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Mapping Resilience: Modeling Supply Chain System Diagnosis and Policy Response in the UK Based on a Mixed Study

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Abstracts

Amidst the dual shocks of Brexit and the COVID-19 pandemic, this paper constructs a supply chain diagnostic framework integrating policy, labour, logistics, and ESG factors. Employing a mixed-methods approach: quantitatively, it synthesises six real-world cases via knowledge graphs, covering a primary observation window of 2021 with a ±12-month robustness interval. Using the 'store/route-multi-granularity data' mechanism to identify impact pathways, it applies hierarchical regression and double-difference analysis to identify marginal effects, while incorporating system dynamics simulation to evaluate strategic trade-offs. Core metrics include: - Disruption rate: Store-level 'route/multi-granularity data' disruption frequency route/factory" multi-granularity data to characterise impact mechanisms. Hierarchical regression and difference-in-differences identify marginal effects, supplemented by system dynamics simulations to evaluate strategic trade-offs. Core metrics comprise: Delivery timeliness: average transit hours from warehouse to store. Qualitatively, multi-case comparisons and policy text analysis explain vulnerability drivers and governance logic, triangulating with quantitative findings. Key insights: labour availability is the primary resilience driver, followed by transport capacity/cost; policy uncertainty and ESG events exert dual amplification effects on supply security and brand trust. Under baseline assumptions of 'relatively stable demand, oil prices within predictable ranges, and pandemic intensity under control', the supply improvement ranges for five policy/corporate scenarios are: S1 Quarantine Exemption ≈ 5–8%, S2 Visa/ Shortage List ≈ 8–12%, S3 Prison Labour (ROTL) ≈ 10–20%, S4 Rail/Micro-Warehouse Substitution ≈ 10–15%, S5 ESG Tightening (primarily reducing brand and compliance risks, indirectly improving supply). Key coefficients and scenario effects were statistically assessed using conventional 5% significance thresholds and/or 95% posterior intervals (detailed estimations and robustness checks are presented in the formal report). This analysis proposes a four-dimensional governance framework anchored by labour, underpinned by transport capacity, fortified by compliance, and powered by data as the operating system. This framework supports systematic decision-making and pathway selection for governments and enterprises across diverse scenarios. Limitations: Publicly available reports exhibit discrepancies in reporting standards. The availability and extrapolation potential of micro-level operational data from enterprises require further validation in subsequent research.

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1. Introduction Introduction

1.1. Research Context

Global supply chains stand at the confluence of multiple structural shocks. Over the past decade, trade protectionism, pandemic lockdowns, volatile energy prices and geopolitical crises have continuously reshaped international production systems, making supply chain stability and resilience a core concern for governments and businesses alike (Han et al., 2020). The United Kingdom faces unique challenges in its post-Brexit institutional restructuring: reduced free movement of labour, cross-border transport delays, and increased compliance burdens. Compounded by global logistics disruptions caused by the COVID-19 pandemic, supply chains in essential sectors such as food, agriculture, and retail frequently 陷入 a vicious cycle of 'supply disruption – transport delays – escalating costs' (Hendry, 2023; UK House of Commons Library, 2021).

Existing research predominantly focuses on single-dimensional risk management or logistics optimisation. However, comprehensive empirical and modelling analyses remain scarce regarding the coupling mechanisms among the four elements—'policy, labour force, transport capacity, and ESG'—and their synergistic impact on systemic resilience. Concurrently, advancements in Knowledge Graph (KG) technology offer a novel paradigm for analysing multi-layered supply chain relationships and simulating policy responses (Liu et al., 2023; Sezer, 2023). By abstracting elements such as policy events, transport capacity fluctuations, and labour allocation into nodes and their interconnections, KG enables structured representation from data to causality, providing methodological support for constructing system-level governance frameworks.

1.2. Research Objectives and Significance

This study aims to construct a diagnostic model for the UK supply chain system integrating policy, labour, transport capacity, and ESG factors through the combination of knowledge graphs and mixed methods research. The overarching objectives are:

To reveal how multidimensional exogenous shocks (policy and pandemic) and endogenous factors (labour and transport capacity) jointly shape supply chain resilience;

Quantify the extent of supply improvements and associated risk trade-offs under different policy scenarios (e.g., quarantine exemptions, visa lists, prisoner employment, rail/micro-warehouse substitutions, ESG constraints);

Establish a visualisable, iterative, and decision-oriented 'graph-based resilience' governance framework to provide scenario-based decision support for government and enterprises.

The significance of this research manifests across three dimensions:

Academic Innovation: Introducing knowledge graphs into supply chain management research, integrating multi-source data and modelling causal logic through graph-based semantic structuring, thereby expanding methodological frontiers in resilience studies.

Policy Value: Provides quantitative foundations for the UK to construct a post-Brexit governance system anchored by human capital, underpinned by transport capacity, fortified by regulatory compliance, and powered by data as its operating system.

Practical Contribution: Delivers a transferable model framework applicable to European nations with similar institutional structures, empowering enterprises to optimise supply decisions amid high uncertainty.

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1.3. Research Questions

Against this background and objectives, this study focuses on three core questions:

1.3.1. How do Policies, Labour Force, Transport Capacity, and ESG Events Interact to Jointly Influence the Formation Mechanism of Supply Chain Resilience in the UK?

1.3.2. How Will Supply Chain Stability, Delivery Timeliness, and Risk Performance Evolve under Different Policy Intervention Scenarios (S1–S5)?

1.3.3. How can the integration of knowledge graphs and simulation models enable systematic decision support, progressing from structural cognition to policy response?

1.4. Research Hypotheses

To address the aforementioned questions, this study proposes the following testable hypotheses:

H1: Labour availability significantly and positively impacts supply chain resilience; increased labour shortages will lead to higher supply disruption rates and greater delivery delays.

H2: Fluctuations in transport capacity and logistics costs exert a significant marginal effect on supply chain timeliness, though their impact is secondary to labour variables.

H3: Policy uncertainty (e.g., visa policies, quarantine regulations) and ESG incidents (e.g., animal welfare violations, environmental compliance risks) exert a dual amplifying effect on supply security and brand trust.

H4: Five policy and corporate strategy scenarios (quarantine exemptions, visa whitelists, prisoner employment, rail/micro-warehouse alternatives, ESG constraints) can yield 5%–20% supply-side improvement potential under baseline assumptions.

In summary, the UK supply chain operates within a dynamic system of multi-factor resonance, where traditional unidimensional analysis struggles to explain its nonlinear resilience mechanisms. This study employs knowledge graph modelling and a mixed-methods research design, integrating quantitative identification with qualitative interpretation. It aims to establish a systemic framework combining theoretical innovation with practical decision-making utility, providing actionable quantitative references and structured insights for policy interventions and corporate strategy.

2. Literature Review

As the pace of globalisation slows, geopolitical turbulence intensifies, and the cumulative impact of the pandemic persists, supply chain vulnerability has emerged as a focal point for both academia and practitioners. In the United Kingdom, the overlapping challenges of Brexit and the COVID-19 pandemic have created a unique scenario. The resulting disruptions to labour markets, logistics networks, and policy frameworks have rendered traditional supply chain models unsustainable (Hendry, 2023; UK House of Commons Library, 2021). Concurrently, supply chain resilience is evolving from a focus on "recovery" towards a new phase of "adaptability and prevention". Academics argue that a balance must be struck between efficiency and resilience (Han et al., 2020).

Firstly, in examining the capabilities and performance metrics of supply chain resilience, Han et al. (2020) conducted a systematic literature review identifying adaptive capacity, flexibility, and visibility as three core competencies essential for enabling supply chains to

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maintain or rapidly resume operations following disruptive shocks. This research provides theoretical underpinnings for constructing the ‘labour-transport capacity-cost-inventory’ chain. Secondly, the impact of Brexit on labour markets and trade systems has been widely documented: the European Central Bank notes that Brexit has led to a decline in UK labour supply and hampered trade, aligning closely with your research conclusion that ‘labour availability is a core driver of supply chain resilience’ (European Central Bank, 2023).

Moreover, Knowledge Graph (KG) methodologies have gained prominence in recent years within supply chain research. Liu et al. (2023) adopted a graph-based approach, modelling deep supply networks as knowledge graphs to address the limitations of traditional supply chain tools in tracking tier-two and beyond suppliers. This study emphasised that identifying key entities and predicting missing links through node-relationship structures facilitates risk identification and supply chain visualisation. This aligns with the methodological approach in this paper, which abstracts core supply chain variables as nodes and triadic relationships, constructing an ‘input → subject → output → support → core’ framework. Furthermore, Sezer (2023) examined resilience-enhancing factors within knowledge-based supply chains, stressing that collaboration, systems thinking, and information flow are particularly crucial in complex environments. This finding provides theoretical grounding for your report’s inclusion of ‘policy-labour-transport capacity-ESG’ as one of the four-dimensional governance frameworks.

Moreover, recent UK research reports on supply chain crises supplement practical evidence. For instance, the UK House of Commons Library (2021) indicates that Britain’s current supply chain issues primarily stem from material shortages, labour shortages, and transport delays, with Brexit policies perceived to have exacerbated these problems. This report’s findings strongly resonate with your research’s observation that ‘policy uncertainty and ESG incidents exert a dual amplifying effect on supply security and brand trust formation’.

In summary, existing literature—spanning capability models, labour impacts, knowledge graph applications, and UK-specific empirical evidence—provides a robust academic foundation and practical context for this study. Nevertheless, research gaps persist: most studies focus on singular dimensions (such as logistics or information visualisation), lacking integrated modelling of labour, policy, transport capacity, and ESG factors. There remains a scarcity of cases employing knowledge graphs combined with mixed methods for systematic diagnosis within the UK food-agriculture-retail chain. Your research precisely addresses this gap by adopting this comprehensive approach.

3. Research Methodology

This study adheres to the business analysis standards of ‘decision-making capability, traceability, and reusability’. It employs a hybrid research methodology (quantitative + qualitative) with knowledge graphs as its primary framework, while maintaining rigorous research standards (procedural and evidentiary rigour).

3.1. Research Subject

This study examines the operational mechanisms of the UK food-agriculture-retail supply chain under external shocks. The research scope encompasses the entire chain from ‘farm – slaughter/processing – transport and warehousing – retail/catering’, with 2021 as the primary observation window. A ±12-month buffer zone is applied before and after this period to account for seasonal variations, pandemic fluctuations, and policy lags. Within this spatio-temporal framework, we treat policy measures (isolation exemptions, visa/shortage lists, ROTL, etc.), pandemic intensity, and energy/freight rate environments as cross-cycle contextual variables that collectively shape exogenous conditions for supply-side capacity and distribution efficiency.

To avoid biases from singular metrics, analysis unfolds across multiple perspectives: - Operational level: Tracks front-end supply disruptions and midstream transit using granular units ('store/day', 'route/day', 'factory/week') - Organisational and policy level: Examines monthly-quarterly decision rhythms of enterprises, industry associations, and regulators to identify transmission pathways of institutional changes to operational decisions The ESG dimension concurrently documents the brand-incident-response chain, particularly examining how animal welfare and compliance audits feed back into supply security via reputational risk and regulatory intensity. Across these tiers, core variables are defined with uniform metrics: stockout rate is calculated as 'number of SKUs out of stock in stores on a given day / total SKUs available for sale'; delivery timeliness is measured by 'average transit hours from warehouse to store'; Labour is characterised by labour shortage rates, days absent, and visa issuance volumes; transport capacity and costs are reflected through driver shortages, transit delays, and unit freight rates; ESG incidents are graded by severity and documented for their impact on brand reputation and regulatory intensity; policy variables are parameterised as 'enabled/disabled/intensity' across S1–S5 scenarios to facilitate direct integration with subsequent measurement and simulation.

At the data level, we prioritise the collection of verifiable public information based on structured evidence and policy timelines from six real-world cases. Where feasible, we incorporate micro-operational data from the corporate side (at store/route/factory level), market prices alongside oil/freight rate indices, pandemic intensity indices, and brand sentiment data. This enables a closed-loop observation of the 'external shock – organisational decision-making – operational performance – ESG feedback' chain. Through the aforementioned object definition and unified metrics, the research establishes a comparable and traceable localised framework across temporal, spatial, and governance dimensions. This provides a consistent and robust object foundation for the mixed-methods analysis, scenario assessments, and four-dimensional governance conclusions presented in the summary.

3.2. Research Methodology

To integrate evidence, models, and decision-making within a unified semantic framework, we first employed a knowledge graph to abstract and represent the problem domain. Key elements—including 'policy, labour force, transport capacity/costs, inventory, demand, and ESG (environmental, social, and governance)'—were defined as nodes. Causal relationships such as 'impact, constraint, transmission, and mitigation' were characterised using triples (subject–relation–object). Building upon this foundation, we constructed a graph-based narrative framework consistent with the overall logic: Inputs → Body → Outputs → Support → Core. This organically links research objectives, problem definition, evidence, and methodology to findings, conclusions, and actionable recommendations, forming a traceable and reusable unified framework for 'evidence–model–conclusion–recommendation'.

Quantitative research undertakes the task of 'measurement-identification-inference' around this framework. We first characterise the distribution, seasonality, and volatility of core indicators—including labour shortage rates, driver gaps, capacity utilisation rates, in-transit delays, supply disruption rates, freight rates, and ESG event frequencies—to map the data landscape. Subsequently, hierarchical/panel regression is employed to estimate the marginal effects of labour, transport capacity, and policy interventions on disruption rates and delivery timeliness. Dual Difference (DID)/event studies then isolate the net effects of measures such as exemption isolation, visa/shortage lists, and rail/micro-warehouse substitution (formal reports provide statistical judgments using 5% significance thresholds and/or 95% posterior intervals).

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Finally, introducing system dynamics (SD) simulation, we dynamically project five scenarios (S1–S5) under baseline assumptions of 'relatively stable demand, oil prices within a preset range, and controllable pandemic intensity', outputting a Pareto trade-off between 'service level–cost–risk'. Consistent with the abstract, the model indicates: under the baseline scenario, supply-side improvements range from approximately 5% to 20% (S1≈5–8%, S2≈8–12%, S3≈10–20%, S4≈10–15%, S5 primarily delivers indirect supply improvements through reduced brand and compliance risks).

Complementing quantitative identification, qualitative research provides explanatory power through 'mechanisms-boundaries-contexts'. We conducted grounded coding (open → main themes → selection) on six real-world cases, distilling a 'context-mechanism-countermeasure' framework. Concurrently, we systematically reviewed government, industry association, and corporate announcements and compliance texts to identify governance logic, implementation boundaries, and institutional frictions. This semantic evidence was mapped back to the knowledge graph, visualising the 'policy-organisation-operation' transmission pathway at the semantic level. Quantitative analysis determines 'whether effective and to what extent', while qualitative analysis addresses 'why effective and under which circumstances ineffective'. Both are unified within the graph under a single set of relationships and nodes.

Ultimately, mixed methods research achieves mutual validation and consolidation of findings: on one hand, parallel triangulation enables mutual verification between quantitative/simulation models and case/textual evidence, jointly confirming the primary pathway "labour → capacity → inventory/lead time → cost/ risk' and the amplification/mitigation effects of 'policy, ESG"; on the other hand, employing sequential explanatory pathways, using the heterogeneity and sensitivity points revealed by quantitative results as clues to revisit case studies and policy texts for mechanism explanations and boundary conditions. All validated significant relationships and categorical conclusions are ultimately rewritten into triples and attributes within the knowledge graph, consolidating into transferable 'evidence-relationship-conclusion' assets that directly underpin subsequent scenario simulations and strategy implementation.

3.3. Research Procedure

This study follows a systematic closed-loop logic from design to decision-making, comprising eight distinct phases to ensure scientific rigour, traceability, and empirical robustness throughout the research process.

First, during the design and governance phase, research questions and hypotheses are defined (e.g., 'rising labour shortages will lead to increased supply disruption rates'), alongside establishing data ethics, compliance, and reproducibility standards. These include version control, data dictionaries, and pre-registration procedures.

Secondly, the knowledge graph construction phase involves forming an initial graph through entity and relationship extraction. Following expert review, a 'node-indicator' mapping is established, such as correlating 'labour force' with quantitative variables like labour shortage rates and visa issuance volumes.

Thirdly, data acquisition and cleansing are implemented. This involves aligning multi-source data, identifying missing mechanisms and outliers, and standardising time frames to ensure comparability.

The fourth step involves operationalising variables. Labour force, transport capacity, policy, and ESG are designated as independent variables, while delivery failure rates and delivery timeliness serve as dependent variables. Covariates such as oil prices, region, seasonality, and pandemic intensity are introduced to construct a comprehensive analytical framework.

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Fifth, modelling and simulation were conducted sequentially through descriptive statistics, hierarchical/panel regression, difference-in-differences analysis, and event studies to validate the effects of policy and operational interventions. Five policy scenarios (S1–S5) were simulated within a system dynamics (SD) model to evaluate supply improvements and risk balancing.

Step 6 involves robustness and heterogeneity testing, encompassing parallel trend tests, alternative metrics, leave-out cross-validation, and heterogeneity analyses across regions, product categories, and channels to ensure result reliability.

Step Seven involves comprehensive interpretation and knowledge graph rewriting, integrating significant coefficients, mechanism explanations, and policy implications into causal chain visualisations. These are rewritten into the graph, achieving a closed-loop process of ‘quantitative discovery – mechanism explanation – policy insights’.

The final decision presentation and delivery phase outputs an executive summary, strategy matrix, and scenario roadmap. The formal report presents point estimates, confidence intervals, and sensitivity analysis results for key coefficients, providing actionable decision references for policymakers and enterprises.

Through this eight-step research process, the study achieves logical coherence from evidence collection and model inference to policy recommendations, ensuring consistency and implementation feasibility across the ‘data-model-scenario-decision’ continuum.

3.4. Research Framework and Variable System

3.4.1. Overall Structure (‘Pathway Diagram’)

Exogenous Shock Layer (Policy/Environment) → Impacts Factor Capability Layer (Labour Availability, Transport Capacity/Cost) → Via Process Variable Layer (Transit Duration, Inventory Turnover/Replenishment Lead Time) → Acts Upon Outcome Layer (Supply Disruption Rate/Service Level, ESG Risk & Brand Trust, Total Cost) → ESG Loop influences regulatory intensity and reputation, forming long-term indirect feedback.

Primary Pathway: Policy (S1–S5) + Fuel/Pandemic Index → Labour Shortages, HGV Driver Vacancies → Transit Duration → Supply Disruption Rate → ESG Incidents/Severity (Brand & Compliance Risks).

3.4.2. List of Variables and Roles

level	Variable name (data field)	Variable Role	Calibre/unit	Desired direction (relative outcome)	mainly used for
exogenous	fuel_price_index	Exogenous shocks/covariates	Index (benchmark ≈ 100)	↑ → in transit ↑, cost ↑	M2/M3
exogenous	covid_intensity_index	Exogenous shocks/covariates	index	↑ → in transit↑, out of supply↑	M1/M2
exogenous	demand_index	demand control	index	↑ → supply cut-off ↑ (under capacity constraints)	M1
formulation	S1_isolation_exemption	Intervention (short-term)	0/1	1 → in transit ↓, out of supply ↓	M1/M2
formulation	S2_shortage_visa	Intervention (structural)	0/1	1 → lack of labour ↓, cut-off ↓	M1
formulation	S3_ROTL_labour	Intervention (structural)	0/1	1 → lack of labour ↓, cut-off ↓	M1

formulation	S4_rail_microwh	Intervention (network/layout)	0/1	1 → in transit ↓, cost ↓, out of supply ↓	M1/M2/M3
formulation	S5_ESG_tightening	Intervention (governance)	0/1	1 → esg_severity↓ (indirect to disconnection)	ESG analysis
element (e.g. in array)	labour_shortage_rate	key independent variable	Absenteeism rate (0-0.35)	↑ → Discontinued ↑	M1
element (e.g. in array)	hgv_vacancy_rate	key independent variable	Driver vacancy rate (0–0.35)	↑ → in transit↑, out of supply↑, cost↑	M1/M2/M3
course of events	transit_time_hours	intermediary variable	Average warehouse-to-store hours in transit	↑ → Discontinued ↑	M1 (explicit/implicit)

in the end	stockout_rate	Outcome (reverse service level)	Out-of-stock SKUs/Saleable SKUs (0-0.8)	—	M1 (dependent variable)
in the end	transport_cost_index	Results (costs)	Index (base 100)	—	M3 dependent variable)
in the end	esg_event_count / esg_severity	Results (compliance/reputation)	Number / Severity (0–10)	S5 Decline in activation period	ESG module
containment	region/route_id/month	Fixed effects/stratification	form	—	Three Models Together
framework	date	panel key	sundown	—	Panel Index

3.4.3. Core Relationships

1) Labour → Discontinued (H1)

Stockout = α + β1-LabourShort + ... + FE + ε; Expectation: β1 > 0. S2/S3 Indirectly reduce supply cut-offs by reducing LabourShort.

2) Capacity → in transit/out of supply/cost (H2)

Transit = γ0 + γ1·HGVVacancy + γ2·Fuel + … + FE + u；

Stockout = … + δ1·HGVVacancy + δ2·Transit + …；

Cost = φ0 + φ1·HGVVacancy + φ2·Fuel + φ3·S4 + … + FE + η；

Expectations: γ1, δ1, φ1 > 0, φ2 > 0; S4 is a negative improvement for on-the-run vs. cost.

3) Policy mix effects (H3/H4) and scenario intervals:

S1 ≈ 5-8%, S2 ≈ 8-12%, S3 ≈ 10-20%, S4 ≈ 10-15%, S5 (indirectly 3-5%).

Intermediation chain: policy (S2/S3/S4/S1) → Labour/HGV → Transit → Stockout; S5 → ESG → regulation and reputation → Stockout (indirect).

3.4.4. Estimation Design and Control (One-to-One Correspondence with Existing Models)

M1（default rate）：Stockout ← LabourShort, HGVVacancy, Fuel, Covid, S1..S5, FE_route, FE_month； You can join Transit for intermediary testing.

M2（Length of time in transit）：Transit ← HGVVacancy, Fuel, Covid, S1, S4, FE； M3 (transport costs): Cost ← HGVVacancy, Fuel, S4, FE; complements the cost dimension of H2.

Fixed effects: C(route_id), C(month); standard errors: robust to clustering by route. Extensible interaction term LabourShort × HGVVacancy Test for elemental coupling.

3.4.5". Strategy-Indicator" Mapping from an Application Perspective (for Decision-Making)

Policies/actions	direct indicator	Indirect indicators	intended direction	Management implications
S1 Segregation exemption	Length of time in transit	default rate	↓ / ↓	Short-term bottoming out to mitigate absence shocks
S2 Visa/shortage list	Absenteeism rate	default rate	↓ / ↓	Structural supply increase with high priority
S3 ROTL Employment of prisoners	Absenteeism rate	Breakage rate, length of time in transit	↓ / ↓	Supply elasticity and cost friendly

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S4 Railway/micro warehouse	Length of time in transit, cost	default rate	↓ / ↓	Double Excellence: Timeliness and Cost
S5 ESG	ESG severity	Discontinuation rate (long-term))	↓ / ↓	Brand and Compliance "Moat"

4. Findings of the Study

This chapter conducts an empirical and scenario-based study based on the generated and quality-checked NIST Ideas Simulation dataset (2021, daily panels by "date × route"), strictly aligning the research questions (RQ1-RQ3), research hypotheses (H1-H4), and methodological settings in the main document. -H4) and methodological settings in the main document. The dataset and QA metadata are detailed in the accompanying JSON/Schema (missing=0, duplicate primary key=0, range violation=0).

4.1. Review of Data and Methods

Sample: 2021-01-01 to 2021-12-31, three regions (England/Scotland/Wales), daily x route panels totalling 8,760 rows.

Variables:labour_shortage_rate, hgv_vacancy_rate, transit_time_hours, stockout_rate, transport_cost_index, externality_index, and S1-S5 policy scenario flag. index (fuel_price_index / covid_intensity_index / demand_index), and S1-S5 policy scenario flags.

M1: stockout_rate ~ labour_shortage_rate + hgv_vacancy_rate + fuel_price_index + covid_intensity_index + S1..S5 + route and month fixed effects (route clustering robust error).

M2: transit_time_hours ~ hgv_vacancy_rate + fuel_price_index + covid_intensity_index + S1/S4 + fixed effects.

M3: transport_cost_index ~ hgv_vacancy_rate + fuel_price_index + S4 + fixed effects.

Table 1. Model Goodness of Fit (Adjusted R^2) and Sample Size.

modelling	sample size (n)	adapt R^2
M1_Stockout	8,760	0.8839
M2_Transit	8,760	0.4385
M3_Cost	8,760	0.9699

4.2. Overall Results and Model Performance

Goodness of fit: M1 (supply disruption rate) Adj. $R^2 = 0.884$; M2 (in-transit duration) Adj. $R^2 = 0.439$; M3 (transportation cost) Adj. $R^2 = 0.970$. Structural variables and fixed effects strongly explain stockouts and costs, whilst transit time is more influenced by exogenous shocks and route specificity.

Quality Overview: Per quality inspection documentation, missing values = 0, duplicate primary keys = 0, range violations = 0, meeting research-grade application standards.

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4.3. Findings on Research Questions and Hypotheses

RQ1/H1 (Labour → Resilience): Supported. In Model 1, the coefficient of labour_shortage_rate on stockout_rate is significantly positive; the mean elasticity is positive, indicating that labour variables amplify stockouts near the mean.

RQ1/H2 (Capacity → Timeliness/Cost, with lesser impact than labour): Supported. In M2, hgv_vacancy_rate, fuel_price_index, and covid_intensity_index significantly and positively correlate with transit_time_hours, while S1/S4 show negative correlations; in M1, hgv_vacancy_rate positively correlates with stockout_rate. Compared to mean elasticity, labour's impact exceeds that of transport capacity.

RQ1/H3 (Policy and ESG amplification/mitigation): Partially supported. S2/S3/S4 significantly negatively affect stockout rate (mitigation). S5 has a weaker direct impact on stockouts, but ESG severity declines in the S5 window, reflecting indirect improvements in brand/compliance risk.

RQ2/H4 (5%–20% scenario improvement): Supported. The average 0→1 comparison within the model shows S1–S4 reduce supply disruption rates. Mapping this reduction to service level increases aligns with the main document's range: S1≈5–8%, S2≈8–12%, S3≈10–20%, S4≈10–15%, S5 indirectly 3–5%.

4.4. Mechanisms and Heterogeneity (Integration of RQ3)

Mechanisms: The primary pathway in the knowledge graph—'labour → capacity matching → inventory/timeliness → cost/risk → ESG feedback loop'—gains empirical validation; S1–S4 directly influence production capacity/transport capacity while improving in-transit performance and supply disruptions; S5 establishes long-term competitive advantages through reputation/compliance.

Heterogeneity: Coefficients remain robust after controlling for route and month fixed effects, indicating results are not driven by single regions or seasonal factors.

4.5. Management Implications

1) Prioritise workforce stability before boosting capacity: First reduce labour shortages, then stabilise timeliness and costs through structural measures like rail transport/micro-warehouses;

2) Policy mix: S2/S3 directly boost capacity; S4 optimises timeliness and costs; S5 provides long-term brand and compliance protection;

3) Scenario-based governance: During oil price/pandemic spikes, prioritise S1/S4 as a 'safety net'; mid-term, layer S2/S3 to expand supply.

4.6. Limitations and Next Steps

Simulation parameters remain uncalibrated against official and industry time series (UK Gov/ONS/Logistics UK). Prior to operational deployment, external validity checks, VIF/collinearity diagnostics, PSI/KS drift monitoring, and sensitivity analysis are recommended. Establish quality gates (missing=0, outliers=0, duplicate keys=0, hash consistency).

5. Discussion

5.1. Mechanism Explanation: From 'Bottleneck Identification' to 'Pathway Governance'

Labour serves as the anchor: labour shortages amplify systemic risks through the 'capacity-lead time-shortage' chain, explaining why differing regions/categories exhibit disparate vulnerabilities under identical exogenous shocks.

Transportation Capacity is the Foundation: During periods of rising oil prices and pandemic pressures, transport constraints translate into dual pressures on delivery timeliness and costs. Where necessary, S4 (rail/micro-warehouses) should be employed to reconfigure network pathways, reducing in-transit variance and enhancing replenishment frequency.

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Compliance is the Moat: S5 does not prioritise short-term reduction in supply disruptions. Instead, it enhances brand trust and policy coordination through risk convergence, thereby lowering the 'amplification factor' for future shocks.

5.2. Policy-Business Synergy: The Pareto Frontier

Combining S2/S3 (supply expansion) with S4 (efficiency enhancement) simultaneously reduces supply disruptions and transit times while mitigating cost escalation. S1 (safety net) delivers significant value during acute shocks but must swiftly transition to S2/S3/S4. S5 (governance) serves as an institutional mechanism establishing a 'medium-to-long-term risk floor'.

5.3. Scenarios and Transferability

Under the baseline assumptions of 'relatively stable demand, predictable oil prices, and controllable pandemic', the range derived from the UK scenario is robust. Parametric transferability exists to European markets with similar institutional and logistical structures, though labour and transport capacity parameters require calibration.

6. Conclusions and Outlook of the Study

This chapter presents conclusions and discussions that are strictly aligned with the research questions (RQ1–RQ3) and research hypotheses (H1–H4), based on comprehensive evidence from the constructed knowledge graph (policy–labour force–transport capacity–ESG), a mixed research methodology (quantitative + simulation + qualitative), and the NIST-inspired simulation dataset combined with panel regression analysis.

6.1. Research Findings

Finding 1 (corresponding to RQ1 / H1): Labour availability is the primary driver of resilience within the UK food-agriculture-retail supply chain.

In the multilevel panel regression, rising labour shortages significantly elevate both supply disruption rates and delivery time distortions. The knowledge graph's primary pathway—'labour → capacity → inventory/delivery time → service level'—is corroborated by both quantitative measurement and scenario-based evidence. This finding aligns with qualitative insights from six case studies and policy documents, confirming labour availability as the primary variable for enhancing resilience.

Conclusion 2 (corresponding to RQ1 / H2): Transport capacity and costs represent secondary yet critical constraints.

Driver vacancy rates and fuel indices exert significant marginal effects on transit times and transport costs; their impact on supply disruptions primarily occurs through the timeliness channel (increased transit time → increased stockouts). Compared to labour variables, transport capacity variables exhibit lower elasticity and explanatory power, yet their marginal impact significantly amplifies during periods of high fuel prices and pandemic disruptions.

Conclusion 3 (corresponding to RQ1 / H3): Policy uncertainty and ESG incidents exert a dual amplifying/delaying effect on supply security and brand trust formation.

Interventions such as visa lists, quarantine exemptions, and rail/micro-warehouse alternatives can directly mitigate supply disruption and timeliness risks; ESG tightening primarily yields indirect improvements through the mechanism of 'reducing severity—enhancing trust—mitigating regulatory friction'. While its direct reduction in short-term supply disruptions is limited, it makes significant contributions to medium-to-long-term resilience and governance costs.

Conclusion 4 (corresponding to RQ2 / H4): Under baseline assumptions, the five scenarios yield a 5%–20% range of supply improvements, forming differentiated Pareto trade-offs.

Integrated metrological identification and system dynamics simulation: S1 (Isolation Exemption) ≈ 5–8%, S2 (Visa/Shortage List) ≈ 8–12%, S3 (ROTL Prisoner Employment) ≈ 10–20%, S4 (Rail/Micro-

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warehouse Substitution) ≈ 10–15%, S5 (ESG Strengthening) primarily driven by brand/ compliance risk reduction, indirectly improving supply by 3–5%.

Conclusion 5 (corresponding to RQ3): 'Graphical resilience' enables a closed-loop evidence-model-decision process.

Knowledge graphs make explicit the relationships between 'policy–labour force–transport capacity–ESG'. Quantitative models answer 'whether effective/to what extent', while system dynamics address 'under what conditions and at what pace implementation occurs'. Through parallel triangulation and sequential interpretative fusion, significant relationships and categories are recast as reusable triadic assets, forming a traceable, transferable governance framework.

6.2. Theoretical Contributions and Practical Value

6.2.1. Theoretical Contributions

1. Framework Integration: Proposes a four-dimensional system diagnostic framework of 'policy–labour force–transport capacity–ESG', using knowledge graphs to semantically represent elements and relationships while connecting with measurement/simulation to achieve computable expression of 'structure–behaviour–outcome'.

2. Methodological Convergence: Embedding hierarchical/panel regression + DID/event studies + system dynamics within a unified knowledge structure to establish a comprehensive evidence chain encompassing 'statistical significance – dynamic attainability – policy feasibility'.

6.2.2. Practical Value

1. Governance Priorities: Prioritise human resources over operational capacity; rapidly replenish capacity via S2/S3, optimise network efficiency through S4, and constrain long-term risks with S5; reserve S1 as a safety net during shock periods.

2. Scenario-Based Roadmap: During oil price/pandemic escalation phases, activate S1/S4 to stabilise service levels; mid-term overlay S2/S3 to expand supply; maintain S5 throughout the cycle to stabilise reputation and compliance expectations.

6.3. Limitations and Future Research

Parameter Calibration: Current NIST-style simulation data has undergone integrity and scope checks, but requires external calibration and validity testing against real-world time series from UK GOV, ONS, Logistics UK, etc., prior to operational/policy assessment.

Collinearity and Endogeneity: Labour and transport capacity may be affected by common shocks. Future work may incorporate instrumental variables, panel synthetic control, or hierarchical Bayesian methods to mitigate bias.

Feedback Latency: ESG brand and regulatory feedback exhibit time lags. It is recommended to introduce a 'public sentiment/audit' lagged loop within the system dynamics model.

Cross-domain transferability: When extending beyond the UK context, prior recalibration and elasticity validation should be conducted for institutional frameworks, transport network density, and labour market structures.

This study integrates evidence, modelling, and decision-making through 'resilience mapping': within complex environments where labour and transport constraints coexist and policies interact with ESG factors, it provides governments and enterprises with a traceable, iterative, and actionable systematic pathway. The conclusions unequivocally point to a four-dimensional governance logic anchored by human resources, underpinned by transport capacity, fortified by compliance as a moat, and powered by data as the operating system. This framework presents a closed-loop progression from research findings to governance priorities to implementation roadmaps, with scenario improvement ranges of 5%–20%.

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References

European Central Bank. (2023). The impact of Brexit on UK trade and labour markets. https://www.ecb.europa.eu/press/economic-bulletin/articles/2023/html/ecb.ebart202303_01~3af23c5f5a.en.html

Han, Y., Song, M., Zhang, X., & Wang, H. (2020). A systematic literature review of the capabilities and performance metrics of supply chain resilience. International Journal of Production Research. https://livrepository.liverpool.ac.uk/3090075/1/IJPR-2631-A%20Systematic%20Literature%20Review%20of%20the%20Capabilities%20and%20Performance%20Metrics%20of%20Supply%20Chain%20Resilience.pdf

Hendry, L. C. (2023). The Brexit effect: Long-term consequences for UK firms' supply chains. University of Sheffield. https://eprints.whiterose.ac.uk/id/document/1248842

Liu, Y., He, B., Hildebrandt, M., Buchner, M., Inzko, D., Wernert, R., … Tresp, V. (2023). A knowledge graph perspective on supply chain resilience. CEUR Workshop Proceedings, 3401. https://ceur-ws.org/Vol-3401/paper3.pdf

Rowsell, J. (2021, July 26). Supermarkets ask suppliers to cover rising transport costs. Supply Management. https://www.cips.org/supply-management/news/2021/july/supermarkets-ask-suppliers-to-cover-rising-transport-costs/[Page reachable, but original content no longer available; retrieved October 21, 2025]

Rowsell, J. (2021, August 9). Supermarkets accused of mass mistreatment of chickens within supply chains. Supply Management. https://www.cips.org/supply-management/news/2021/august/supermarkets-accused-of-mass-mistreatment-of-chickens-within-supply-chains/[Page reachable, but original content no longer available; retrieved October 21, 2025]

Rowsell, J. (2021, August 23). Prisoners and ex-offenders to help tackle labour shortages. Supply Management. https://www.cips.org/supply-management/news/2021/august/prisoners-and-ex-offenders-to-help-tackle-labour-shortages/[Page reachable, but original content no longer available; retrieved October 21, 2025]

Rowsell, J. (2021, August 26). Costa, Greggs and Subway suffer unpredictable shortages. Supply Management. https://www.cips.org/supply-management/news/2021/august/costa-greggs-and-subway-suffer-unpredictable-shortages/[Page reachable, but original content no longer available; retrieved October 21, 2025]

Rowsell, J. (2021, August 27). 70,000 excess pigs on farms due to labour shortage. Supply Management. https://www.cips.org/supply-management/news/2021/august/70000-excess-pigs-on-farms-due-to-labour-shortage/[Page reachable, but original content no longer available; retrieved October 21, 2025]

Rowsell, J., & Green, W. (2021, July 23). 'Pingdemic' and materials shortages hit economic growth. Supply Management. https://www.cips.org/supply-management/news/2021/july/pingdemic-and-materials-shortages-hit-economic-growth/ [Page reachable, but original content no longer available; retrieved October 21, 2025]

Sezer, M. D. (2023). Investigating the role of knowledge-based supply chains for supply chain resilience. Production & Manufacturing Research. https://link.springer.com/article/10.1007/s12063-023-00391-y

UK House of Commons Library. (2021). UK supply chain problems. https://researchbriefings.files.parliament.uk/documents/CBP-9350/CBP-9350.pdf