evidence base. Table 3 documents the contextual evidence alongside its interpretative limitations. The remaining scholarly publications substantiate the conceptual arguments developed in Sections 1 and 2, rather than providing empirical observations of refrigerated-food shipments or logistics operations within Saudi Arabia.

Table 3: Contextual Evidence Ledger and Limits of Inference

Source and Locator	Retained Claim	Inference Limit
FAO (2026) information note	Hormuz disruption creates energy, fertilizer and agrifood risks	No Saudi reefer-level losses, delays or import-exposure share
U.S. Energy Information Administration (2026), September 2026; Global Oil Markets, printed pp. 4–5	Both corridors constrain energy movements; Saudi oil routes adjust	Oil movement is contextual evidence, not food-shipment measurement
United Nations Conference on Trade and Development (2024) rapid assessment	Multiple maritime disruptions can affect routes and trade logistics	Earlier-period evidence cannot quantify 2026 Saudi outcomes
(Alshdadi et al., 2024), Saudi IoT cold-chain study	Prototype monitoring framework with a small-scale Jeddah scenario	Monitoring evidence only; not route-feasibility or disruption measurement

Note: FAO = Food and Agriculture Organization of the United Nations; EIA = U.S. Energy Information Administration; UNCTAD = United Nations Conference on Trade and Development. Numeric source tags were replaced with APA author–date citations.

Table 3 shows that each contextual source is retained only for the claim it can support and is paired with an explicit inference limit, so none of them is used as a measurement of Saudi refrigerated-food shipments.

Scope and Observation Unit

The analytical unit is an individual candidate itinerary associated with a specified refrigerated-food consignment, a designated Saudi receiver and a particular decision point in time. The framework encompasses maritime transportation and subsequent inland distribution following arrival at the gateway. Petroleum pipelines are excluded because they do not constitute viable transport alternatives for food consignments. Although air cargo, domestic food production and inventories already held within Saudi Arabia may offer additional mechanisms for maintaining supply, these responses fall outside the four maritime routing families considered in the model. Consequently, the absence of feasible alternatives within the modelled route set must not be interpreted as evidence of nationwide food unavailability.

The analysis distinguishes four conditional routing families according to their geographical approaches and transport configurations. Family E represents shipments entering a Gulf gateway through Hormuz, whereas family W comprises movements reaching a Saudi Red Sea gateway from the southern approach via Bab al-Mandab. Family N covers access to a Saudi Red Sea gateway from the northern direction through Suez, while family O represents discharge at a gateway outside Hormuz followed by cross-border inland transportation. Each category may encompass multiple operationally distinct shipping services and associated logistics arrangements. These classifications therefore represent potential contingency-planning configurations rather than verified evidence that particular carriers operated the corresponding services during 2026. For any individual consignment, operational admissibility remains conditional on confirming origin compatibility, actual service availability, applicable authorisations and appropriate product-handling arrangements.

Variables and Feasibility Rule

Two binary indicators, H and B, describe the accessibility of the focal maritime chokepoints for a particular shipment at the relevant decision time. Specifically, H = 1 denotes that Hormuz is unavailable to the consignment, while B = 1 indicates equivalent unavailability of Bab al-Mandab; a value of zero signifies that the respective passage remains usable. These classifications are shipment-specific and time-dependent rather than universal declarations of physical closure. For example, a security-related restriction or a carrier's refusal to transit may render a corridor inaccessible to a particular shipment even when other maritime movements remain possible. Route dependence on the respective chokepoints is represented by d(r,H) and d(r,B), with the resulting corridor-access condition A(r) defined in Equation (1). Additional operational threats, including restrictions affecting Suez or interruptions at inland borders, are incorporated through the route-eligibility requirement rather than omitted from the analytical framework.

$$A(r) = [1 - H\,d(r,H)]\,[1 - B\,d(r,B)] \quad (1)$$

Table 4 shows that the model has three binary gates (G, K and Q), a corridor-access term A and three time terms (J, L and D). The gates decide whether a route exists at all, the time terms decide whether it exists in time, and F is their conjunction.

Table 4: Model Notation and Operational Interpretation

Symbol	Definition	Operational Measurement
G(r)	Origin, service and legal eligibility; binary	Confirmed itinerary, permissions and handling compatibility
K(r)	Capacity sufficient for the shipment; binary	Booked reefer slots, power, storage and onward transport
Q(r)	Product condition admissible under the candidate plan; binary	Validated commodity rules and temperature history
J(r)	Physical journey and handling time remaining	Sailing, terminal, clearance and inland time; common time unit
L(r)	Decision and execution mobilization latency	Alert or decision trigger to implementable departure or transfer
D	Maximum remaining delivery time budget	Product-specific usable life less required receiver life reserve
F(r)	Route feasibility indicator	Conjunction of all gates in Equation (2)

Note: Binary = takes the value 0 or 1. Equation numbers refer to the model equations in the text.

Refrigerated capacity is treated as a constraint at the level of confirmed service reservations, since the nominal availability of terminal infrastructure does not establish that the required transport or handling resources can be secured for an individual consignment. The delivery-time budget D is evaluated at the same decision epoch as J and L, with all temporal quantities expressed in consistent units under a specified candidate temperature regime. Where alternative itineraries involve materially different thermal conditions, a validated product-quality model must first account for these differences by establishing route-specific eligibility criteria or corresponding time budgets. Accordingly, the subsequent comparison based on a common delivery-time budget is restricted to routes satisfying the stated temperature-regime assumption and does not presume that a universally applicable conversion of product shelf life can be established.

$$F(r) = A(r)\,G(r)\,K(r)\,Q(r)\,I[J(r) + L(r) \leq D] \quad (2)$$

The indicator function I[·] takes a value of one when the specified condition is satisfied and zero otherwise. Accordingly, the set of admissible routing alternatives is defined as $S(H,B) = \{r \in \{E, W, N, O\} : F(r) = 1\}$, where F(r) is evaluated at corridor state (H,B).

Analysis and Logical Verification

The analytical procedure comprised four sequential stages. Initially, chokepoint dependencies were established according to the geographical and operational characteristics defining each route family. The resulting configurations were then evaluated across four corridor states, with all conditions unrelated to the focal chokepoints maintained constant. Subsequently, response latency was reduced from L0 to L1, where $L1 < L0$, to identify the precise interval within which this reduction changes the binary feasibility outcome. Finally, individual digital capabilities were associated with the model variables they could monitor, inform or modify, while explicitly identifying the physical interventions required to translate informational improvements into operational responses. Neither expert-derived weighting factors nor ordinal measures of technological effectiveness were introduced.

To establish the internal consistency of the analytical formulation, the non-corridor conditions specified in Equation (2) were consolidated into a single binary eligibility gate, k(r), for each routing alternative. Exhaustive enumeration was subsequently performed across all 64 possible configurations of H, B, k(E), k(W), k(N) and k(O). This procedure covers the complete set of Boolean combinations permitted by the defined model, rather than representing the full spectrum of disruption intensities encountered in operational environments. The resulting frequencies describe unweighted logical configurations and must not be interpreted as probabilities of occurrence. Appendix A documents the enumeration procedure and its outcomes, providing verification of the algebraic relationships and feasible-set comparisons. This internal consistency assessment does not constitute empirical validation of the underlying assumptions against observed shipment operations.

Assumptions and Competing Explanations

The comparative analysis assumes a fixed shipment demand lot, a common decision epoch and unchanged non-corridor eligibility conditions across the evaluated route configurations. Actual maritime disruptions may, however, simultaneously alter refrigerated-capacity availability, transport duration and the accessibility of associated logistics services. Such variations must be incorporated through reassessment of the corresponding feasibility gates rather than being automatically attributed to restrictions affecting either focal chokepoint. Comparable operational difficulties may also originate from adverse weather, seasonal fluctuations in demand, routine regulatory inspections, inland traffic congestion or refrigeration-equipment shortages that predate the disruption. In the absence of a longitudinal shipment-level dataset, the investigation cannot empirically isolate the contribution of these competing explanations. Accordingly, its findings are formulated as conditional analytical deductions rather than estimated causal effects of the 2026 events.

RESULTS

Route Exposure Is Conditional on Approach Direction

The specified routing families yield the chokepoint-dependency relationships presented in Table 5 and Figure 1. Family E requires access through Hormuz, whereas family W depends on the availability of Bab al-Mandab. By contrast, families N and O are defined as independent of both focal passages. Such independence must not be interpreted as freedom from wider maritime, border-crossing or temperature-related constraints. For consignments originating in Asia, access through family N may necessitate a substantially longer voyage around Africa before approaching the destination from the Mediterranean. The same routing family may provide a more geographically direct connection for cargo originating in the Mediterranean region. In either situation, geographical accessibility alone is insufficient to demonstrate commercial or operational feasibility unless all remaining eligibility, capacity and product-time requirements are satisfied.

Table 5 shows that exposure is route-specific: E depends only on Hormuz, W only on Bab al-Mandab, and N and O on neither. A receiver's exposure therefore cannot be read from the destination coast alone.

Table 5: Route Families and Focal Corridor Dependence

Route	Itinerary Condition	d(r,H)	d(r,B)	Additional Qualification
E	Gulf entry through Hormuz	1	0	Origin must not require another unmodeled restricted passage
W	Red Sea entry from the south	0	1	Service must reach the Saudi gateway and onward receiver
N	Red Sea entry from the north through Suez	0	0	Suez access and a compatible origin or longer itinerary
O	Outside-Hormuz landing and inland border transfer	0	0	Cross-border permits, cold transfer and onward capacity

Note: d(r,H) and d(r,B) = dependence of route r on Hormuz and Bab al-Mandab (1 = dependent, 0 = independent). E = Gulf entry through Hormuz; W = Red Sea entry from the south; N = Red Sea entry from the north through Suez; O = outside-Hormuz landing with inland border transfer.

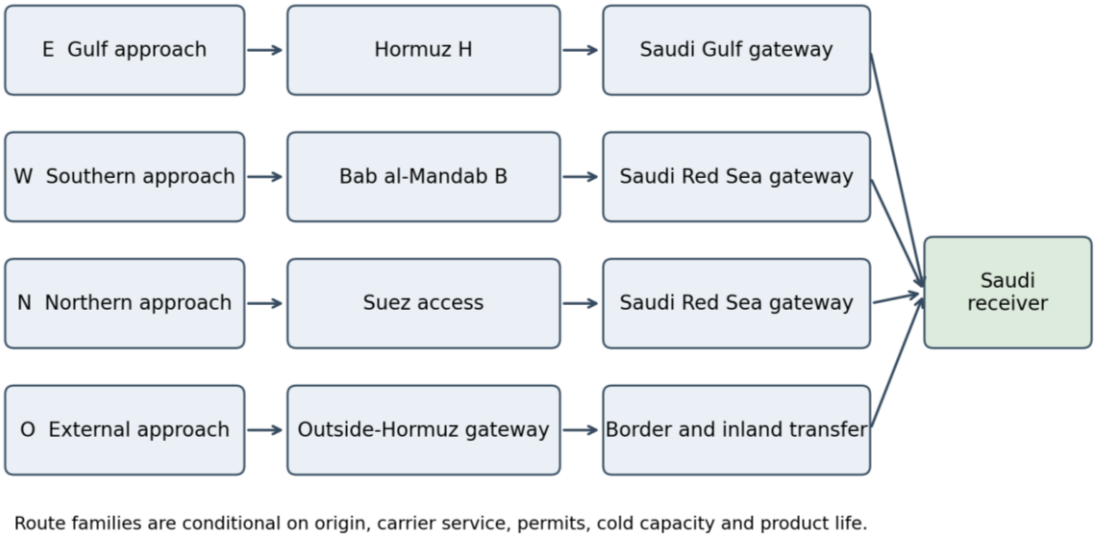


Figure 1: Conditional Route Families Serving a Saudi Receiver

Note: The schematic represents itinerary dependence, not observed 2026 traffic, geographic scale, or guaranteed commercial services. All routes remain subject to Equation (2).

Figure 1 visualises the dependence pattern in Table 5: the two Gulf and southern Red Sea approaches pass through a focal strait, whereas the northern and outside-Hormuz approaches avoid both but carry their own qualifications.

Let e, w, n and o represent routing families E, W, N and O, respectively, conditional on satisfaction of their associated non-corridor feasibility gates. Failure to satisfy any such gate excludes the corresponding alternative from the admissible route set. Table 6 presents the feasible-set expressions for all four corridor configurations. When the remaining model conditions are held constant, restricting access to a maritime chokepoint cannot expand the set of feasible alternatives; it can only preserve or contract that set. Accordingly, S(1,1) is a subset of both S(1,0) and S(0,1), while each of these sets is, in turn, a subset of S(0,0). This monotonic relationship follows directly from Equation (2) and constitutes an exact mathematical property of the specified feasibility formulation. It does not imply that observed shipments underwent the corresponding sequence of corridor restrictions or changes in routing availability.

Table 6 shows that the candidate set shrinks from four routes when both corridors are open to three when either is restricted and to two (N and O) when both are restricted. Each restricted state is a subset of the open state, so restrictions can only preserve or contract the set, and continuity under dual restriction rests entirely on N and O.

Table 6: Four-State Route Comparison With Non-Corridor Conditions Held Fixed

H	B	Admissible Members If Individually Qualified	Decision Implication
0	0	{e, w, n, o}	Compare all qualified itineraries
1	0	{w, n, o}	Southern Red Sea access can substitute only if qualified
0	1	{e, n, o}	Gulf access can substitute only if qualified
1	1	{n, o}	Continuity requires a qualified bypass of both focal straits

Note: H = 1 and B = 1 indicate that Hormuz and Bab al-Mandab, respectively, are unavailable to the consignment. Members are admissible only if individually qualified under Equation (2).

The first finding consequently establishes a distinction between gateway diversification and corridor diversification, demonstrating that these strategies do not necessarily provide equivalent protection against disruption. Multiple gateways may depend on the same restricted maritime approach, whereas destinations situated along a common coastline may remain accessible through geographically distinct approaches. An alternative-port inventory that disregards the direction of vessel movement may therefore exaggerate the independence of available transport options. Conversely, classifying every western Saudi gateway as dependent on Bab al-Mandab may overlook feasible northern approaches. Both forms of misclassification arise at the route-definition stage, independently of subsequent assessments of temperature compliance or product deterioration.

Physical Alternatives Are Necessary but Insufficient

When H = B = 1, at least one of the two corridor-independent routing families, N or O, must satisfy every non-corridor feasibility requirement for delivery to remain possible within the modelled network. This condition is both necessary and sufficient under the specified route definitions. The geographical existence of a bypass does not constitute an executable alternative when either route eligibility G or confirmed refrigerated capacity K equals zero. Moreover, satisfying G = K = Q = 1 does not establish feasibility if the combined physical journey duration and response latency exceed the remaining delivery-time budget, such that J + L > D. The second analytical finding therefore identifies the shipment–service–product combination as the appropriate level for evaluating operational resilience, rather than relying exclusively on geographical network connectivity.

Exhaustive logical verification identified nine configurations with no admissible routing alternative among the 64 evaluated combinations. When both maritime passages remained accessible, the feasible set was empty under one of the 16 possible non-corridor gate configurations. Restricting either chokepoint individually increased this count to two of 16 configurations, whereas simultaneous restrictions produced four empty configurations among the corresponding 16 combinations. These results describe the Boolean structure of the analytical formulation and carry no probabilistic interpretation. They neither represent observed disruption frequencies nor provide estimates of shipment failure, logistics reliability or national food security in Saudi Arabia. Instead, the enumeration verifies that nominal

corridor accessibility cannot ensure delivery continuity when all remaining routing candidates fail one or more necessary operational conditions.

In interpretive terms, the nine empty configurations (1, 2, 2 and 4 of 16 across the four states) show that closing a corridor removes members and multiplies the ways in which no deliverable alternative remains. The counts are logical, not empirical.

Digital Response Has a Specific Restoration Interval

To establish the circumstances under which accelerated digital coordination can recover an otherwise infeasible delivery option, consider a candidate route satisfying A = G = K = Q = 1. Let its physical transport duration J remain constant, and distinguish the baseline response latency L0 from the reduced latency L1. The residual delivery-time margin is defined as M = D − J. Under these conditions, reducing response latency converts the route from infeasible to feasible if and only if the inequality specified in Equation (3) is satisfied.

$$L1 \leq M < L0, \quad where\, M = D - J\, and\, 0 \leq L1 < L0 \quad (3)$$

The result follows directly from the binary feasibility indicator defined in Equation (2). Under the baseline response arrangement, infeasibility occurs when J + L0 > D, which is equivalent to M < L0. Following the reduction in latency, the route becomes feasible only when J + L1 ≤ D, corresponding to M ≥ L1. Combining these two requirements produces the necessary and sufficient restoration condition expressed in Equation (3). Where M < 0, the physical journey itself exceeds the available delivery-time budget, meaning that no reduction in nonnegative response latency can recover feasibility. Conversely, when M ≥ L0, both response arrangements already satisfy the delivery deadline, although faster intervention may still yield improvements in transportation cost, service performance or product quality. Figure 2 illustrates these analytical boundaries without introducing empirically estimated temporal values.

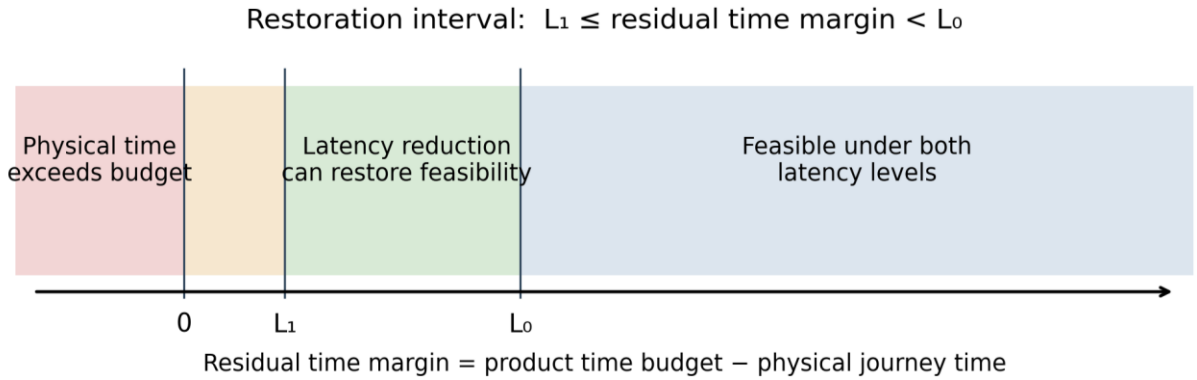


Figure 2: Analytical Response-Latency Boundary

Note: Positions are schematic and have no measured time scale. The restoration region begins at L1 and ends strictly before L0; a negative physical margin cannot be repaired by latency reduction alone.

Figure 2 shows three regimes: below zero margin no latency reduction helps, within [L1, L0) faster response decides feasibility, and at or above L0 both responses already meet the deadline.

The third finding challenges the assumption that the operational value of digital technologies necessarily diminishes as physical constraints become more restrictive. Such a relationship is not universally monotonic. When a shipment approaches the feasibility threshold, even a

marginal reduction in decision-making latency may determine whether its delivery remains admissible. By contrast, once the physical transport requirement substantially exceeds the available time budget, faster information processing cannot restore feasibility for that route. The contribution of digital intervention is therefore governed by the residual delivery-time margin and the availability of an actionable response, rather than by disruption severity in isolation. Monitoring technologies may identify the remaining margin, but they cannot independently increase it.

The analytical formulation isolates response latency to establish a clearly identifiable mechanism linking digital intervention with changes in delivery feasibility. Other technological capabilities may influence different components of the model: route optimisation may identify an alternative with a different physical journey duration J, capacity coordination may enable confirmation of refrigerated resources represented by K, and condition-monitoring systems may inform reassessment of product eligibility Q or the applicable delivery-time budget. Each mechanism constitutes a distinct intervention whose operational effectiveness requires separate supporting evidence. Aggregating these effects into a single, undifferentiated artificial intelligence (AI) contribution would conceal the specific feasibility constraint being modified and weaken the explanatory precision of the framework.

Transmission Mechanisms and Intervention Points

Five distinct transmission mechanisms are identified to explain how maritime corridor disruptions may affect the operational conditions governing delivery feasibility. These mechanisms are analytically derived from the proposed model and supporting literature rather than empirically coded observations of refrigerated-food spoilage in Saudi Arabia. Table 7 differentiates the immediate logistical consequences of disruption from their potential implications for product condition and commercial acceptability. Maintaining this distinction avoids two misleading interpretations: assuming that every transport delay necessarily produces a temperature excursion and presuming that every successful diversion automatically prevents product loss.

Table 7: Maritime-to-Cold-Chain Transmission Mechanisms

Mechanism	Intermediate Process	Affected Terms and Conditional Consequence
M1 Access restriction	Service refusal, corridor avoidance or itinerary removal	A and G; a route may disappear before arrival delay is observed
M2 Gateway and handoff pressure	Rebooking, clearance and storage coordination	K, J and L; alternative gateway is usable only with complete onward arrangements
M3 Longer exposure duration	Longer sailing or inland movement under refrigeration	J and D; saleable life can diminish without a temperature breach
M4 Reefer and power mismatch	Equipment repositioning, plug or cold-store reservation failure	K and Q; intact access is insufficient without temperature-control continuity
M5 Commercial response delay	Freight approval, insurance acceptance or fragmented decisions	G and L; late authorization can exhaust an otherwise adequate margin

Note: Terms in the last column refer to the model variables defined in Table 4.

Table 7 shows that each mechanism acts on a specific model term, so a transport delay can remove a route (A, G), consume the margin (J, D) or delay authorisation (G, L) without any temperature breach.

These transmission mechanisms may operate simultaneously and reinforce one another. Restrictions on corridor accessibility can redirect cargo demand towards alternative gateways, increase physical transit duration and progressively reduce the residual response-time margin as refrigerated equipment and associated services are rebooked. Although the analytical framework accommodates concurrent changes across these pathways, the four-state comparison intentionally holds non-corridor conditions constant to isolate the effects of chokepoint dependence. Consequently, practical application requires comprehensive reassessment of the entire routing configuration following any operational change, including the onward inland transport segment, rather than simply substituting one destination-port designation for another. Table 8 maps eight digital capabilities to the variables they can affect.

Table 8: Digital Capability Map With Explicit Action Requirements

Capability	Variable or Decision Supported	Physical or Organizational Requirement
C1 Condition telemetry	Q and product-budget reassessment	Calibrated sensors, representative placement and a qualified disposition decision
C2 Shared exception visibility	L and synchronized handoffs	Authorized decision owner and accessible carrier, terminal and receiver records
C3 Predictive reefer maintenance	K and Q through equipment reliability	Validated failure model, maintenance access and replacement equipment
C4 Route and gateway analytics	G, A and J across candidate itineraries	Current service acceptance, permits and feasible onward transport
C5 Shelf-life-aware allocation	D and destination matching	Validated commodity rules and receivers able to accept the available life
C6 Capacity coordination	K across refrigeration handoffs	Enforceable slot, power, storage and truck reservations
C7 Scenario or digital-twin analysis	Stress tests of S(H,B)	Verified network inputs; infeasibility reported explicitly
C8 Document interoperability	G and L at clearance and custody changes	Accepted documentation and accountable human release authority

Note: The map is a taxonomy of potential interventions and does not report effectiveness ratings.

The intervention framework deliberately avoids assigning qualitative effectiveness classifications, such as strong, medium or weak, to individual technological capabilities. Improved predictive accuracy may leave delivery feasibility unchanged when a candidate route remains disqualified by another operational constraint. Conversely, a straightforward shared authorisation instruction may preserve an otherwise unavailable delivery alternative if it reduces response latency sufficiently to satisfy Equation (3). Accordingly, the capability map constitutes a structured taxonomy of potential interventions rather than a system of expert-derived ratings or empirically quantified treatment effects.

Table 8 shows that every capability is tied to a physical or organisational precondition, so a capability changes feasibility only where its precondition is met.

DISCUSSION

Contribution to Digital Resilience Research

The principal theoretical contribution lies in redirecting the evaluation of digital resilience from the availability of information towards the preservation of operationally executable alternatives. Existing scholarship establishes the relevance of sensing technologies, analytical capabilities and coordinated disruption responses to supply-chain resilience (Dubey et al., 2022; Modgil et al., 2021; Zamani et al., 2022). Saudi cold-chain monitoring work similarly treats real-time visibility to all parties as a basis for decision making (Alshdadi et al., 2024). Extending these foundations, the present analysis identifies a necessary boundary condition governing that progression: information can change delivery feasibility only when it enables modification of an operational constraint within the remaining product-specific time budget. Consequently, a monitoring platform may accurately anticipate delivery failure without providing any intervention capable of preventing it. This distinction accords with supply-chain viability research, which emphasises the preservation of essential operational functions under disruptive conditions rather than information availability alone (Ivanov, 2022).

Recognising this boundary condition also necessitates reconsideration of the indicators used to evaluate digital resilience. Measures such as forecasting accuracy, the frequency of automated alerts and the extent of platform adoption provide limited evidence concerning whether an executable delivery alternative has actually been maintained. A more operationally discriminating assessment would establish whether an intervention converts a candidate route from $F = 0$ to $F = 1$ or improves a specified performance objective within an already nonempty feasible set. These outcomes represent analytically distinct forms of benefit and therefore require different empirical evaluation strategies. Demonstrating restored feasibility necessitates identifying the binding operational constraint and establishing when the intervention occurred, whereas evaluating improvements among admissible alternatives requires comparative evidence concerning cost, product quality or service performance.

The route-dependent formulation additionally qualifies broader claims about regional logistics resilience. Although Saudi Arabia's access to two coastlines creates potential opportunities for geographical diversification, the exposure of an individual refrigerated-food consignment remains contingent on its origin, complete itinerary, carrier acceptance and subsequent inland distribution arrangements. Adaptations documented within Saudi petroleum-export logistics therefore cannot independently establish equivalent resilience among refrigerated-food imports (U.S. Energy Information Administration, 2026). Official evidence concerning oil-routing adjustments provides a contextual basis for examining interacting maritime corridors, while conclusions about food-specific routing feasibility remain conditional analytical deductions requiring operational verification.

Capacity and Information Are Complements with Thresholds

Refrigerated-resource availability and accelerated operational coordination may provide complementary contributions to delivery continuity. Reserving an appropriate temperature-controlled vehicle offers limited practical benefit when the necessary authorisation is received

after the product's delivery-time budget has expired. Equally, rapid authorisation cannot recover an otherwise infeasible route when suitable refrigerated transport is unavailable. Nevertheless, this complementarity should not be interpreted as evidence that increasing spare capacity necessarily amplifies the measurable feasibility benefit of reducing response latency. Where sufficient operational slack already exists, both baseline and accelerated responses may satisfy the delivery deadline. The greatest discrete change in the binary feasibility outcome arises when an otherwise eligible route crosses the threshold established by Equation (3).

This threshold-based interpretation provides a more targeted basis for resilience investment decisions. Before allocating resources to increasingly sophisticated predictive technologies, importers should determine whether the principal binding constraint concerns corridor accessibility, confirmed refrigerated capacity, product eligibility or the time required to mobilise a response. Additional analytical capabilities may be appropriate where uncertainty conceals an executable alternative or delays the authorisation needed to activate it. Conversely, when the decisive restriction originates outside the information system, maintaining reserved physical resources or establishing alternative sourcing arrangements may be necessary. These implications are deductions from the proposed feasibility framework and do not constitute evidence that particular Saudi enterprises have implemented the recommended measures successfully.

Operational Implications for Saudi Importers and Coordinators

An operational contingency register should extend beyond destination-port information to document each consignment's origin, complete transport itinerary, maritime corridor dependencies, commodity-specific handling requirements, confirmed refrigerated resources, customs and clearance obligations, and receiving-site criteria governing acceptable remaining product life. Candidate alternatives should retain provisional status until sufficient evidence supports satisfaction of every feasibility condition. Because carrier acceptance and capacity reservations may change during disruption, confirmations should be accompanied by timestamps identifying their validity at the relevant decision point. Furthermore, multiple destination ports should not be treated as independent contingency options when their associated services rely on a common restricted passage or the same unreserved downstream resource. This emphasis on complete and executable transport arrangements is consistent with evidence that chokepoint closures shift port activity and can disrupt supply chains long after a blockage is cleared (Pratson, 2023; Yap & Yang, 2024).

The escalation of operational exceptions should be governed by comparison between the remaining delivery-time margin and a realistic interval for decision-making and mobilisation. When the available margin exceeds baseline response latency, operators may retain sufficient flexibility to compare admissible alternatives according to cost, quality and service considerations while preserving a temporal buffer. Where the margin falls within the restoration interval separating baseline and accelerated response, prompt escalation can directly determine whether delivery remains feasible. If no qualified itinerary can satisfy the remaining time budget, the appropriate decision shifts towards compliant product disposition, alternative supply arrangements or demand allocation. Such decisions must continue to observe commodity-specific safety and regulatory requirements; the analytical feasibility condition does not permit the release of food whose condition fails applicable acceptance standards.

For maritime authorities, terminal operators and public-sector coordination bodies, the framework identifies the value of appropriately aggregated information concerning carrier acceptance, refrigerated-resource availability and the status of logistics handoffs. Aggregate port-throughput statistics, although potentially informative for network planning, cannot independently confirm whether a particular shipment satisfies the requirements for operational admission. Effective governance should therefore assign clear responsibilities for verifying individual feasibility conditions and authorising subsequent routing changes. Interoperability among information systems becomes operationally meaningful when it accelerates an identifiable decision or strengthens assessment of a specified eligibility condition, rather than merely expanding the number of digitally connected organisations.

Falsifiable Implications and Empirical Validation

Four propositions translate the analytical deductions into testable empirical expectations. P1: after controlling for shipment origin and non-corridor eligibility, the unavailability of a focal maritime passage reduces the set of usable alternatives only among routes dependent on that passage. P2: for candidate itineraries satisfying corridor-access, refrigerated-capacity and product-eligibility requirements, reduced response latency restores delivery feasibility exclusively when the residual time margin crosses the interval defined in Equation (3). P3: diversification indicators based solely on the number of available ports overstate operational continuity when additional gateways depend on a common chokepoint or share a binding downstream resource. P4: where physical constraints render a route ineligible, enhanced monitoring alone cannot restore compliant delivery, although it may improve disruption diagnosis or subsequent product-disposition decisions.

Empirical examination of these propositions would require an integrated shipment-level dataset connecting consignment and lot identifiers with time-stamped itinerary modifications, carrier-service refusals, confirmed transport bookings, terminal-processing and border-clearance events, refrigerated-storage handoffs, equipment availability, sensor-calibration records, temperature histories and final product-acceptance or disposal outcomes. Separate analyses would be necessary for different commodity categories because their handling requirements and deterioration characteristics are not interchangeable. Corridor dependence, verified refrigerated capacity and response latency would constitute principal explanatory measures, while observed outcomes should distinguish physical arrival, acceptance based on product quality and remaining commercially usable life. Importantly, absent or incomplete temperature records must not be classified as evidence of satisfactory thermal compliance.

A rigorous operational evaluation of P2 would need to reconstruct the information available to decision-makers at the actual decision epoch, rather than retrospectively substituting realised journey durations for forecasts that were necessarily uncertain at the time. Similarly, comparing organisations using digital technologies with those lacking such systems, without accounting for differences in available spare capacity, would confound informational advantages with pre-existing physical preparedness. Quasi-experimental investigation would therefore require a credible comparison group alongside explicit assessment of anticipatory route adjustments and concurrent disruptive events. As a less demanding preliminary approach, prospective audits could compare recorded classifications of binding constraints with subsequent routing decisions and delivery outcomes. None of these proposed empirical validation procedures has been undertaken within the present investigation.

Comparison with Prior Evidence

The deductions are consistent in direction with documented 2026 evidence while remaining distinct in scale. Goharbakhsh et al. (2026) report that overland rerouting raised ton-kilometre costs and emissions relative to direct maritime transit while remaining cheaper than shipping burdened by war-risk surcharges, which fits the treatment of family O as an executable but capacity- and permit-dependent bypass. The same study finds no statistically distinguishable short-horizon response of a global food-price index, which supports the point that aggregate price indicators cannot show whether individual refrigerated consignments retained a feasible route. Studies of the Red Sea crisis show that carriers adjust routing and port calls (Notteboom et al., 2024; Yap & Yang, 2024), which is why carrier acceptance is modelled as a gate and not assumed. Evidence from a developing-country cold chain lists digitalisation and securing of logistics among resilience strategies (Khan & Ali, 2022), and regional resource differences constrain cold-chain development (Fan et al., 2024); the present results add that such strategies change feasibility only when the binding constraint is time-related.

LIMITATIONS AND FUTURE RESEARCH

The principal limitation concerns the absence of external empirical validation. Although the reported findings follow logically from explicitly defined assumptions, they do not quantify actual logistics performance during the 2026 disruptions. Representing chokepoint accessibility through binary indicators necessarily simplifies conditions involving partial restrictions, selective security threats and changing carrier transit policies. Similarly, the four routing families abstract from more complex transshipment arrangements and exclude several potential sources of food supply. Treating refrigerated capacity as a binary condition at the individual-shipment level does not capture competition for shared resources among simultaneous consignments. Moreover, exhaustive Boolean enumeration establishes logical completeness within the specified model but does not provide probability distributions for real-world disruption scenarios.

The delivery-time formulation is also subject to deliberately restricted interpretation. Its application requires commodity-specific qualification and does not independently estimate microbial proliferation, sensory degradation or other product-deterioration processes. The latency-restoration proof additionally assumes that physical journey duration remains constant, whereas operational implementation would need to account for transport-time uncertainty through appropriate intervals or probability distributions. Under an interval-based formulation, robust admission could require the upper bound of physical journey duration, combined with response latency, to remain within a conservatively specified delivery budget. Establishing defensible bounds would require additional empirical investigation. Existing cold-chain scholarship reinforces the importance of commodity characteristics, handling procedures and validated quality-assessment methods in determining such requirements (Mustafa et al., 2024; Trotter et al., 2023).

Further limitations arise from the purposive approach to source selection, which may exclude relevant scholarly contributions. Although official publications concerning energy transport and agrifood systems substantiate the contextual significance of maritime disruption, they do not provide comprehensive records of individual vessel movements or refrigerated-food consequences. Accordingly, the study makes no assertion that both focal straits remained continuously closed, nor does it estimate Saudi Arabia's national import dependence, the

proportion of food consignments exposed to disruption or any causal increase in refrigerated-food spoilage. These evidentiary restrictions limit the generalisability of the findings but do not undermine the transparency or reproducibility of the route-dependence and response-latency deductions.

Future research should assemble shipment-level datasets to test propositions P1 to P4, extend the model with interval or probabilistic journey times, and develop commodity-specific quality models that fix route-specific delivery budgets.

CONCLUSIONS

Maintaining the continuity of Saudi Arabia's refrigerated-food supply chains during the 2026 disruptions affecting Hormuz and Bab al-Mandab requires more than enhanced shipment visibility or the identification of geographically alternative gateways. Operational resilience depends on the complete itinerary through which a consignment reaches its receiver, the availability of confirmed temperature-controlled logistics resources, compliance with product-specific eligibility requirements and the time remaining for an executable response. The analysis establishes that maritime corridor exposure is route-dependent, while the feasibility of alternative delivery arrangements is jointly determined by physical constraints and product-life limitations. It further identifies the precise conditions under which accelerated digital coordination can recover an otherwise inadmissible delivery option, as well as the circumstances in which physical restrictions make such recovery impossible. The investigation advances a route-dependent delivery-feasibility model, a comparison across four maritime corridor states and a threshold condition connecting digital-response latency with product-specific delivery-time budgets. Five disruption-transmission mechanisms and eight categories of digital capability translate these analytical relationships into operationally interpretable intervention points. The findings are derived from explicitly stated assumptions, supported by relevant scholarly literature and situated within an officially documented disruption context, without introducing unverified field observations or unsupported statistical estimates. Their principal contribution is to establish a falsifiable basis for evaluating digital resilience through the preservation of executable delivery alternatives. Rather than treating technological visibility as evidence of continuity, the framework directs attention towards which admissible routing option an intervention can preserve, under what refrigerated-capacity and product-eligibility conditions, and within which remaining delivery-time interval.

Author Contributions

The manuscript is prepared as a sole-author contribution by Bandar Altubaishe.

Declaration of Generative AI Use

During preparation of this manuscript, ChatGPT (OpenAI) was used to assist with literature discovery, drafting, analytical formalization, logical checking, reference verification, figure preparation and document formatting. The author must review and approve the full content and accepts responsibility for the submitted work. The tool was not used to fabricate field data or statistical results.

Abbreviations

AI, artificial intelligence; EIA, U.S. Energy Information Administration; FAO, Food and Agriculture Organization of the United Nations; IoT, Internet of Things; UNCTAD, United Nations Conference on Trade and Development.

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APPENDIX A REPRODUCING THE LOGICAL ANALYSIS

A1. Define the route dependence pairs as E = (1,0), W = (0,1), N = (0,0) and O = (0,0). For each route, k(r) is the conjunction of origin/service eligibility, sufficient reserved capacity, qualified product condition and the time test. This collapse is used only for Boolean verification; operational applications should retain the separate terms.

A2. Execute the following Python code. The assertion checks the full counts and the conditional counts of empty sets. The script uses only the Python standard library. Enumeration assigns no empirical likelihood to any state. Route gates held constant across corridor states are a logical comparison device, not a claim that real capacity remains unchanged during disruption.

```
from itertools import product
dependencies = ((1, 0), (0, 1), (0, 0), (0, 0))
empty = {(h, b): 0 for h, b in product((0, 1), repeat=2)}
total = 0
for h, b, *k in product((0, 1), repeat=6):
    feasible = [ki * (1-h*dh) * (1-b*db)
                for ki, (dh, db) in zip(k, dependencies)]
    empty[(h, b)] += int(not any(feasible))
    total += 1
assert total == 64
assert empty == {(0, 0): 1, (0, 1): 2,
                 (1, 0): 2, (1, 1): 4}
assert sum(empty.values()) == 9
print(total, empty)
```

A3. Independently verify the latency result by substituting M = D − J into Equation (2). Baseline failure is M < L0, improved success is M ≥ L1, and their intersection is [L1, L0). Equality at the improved threshold admits the route; equality at baseline means the baseline was already feasible. This boundary convention is necessary for reproducibility.

A4. Reuse requires recording the decision timestamp, route origin and dependencies, source and validity period of each booking, definition of the time budget, temperature qualification, assumed physical journey time and intervention latency. If a gate is unknown, report the route as unconfirmed rather than silently assigning eligibility. The calculation should then be repeated under documented alternatives or conservative bounds.